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SEMINAR ON GEOPHYSICAL INVESTIGATIONS IN THE PENINSULAR SHIELD

May 27—31, 1963

HELD IN THE
GEOLOGY DEPARTMENT, OSMANIA UNIVERSITY,
HYDERABAD.

EDITORS:
M. S. KRISHNAN AND S. BALAKRISHNA

Sponsored by the University Grants Commission

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DR. D. S. KOTHARI
Chairman, University Grants Commission
New Delhi.

Geophysics is one of the most important subjects, both from the point of view of fundamental study and in relation to the development of the natural resources of the country. I am confident the Seminar which you are organising would serve a most useful purpose, and I wish you all success.

Yours sincerely,

(D. S. KOTHARI)

Report on the Seminar on "Geophysical Investigations on Peninsular Shield" organised by the Geology Department of the Osmania University, Hyderabad, under the auspices of the University Grants Commission.

Introduction

THERE has been a long-felt need to hold seminars on Geophysics relating to the Peninsular Shield so that all scientific workers in the field of Geophysics could congregate together and discuss their relative problems in their respective fields. With this view, the Geology Department of the Osmania University, which itself has been conducting researches in this line, approached the University Grants Commission for a generous grant to organise the Seminar. The U. G. C. very kindly acceded to this request and gave enough financial assistance to conduct the Seminar on "Geophysical Investigations on the Peninsular Shield" in Hyderabad during the last week of May 1963.

Planning the Seminar

Collection of active geophysical research workers, special invitees and more senior men has to be done meticulously carefully. A list of invitees mainly from the universities and research institutions were therefore drawn up as a first step in this direction. The planning and organising the seminar was done by Dr. S. Balakrishna, Head of the Geology Department, who is also the Assistant Director of the National Geophysical Research Institute, guided by Dr. M. S. Krishnan, Director, NGRI. Dr. Krishnan's vast experience in the field of Geology and Geophysics and his mature advice has always been forthcoming freely, and, taking advantage of him, a list of specialists in different fields of geophysics was drawn up. In fact an approach to hold this seminar was made as early as October 1962 and several senior scientists readily promised to cooperate in the first instance. This list was originally restricted only to members of the universities, research institutions and professional organisations like the Geological Survey of India and the Oil and Natural Gas Commission. The Council of Scientific and Industrial Research fixed the date of the meeting

of the Geophysics Research Board of the NGRI on 27th May 1963. Taking advantage of this meeting, the holding of the seminar was also decided for 27th May to 31st May 1963 as most of the members of the Geophysics Research Board belonging to the India Meteorological Department, Geodetic Survey, Ministry of Defence, etc., could participate in the seminar and give the benefit of their valuable experiences. Dr. D. S. Kothari was approached to participate in the seminar but he expressed his inability to do so owing to important engagements in Delhi. He was however kind enough to send the following message to the seminar.

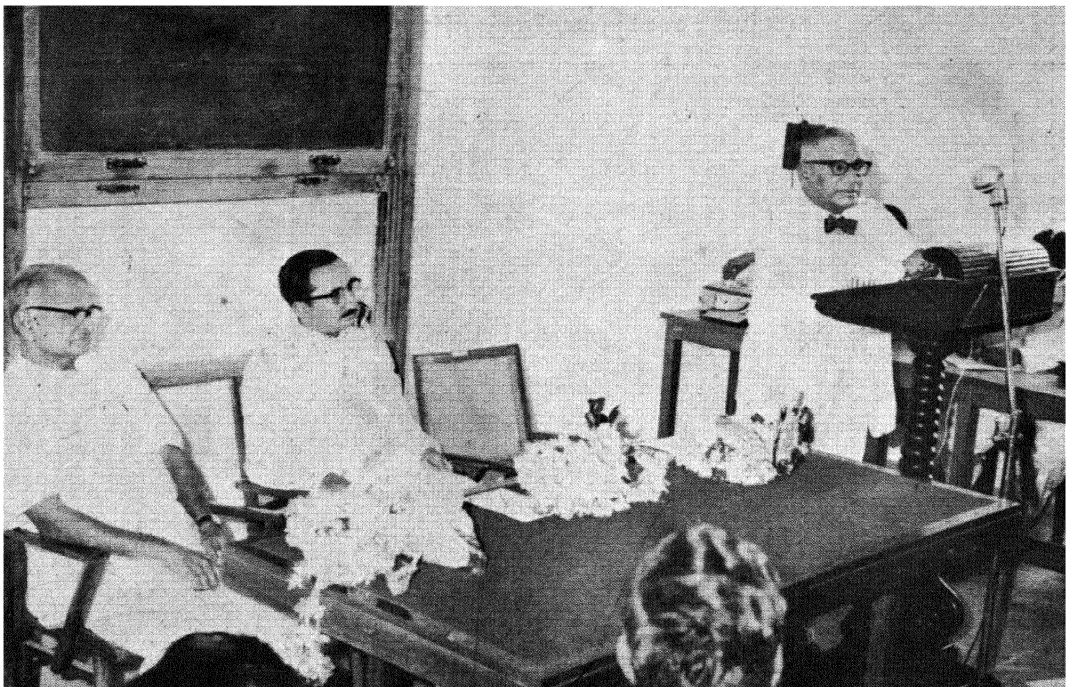
"Geophysics is one of the most important subjects, both from the point of view of fundamental study and in relation to the development of the natural resources of the country. I am confident the Seminar which you are organising would serve a most useful purpose and I wish you all success".

A list of participants together with their designations is attached (Enclosure 1).

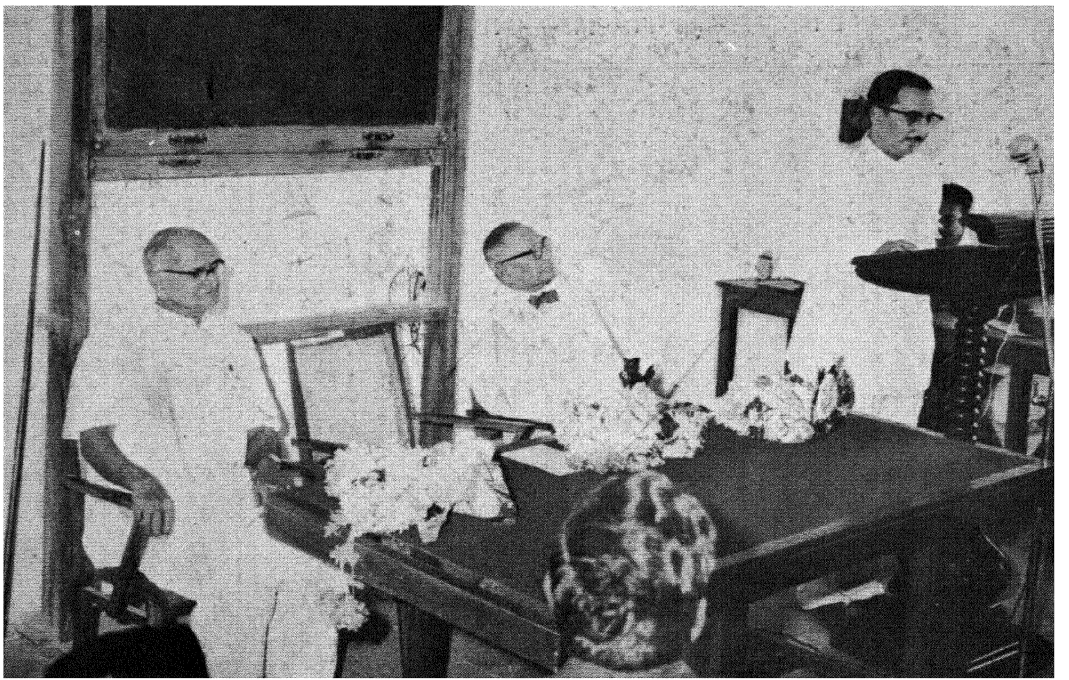
As stated earlier, many research workers of different organisations and several distinguished geophysicists and geologists participated in the seminar in response to our invitation. However, due to pressure of work, Prof. Jai Krishna of the Roorkee University, Sri L. N. Kailasam of the Geological Survey of India, and Dr. Narinarain of the Oil & Natural Gas Commission could not attend the seminar due to very important engagements cropped up at the last minute. It is regrettable that the Geological Survey of India and the Oil & Natural Gas Commission did not send their representatives in as large a measure as we expected. They in fact possess much information and knowledge about the Peninsular Shield and their participation in the seminar would have been of great value. It is hoped that in future there would be much cooperation between the educational institutions, especially the universities and the organisations like the GSI and ONGC.

Sessions

The Seminar was inaugurated by Sri P. V. G. Raju, Hon'ble Minister for Education, Government of Andhra Pradesh on Monday the 27th May 1963 at 4–00 P. M. in the Geology Department of the Osmania University. Dr. D.S. Reddi, Vice-



Dr. D. S. Reddy, Vice-Chancellor making his Presidential Remarks.



Shri P. V. G. Raju Inaugurating the Seminar.

Dr. M S. Krishnan delivering his Opening Address to the Seminar.

Chancellor, Osmania University, presided over the meeting. Dr. M. S. Krishnan, Director, National Geophysical Research Institute, delivered the Opening Address to the Seminar on 'Development of Geophysics' (Enclosure 2). Several distinguished geophysicists and geologists representing various governmental and non-governmental organisations attended the inaugural function.

The Seminar was later divided into seven sessions and about 50 research papers were presented. The following were the seven sessions presided over by the persons mentioned against each :

Session	*President*
1. Surface & Interior of the Earth	Dr. K. R. Ramanathan, Director, P. R. L., Ahmedabad.
2. Gravity & Geodesy	Col. K. L. Khosla, Deputy Director, Geodetic & Research Branch, Survey of India, Dehra Dun.
3. Magnetism	Prof. B. S. R. Rao, Professor of Geophysics, Andhra University.
4. Seismology	Prof. V. S. Mironov, Visiting Professor in Geophysics, (from U. S. S. R.) Osmania Univ.
5. Seismic Prospecting	Prof. B. S. R. Rao.
6. Applied Geophysics	Dr. P. V. Sanker Narayan, Senior Geophysicist, N. G. R. I. Hyderabad.
7. Tectonics	Dr. M. S. Krishnan, Director, N. G. R. I., Hyderabad-7.

A list of papers presented by the participants at the Seminar is enclosed (Encl. 3).

During the Seminar, several popular lectures were delivered by prominent scientists under the auspices of different

Unions. Prof. S. Bhagavantam delivered a popular lecture on the "Earth and the Universe around us" under the auspices of the Indian Geophysical Union, on 28th May at 5-30 p. m. Prince Mukarram Jah , Pro-Chancellor of the Osmania University, presided over the meeting.

Dr. K. R. Ramanathan, Director of the Physical Research Laboratory, Ahmedabad, on behalf of the Geology Association of the Osmania University delivered a popular lecture on "Satellites in Geophysics". Dr. N. V. Subbarao, Principal and Dean, College of Science, presided over the meeting. Prof. K. V. Subramaniam, Professor of Mining Engineering, O. U., delivered a popular lecture on the "Growth of Steel Industry" in India, on behalf of the Deccan Geological and Mining Society. Dr. M. S. Krishnan, President of the D. G. M. Society presided over the meeting.

All the scientific sessions were very well attended by visiting delegates and members of the Geology Department and the National Geophysical Research Institute.

Acknowledgement

We are highly thankful to the Director of the Regional Research Laboratory, Hyderabad, the Director of the N.G. R.I., and the Coordinating Unit of the U. G. C. for having placed at our disposal their vehicles for the Seminar.

Dr. D. S. Reddy, Vice-Chancellor, Osmania University, has very kindly placed before us all the facilities that the University could give. Our cordial thanks are due to him. Our thanks are due to various organisations like the Andhra University, B. H. U., Sri Venkateshwara University, Madras Univ., Roorkee Univ., Indian Institute of Technology (Kharagpur),Ministry of Defence, India Meteorological Department, G. S. I., O. N. G. C., Geodetic Survey of India, Institute of Tropical Meteorology, the N.G.R.I. and a few other organisations for deputing their scientific workers to participate in the Seminar and making the seminar worthy of its purpose.

Two foreign scientists, viz. Prof. V. S. Mironov who is an expert in applied Geology and Prof. N. A. Eremenko, Consultant, United Nations office at Dehra Dun, participated in the deliberations of the Seminar. Senior geophysicists like

Dr. K.R. Ramanathan, Director, P.R.L., Ahmedabad, Dr. M.S. Krishnan, Director, N. G. R. I. Hyderabad, Dr. S. Bhagavantam, Scientific Adviser to the Minister for Defence, Govt. of India, Sri P. R. Krishna Rao, Director-General, India Meteorological Dept., had taken very special interest in the Seminar and delivered most outstanding lectures and addresses. We are highly grateful to them.

We are most grateful to Dr. D. S. Kothari, Chairman, U. G. C. for taking keen interest in the seminar and sending valuable message. Our thanks are also due to the U. G. C. for financial assistance and encouragement in holding the Seminar.

The help given by Drs. V. S. Patankar, D. Shankernarayan and R. D. Deshpande of the University Grants Commission at various stages of the planning the Seminar is gratefully acknowledged. It is no exaggeration to say that the success of this Seminar is entirely due to the cooperation, help and assistance given by these officers of the University Grants Commission.

An Organising Committee consisting of Dr. S. Balakrishna (Chairman), Prof. V. S. Mironov, Dr. Y. J. Rao, Sri Baleeguddin Husain, Sri P. V. Johnson, Dr. G. Sankernarayana, Sri Y. V. Ramana, Sri G. Christopher, Sri A. R. Jayaprakash, and Sri A. V. Ramana Rao (members) has been formed to successfully run the Seminar. I gratefully acknowledge the help given by all the members of the Organising Committee and other members of the Staff, Research Scholars and Postgraduate student of the Geology Department. Particular thanks are due to Mr. D. V. N. Murthy, P. A. to Director, N. G. R. I. and Mr. Uppakayya (Sarma), Mr. Asgar Ali and the staff of UGC Unit for their active assistance and help rendered in organising the Seminar right from the beginning, without which it would not have been possible to conclude the Seminar successfully.

S. Balakrishna

Director of the Seminar and
Head of the Geology Dept.,
Osmania University.

PARTICIPANTS

1.	Balakrishna, S. Dr.	Assistant Director, National Geophysical Research Institute, and Honorary Head of the Geology Dept., O. U., Hyderabad.
2.	Bhagavantam, S. Dr.	Scientific Adviser to the Minister for Defence, New Delhi.
3.	Bhaskara Rao, V. Dr.	Reader in Geophysics, Andhra University, Waltair.
4.	Bhattacharjee, J.G.Sri	Officer Surveyor, G and R Branch, Survey of India, Dehra Dun.
5.	Bhattacharya, T. K. Sri	Lecturer in Geophysics, Indian Institute of Technology, Kharagpur.
6.	Chelam, E. V. Dr.	Meteorologist, Institute of Tropical Meteorology, Poona.
7.	Christensen, A. F. Sri	Geology Department, Osmania University, Hyderabad.
8.	Christopher, G. Sri	Research Fellow, Geology Dept., Osmania University, Hyderabad.
9.	Dhoolappa, G. Sri	Research Fellow, Geology Dept., Osmania University, Hyderabad.
10.	Gaur, V. K., Dr.	Geology Dept., School of Research and Training in Earthquake Engineering, University of Roorke, Roorke.

11.	Gokhale G. S. Sri	Fellow, Tata Institute of Fundamental Research, Bombay.
12.	Hari Narain, Dr.	Director, O. N. G. Commission, Research and Training Institute, Dehra Dun.
13.	Jai Krishna, Dr.	Professor and Director,School of Research and Training in Earthquake Engineering, University of Roorke, Roorke.
14.	Johnson, P. V. Sri	Lecturer, Geology Dept., Osmania University, Hyderabad.
15.	Khosla, K. L. Lt. Col.	Director, G & R Branch, Survey of India, Dehra Dun.
16.	Kovalev, A. V. Prof.	Indian Institute for Petroleum Exploration, 9 Cross Road, Dehra Dun.
17.	Krishnan, M. S. Dr.	Director, National Geophysical Research Institute, Hyderabad.
18.	Krishna Rao, K. V. Dr.	Reader in Physics, Osmania University, Hyderabad,
19.	Krishna Rao, P. R. Sri	Director-General of Observatories, Indian Meteorological Dept., New Delhi.
20.	Krishna Kartha T. D. Sri	Naval Physical Laboratories, Cochin.
21.	Lal, D. Prof.	Professor, Tata Institute of Fundamental Research, Colaba, Bombay.
22.	Leelananda Rao, N. Dr.	Reader in Geology, Madras University, Madras.

23.	Menon, N. G. K. Prof.	Professor, Tata Institute of Fundamental Research, Colaba, Bombay.
24.	Mironov, V. S. Prof.	Expert in Applied Geophysics, Osmania University, Hyderabad.
25.	Nilcola A. Eremenko, Prof.	Project Manager, U. N. Special Fund, Indian Institute for Petroleum Exploration, 9 Cross Road, Dehra Dun.
26.	Pattabhirama Rao, A.	Senior Scientific Assistant, Research and Development Cell, Geology Dept., O. U., Hyderabad.
27.	Pitchamutha C. S. Prof.	Professor of Geology, Andhra University, Waltair.
28.	Poornachandra, Rao M. Dr.	Reader in Geology, Andhra University, Waltair.
29.	Prasad, C. V. R. K. Sri	Demonstrator, Geology Dept. Sri Venkateswara University College, Tirupathi.
30.	Qureshy, M. N. Dr.	Pool Officer, Geological Survey of India, Calcutta.
31.	Raghavendra Rao, V. Dr.	Assistant Director, Research & Training Institute, O. N. G. C., Dehra Dun.
32.	Ramanathan, K. R. Dr.	Director, Physical Research Laboratory, Ahmedabad.
33.	Ramachandra Rao, M. B. Sri	Consultant, O.N.G. Commission, Dehra Dun.
34.	Ramakrishna, S. Dr.	Senior Scientific Officer, Defence Electronics Research Laboratory, Hyderabad.

35.	Ramaswami, G. Sri	Scientific Adviser, ESSO Standard, Parliament Street, New Delhi.
36.	Rao, B. S. R. Dr.	Professor and Head of the Dept., Geophysics Department, Andhra University, Waltair.
37.	Rao, K. N. Sri	Director, Colaba Observatory, Bombay.
38.	Rao, S. H. Sri	Lecturer in Geophysics, Indian Institute of Technology, Kharagpur.
39.	Rao, Y. J. Dr.	Geology Dept., Osmania University, Hyderabad.
40.	Ramana, Y. V. Sri	Research Assistant, Geology Dept., Osmania University, Hyderabad.
41.	Redkar, R. T. Sri	Research Fellow, Tata Institute of Fundamental Research, Bombay.
42.	Sahasrabudhe, P. W. Sri	Research Fellow, Tata Institute of Fundamental Research, Bombay.
43.	Sankarnarayan P. V. Dr.	Senior Scientific Officer, National Geophysical Research Institute, Hyderabad.
44.	Sarma, V. V. J. Dr.	Lecturer in Geology, Andhra University, Waltair.
45.	Sastry, A. V. R. Dr.	Lecturer in Geology, Andhra University, Waltair.
46.	Sen, S. N. Sri	Superintending Geologist, Geological Survey of India, Andhra Pradesh Circle, Hyderabad.

47.	Shankarnarayana, G. Dr.	Lecturer in Geology, Osmania University, Hyderabad.
48.	Singh, B. N. Dr.	D. C. S. O., Air Head Quarters, New Delhi.
49.	Sithapathi Rao, P. Sri	Research Fellow, Geophysics Dept., Andhra University, Waltair.
50.	Srinivasan, Dr.	Officer-in-charge, Naval Research Laboratory, Cochin.
51.	Sri Rama Das, A. Dr.	Reader in Geology, Andhra University, Waltair.
52.	Srivastava, S. S. Dr.	Director of Scientific Research, Naval Head Quarters, New Delhi.
53.	Subba Rao, K. V. Sri	Geology Dept., Sri Venkateswara University Tirupathi.
54.	Subramaniam, A. P. Dr.	Superintending Geologist, Geological Survey of India, Maharastra circle, Poona.
55.	Subramanyam, K. V. Prof.	Professor in Mining Engineering, College of Engineering, O. U., Hyderabad.
56.	Tandon, A. N. Dr.	Director of Seismology, Indian Meteorological Dept., New Delhi.
57.	Varma, R. K., Dr.	Senior Scientific Officer, National Geophysical Research Institute, Hyderabad.

LIST OF PAPERS PRESENTED AT THE SEMINAR ON "GEOPHYSICAL INVESTIGATIONS ON PENINSULAR SHIELD"

S. No.	*Name.*	*Title.*
	Surface and Interior of the Earth	
1.	Prof. K.R. Ramanathan	Earth and its Surface Features.
2.	Dr. S. Bhagavantam	Matter under High Pressure.
3.	Dr. M. S. Krishnan	The Crust of the Earth.
4.	Dr. K. N. Rao	Equatorial Electrojet.
5.	Dr. A. N. Tandon	Crystal Structure.
6.	Dr. E. V. Chelam	Elastic Wave velocities of Rocks under a Generalised Stress Field.
7.	Dr. S. Ramakrishna	M_2 Component of the Earth Tides at Hyderabad.
	Gravity and Geodesy	
8.	Lt. Col. K. L. Khosla	Progress of the Survey of India.
9.	Prof. V. S. Mironov	Local Gravity Anomalies and Geological Structure of Rudny Altay.
10.	Dr. M. N. Qureshy	A Correlation of Gravity Data with Regional Geology of Southern Peninsular India.
11.	Dr. P.V. Sankernarayan	A Regional Gravity Study of Peninsular India south of latitude 16°N.

12.	Shri J. C. Bhattacharjee	On the character of Isostatic gravity anomalies in Peninsular India and a new method of determination of the variation of Azimuth.

Magnetism

13.	Prof. B. S. R. Rao	Rock magnetism and Continental Drift.
14.	Dr. V. Bhaskara Rao	An outline of the magnetisation of Deccan Traps of the Lower Godavari Valley.
15.	Dr. R. K. Varma	Palaeomagnetism of Deccan Traps of the Vikarabad-Chincholi-Gulbarga area.
16.	Shri P. Sitapathi Rao	Analysis of the magnetic anomalies in relation to Geology and structure of Lower Godavari Valley.
17.	Shri G. Christopher	Analysis of the magnetic anomalies on the Granites of Hyderabad.
18.	Shri P. V. Sahasrabudhe	Palaeomagnetism and the Geology of the Deccan Traps.
19.	Shri G. Doolappa	Remanent magetism of Dolerite dykes of Hyderabad.
20.	Shri A. Pattabhi Rama Rao	Magnetic storms at Hyderabad.

Seismology

21.	Prof. V. S. Mironov	Seismologieal method for determining thickness of the layer.
22.	Dr. V. K. Gaur	Factors governing the attenuation of Seismic waves.

23.	Shri T. D. Krishna Kartha	Nature and origin of Microseisms at Cochin.
24.	Dr. S. S. Srivatsava	Techniques in the study of Ocean bottoms.
25.	Prof. Jaikrishna	Seismological instrumentation.
26.	Shri P. V. Johnson	Seismic disturbances recorded by Gravimeter.

Seismic Prospecting

27.	Shri Y. V. Ramana	Instrumentation for Ultrasonic Investigations in rocks.
28.	Dr. S. Balakrishna	Experimental studies on Elastic properties of some Indian rocks.
29.	Dr. S. H. Rao	Model Seismology.

Applied Geophysics

30.	Dr. P. V. Sanker Narayan	Part played by applied Geophysics in the development of theoretical Geophysics.
31.	Dr V. V. J. Sarma	Laboratory resistivity determinations of some of the rock formations of Visakhapatnam and W. Godavari Dts. of A. P.
32.	Dr. K. V. Krishna Rao	X-ray studies on limestones.
33.	Dr. V. Bhaskara Rao	Marine Geophysics.
34.	Dr. G. Shankara Narayana	Physical properties of Limestones.
35.	Prof. K. V. Subramaniam	Some applications of Geophysics to Mining Engineering.

Tectonics

36.	Dr. M. S. Krishnan	Structure of Southern Asia.

37.	Prof. C. S. Pitchamuthu	The relationship between Tectonics and Metamorphism in S. India.
38.	Dr. A. Sriramdas	Structure and Tectonics of the Eastern Ghats in Srikakulam Dt., A. P.
39.	Shri M. B. Ramachandra Rao	A review of thoughts on the evolution of the Indian Peninsula.
40.	Prof. N. A. Eremenko	Deep seated faults of Asia.
41.	Dr. M. Purnachandra Rao	Review of studies in Marine Geology (along the east coast of India) at Andhra University, Waltair.
42.	Dr. Y. J. Rao	Petrofabric studies in the precambrian rocks of Yellandlapad Area, Andhra Pradesh.
43.	Sri S. N. Sen	Recent findings in the Eastern margin of the Cuddapah Basin.
44.	Dr. A. V. R. Sastry	Review of Geochronologic Peninsular India.
45.	Shri A. F. Christensen	Tectonics of the Laurentian Shield.
46.	Dr. N. Leelananda Rao	Tectonics of Granite around Boommasamudram, Chittoor Dt., A. P.

Popular Lectures

47.	M. S. Krishnan	The rise and growth of Geophysics.
48.	Dr. S. Bhagavantam	Earth and the Universe around us.
49.	Prof. K.R. Ramanathan	Satellites and Geophysics.
50.	Prof. K. V. Subramanyam	Steel Industry in India.

Opening Address

THE SCOPE OF MODERN GEOPHYSICS

BY

DR. M. S. KRISHNAN

DURING the last three decades or so, the group of disciplines called 'Geophysics' has been recognised as separate from both Physics and Geology. For a long time before that, certain aspects of geophysics were already receiving attention. Meteorology and Atmospheric study is certainly an ancient subject, because man has always been interested in his climatic environment, in the seasons and day-to-day changes of weather. In the past, meteorologists were thought of mainly as weather prophets but now meteorology comprises other things than weather and it comprises a study of structure and movements of the atmosphere, clouds, rain, etc. The origin of the earth and its evolution as a member of the solar system were the main concern of astronomers though geologists were equally interested in certain aspects of the evolution of the earth. Geophysics was considered an appendage of Astronomy by the British Astronomical Society until a few years ago but that society now issues a regular quarterly journal dealing entirely with geophysics.

In addition to the two aspects mentioned above (Meteorology and earth as a planet), another aspect assumed importance during the last two centuries. The science of Geodesy grew out of the necessity for making accurate maps, for precise levelling and the determination of latitude and longitude. In some countries this was considered to be the function of the War Department because armies were very much interested in maps, especially of countries other than their own. In some countries, however, precise trigonometric surveying has continued to be the function of a Civil Department which dealt with either Astronomy, Geography or Geology. Most countries have now organisations for map-making which includes precise levelling, triangulation, measurement of latitude

and longitude etc. The precision of these depends on the assumptions made as to the shape and size of the earth. A fourth subject, known as Seismology, grew out of the necessity for knowing something about where, how and why earthquakes occur and whether it is possible to predict earthquakes in order to minimise the great damage which often accompanies them. In this field, Japan took the lead, and Japan and Britain contributed much to Seismology through the pioneering work of Milne. Since then seismic research studies have been established in many countries though Japan continues to be important in this subject.

Until the present century the study of the oceans scarcely received any attention even though maritime commerce has been carried on since early historic times by many countries like Egypt, Greece, Phoenicia, Rome, China, Japan, India and others. The British Challenger Expedition over 80 years ago was a pioneer in this respect. Yet until some 20 years ago, no systematic oceanographic work was done on a large scale. The deficiency has now been rectified by the establishment of Oceanographic Institutes in several countries. This year an International Indian Ocean Expedition has been organised in which some 40 ships belonging to some 20 countries are taking part.

Since the 1920's people interested in prospecting for minerals (especially for petroleum) have shown great interest in employing certain physical principles and appliances for obtaining geological data from which they infer the presence of structures favourable for the occurrence of oil, gas, water or various solid minerals. This is called Applied Geophysics or Geophysical Prospecting. Finally, we have another new branch which, because of its great importance for defence purposes, is claiming much attention from the most advanced countries. This branch is known as 'Space Science' or Planetary science as it aims at exploring the space around the earth as well the planets.

To coordinate the work of this large group of disciplines coming under the term 'Geophysics' and to bring together people engaged in the work, there is an international body called the International Union of Geodesy and Geophysics. At present this organisation has now 7 branches *viz.*, (1) Meteorology and Atmospheric science; (2) Geodesy;

(3) Physical Oceanography; (4) Seismology and interior of the earth; (5) Geomagnetism and Aeronomy; (6) Volcanology and Petrology; and (7) Scientific Hydrology. This International Union is a world-wide organisation which meets once in three years in a General Assembly to discuss the developments. Several such Assemblies have taken place already, the last few having been held at Brussels (1950); Rome (1954); Toronto (1957); and Helsinki (1960). The next Assembly will be held in August this year at Berkeley in California (U. S. A.). This very active organisation has done much useful work and has sponsored several symposia through its Associations.

Geodesy

The shape of the earth is now known to a great degree of accuracy. It is an oblate ellipsoid with a slight bulge around the equator. The figure is conventionally expressed in terms the so-called "Geometric Flattening" which gives the ratio of the difference between the equatorial and polar radii and the equatorial radius. The present accepted value for these radii approved by the International Union of Geodesy and Geophysics in 1930, are 6,378.388 metres and 6,356.909 metres for the equatorial and polar radii respectively and with these figures the geometric flattening works out to 1/297. However, very recent measurements with the help of the artificial satellites launched in USSR and USA give a slightly different value of 1/298 for the flattening. Thus, the artificial satellites not only tell us a great deal about the atmosphere and the electromagnetic fields around the earth and the space beyond, but also provide very vital data on the figure of the earth and the pattern of mass distribution within it.

Seismology and Interior of the Earth

Seismology is now a well-established branch of Geophysics. It provides data on the different types of earthquake waves which include the compressional and torsional body waves and the surface waves. From the behaviour of these waves we derive a lot of information about the internal structure of the earth. In fact these are almost the only tools which can be used to wrest some knowledge about the interior of the globe. The various reflected and refracted waves from natural earthquakes and from artificial explosions (including the more recent

explosions of atomic devices) are used for obtaining information about the different shells of matter inside the earth, and their physical properties like density, rigidity, etc. From the data, various models of the earth have been proposed from time to time and we shall ultimately be able to reduce the number of these models to 2 or 3 from the rapidly accumulating data. We now know that the outermost part of the earth, *the crust*, is on an average 30 to 35 Km. thick on continents and barely 6 to 8 Km. thick in the ocean basins. The crust lies on the outer spherical shell of the earth called the Mantle and the zone or plane of separation is called the *Mohorovicic discontinuity*, names after Mohorovicic who recognised it in 1910 in Jugoslavia during the investigation of an earthquake near Zagreb. Below this, down to a depth of 2900 Km. is the mantle which itself may be divided into two or three shells in which the wave velocities differ. It is now generally agreed that the upper portion of the mantle may be taken as extending down to about 900 or 1000 Km. The composition of the mantle is not known from direct observations. It is inferred indirectly from the Laboratory determinations of seismic velocities in certain types of rocks found at the surface, these being ultramafic rocks of the nature of peridotite. This is partly supported by the fact that nodules of serpentinised *peridotite* have been dredged from the mid-Atlantic ridge. Similar rocks are also exposed in the deep roots of ancient mountains which are seen at the surface as a result of erosion. Another view is that the mantle is composed of a rock similar to *eclogite*, consisting of the magnesian garnet pyrope, the pyroxene omphacite, spinel and magnesian olivine. It is well known that the composition of eclogite is practically the same as that of olivine-dolerite or basalt and that eclogite can be formed as a high pressure modification of such a rock. Eclogite and some of its characteristic minerals are associated in the breccia forming the diamond bearing pipes of South Africa. It is thought that the mantle of the earth has been gradually undergoing changes through the operation of convection currents which help in the differentiation of the mantle material. A corollary to this is that the core of the earth *i. e.*, the portion below a depth of 2900 Km., is gradually growing at the expense of the mantle. The differentiation of the mantle would therefore produce a certain amount of metals like iron, nickel, etc., which will sink into the core while the lighter materials, mainly in the form of silicates, would rise to the surface to be incorporated into the crust. There would also

be other compounds such as sulphides which may remain in the mantle. The core was at one time believed to be composed entirely of a highly viscous liquid because it does not transmit shear waves. Evidence has recently been found which is interpreted as indicating the presence of a solid core surrounded by a fluid shell or outer core.

There is much speculation about the real nature and composition of the core. The general opinion is that it consists of nickel-iron particularly as nickel-iron meteorites fall on the surface of the earth from space, and these are regarded as parts of a disrupted planet. It may of course contain some other metals also. One suggestion has been put forward that it may consist mainly of Hydrogen in metallic form but this does not seem to have gained much support. The temperature of the interior of the earth is thought to be not more than about 5000° to 6000° C which is low in contrast with millions of degrees Centigrade in the sun and the stars where atomic transformations are constantly taking place and where matter is turned into energy. The other physical parameters of the interior of the earth *viz.*, pressure, density and velocities of P and S waves are known to a fair degree of accuracy. The density of the core is now taken to be 16 or 18 grams/Cm^3 (Bullen : Earth's central density. *Nature*, No. 4858, p. 973, 1962). In one of the other models proposed for the earth, a density of as much as 21 to 22 grams/Cm^3 has been suggested.

Oceanography

Knowledge of the oceans, which actually cover over 70% of the area of the globe, is still very scanty. It is only during the last 80 years or so data on the oceans have been slowly gathered ; only during the last two decades has Oceanography become a subject of some importance. At present certain portions of the North Atlantic and the Pacific are known in fair detail and the other oceans are yet to be studied. An important international project has been launched last year for the study of the Indian Ocean and we are informed that over 40 ships are now engaged in this study. This programme will continue for 3 years or more. The oceans are undoubtedly just as interesting as the land masses. They also contain mountain ranges and deep basins, volcanic cones and rift valleys fault scarps and other features. The under-sea topography is less sharp and more rounded than on land. Perhaps the most important discovery of the last decade is that there is an

almost continuous mid-ocean ridge, this being extraordinarily symmetrical to the continental coasts on either side. It has been traced from the mouths of the Lena river across the Arctic ocean through Jan Mayen, Iceland, Azores and other Atlantic islands to Tristan da Cunha and Bouvet Island in the south where two branches take off, one going between South Africa and Antarctica and joining the mid-Indian ridge near Reunion Island. The mid-Indian ridge is called the Carlsberg ridge in the north and it is continuous with the Red sea rift and is more or less symmetrical between Africa and India. Two new submarine ridges (Carpenter and Carnarvon ridges) have recently been discovered to the west of Australia. From Reunion, the Mid-Indian ridge goes in a southeast direction between Australia and Antarctica down to the Macquarie Island south of New Zealand and thence into the Easter island rise. This last portion (the south Pacific ridge) is situated somewhat asymmetrically, being nearer to South America than to Australia; but this is very likely due to the fact that the sea between Australia and New Zealand is really a part of the continental area and this may have had its influence upon the position of the South Pacific ridge. This Easter Island ridge proceeds towards the Gulf of California, while the major branch marked by numerous sunken islands goes through Tuomotu and other island groups of the Central Pacific to the south of the Japanese islands.

These ocean ridges are of somewhat different characters in the different regions. In the Atlantic and in the Indian oceans they are like mountain chains with broad flanks, with a comparatively narrow rift along its crest. This rift is the locus of present day volcanism and it is also active seismically, the earthquakes being all of shallow origin. Heat evolution is higher along this rift than on the flanks of the ridges or elsewhere in the oceans. The Easter island ridge (South Pacific Rise), on the other hand, is a broad plateau-like domal structure and its top is a zone of high heat evolution. So far as known, this ridge is not cleaved by a rift similar to the one on the mid-Atlantic ridge. The Central and North Pacific ridge is, however, capped by numerous sea-mounts and guyots which mark ancient volcanoes that have been probably extinct since the Cretaceous. They therefore represent an earlier stage of development of the mid-ocean ridge while the Easter island ridge may be the manifestation of an incipient stage in development.

A very interesting and intriguing fact is that the oceans are covered only by comparatively a thin blanket of sediment 0.5 to 1 Km. thick. The mid-Ocean ridges have little or no sedimentary cover; this may mean that either the deposits are swept off by ocean currents or that they are periodically incorporated in the lavas issuing from the rift. Drilling in several islands in the west-central Pacific has shown that there are no sedimentary rocks older than early Cretaceous. The same appears to be true in the other oceans as well. Those who believe in continental drift will readily realise that in the Atlantic and Indian oceans any sedimentary rocks older than early Cretaceous cannot be expected because it was only at that time that Gondwanaland split up into its various fragments which drifted away in different directions; but with regard to the Pacific it is difficult to understand what happened to the sediments which must have accumulated during the ages. There is an opinion that the moon separated from the earth at some stage in its history. Those who support this idea believe that this separation must have occurred in the Pre-Cambrian times and certainly not as late as in the Jurassic.

The Pacific offers other surprises. More than half a dozen important fault scarps have been found with E-W trend, more or less perpendicular to the American coast, in the North Pacific from Cape Mendicino in the north to opposite Colombia in the south. These fractures mark off the different adjacent blocks of the crust which are graben or horsts. Some of the scarps are over 2 Km. high but the faults do not seem to continue into the continental crust of North America. It may be that they are more or less confined to the oceanic crust and do not continue up into the continental sial.

Some areas of this part of the Pacific have been mapped with the magnetometer and the magnetic maps appear to show that large horizontal displacements have occurred, offsetting the sides by 150 to 200 Km. from one another. Similar faults with such large displacements are known at a few places on land also. One is the Great Glen fault in Scotland; another may be the Cabot fault which cuts across New Foundland; another still is the San Andreas fault along the California coast. It is not known whether the faults in the Pacific basin are as old as the Jurassic or Cretaceous; if so, the movements which have affected the upper continental crust since then in

Western North America may have obliterated these faults near the surface though they may still be present at some depth below.

The Pacific Ocean has certain other interesting characters also. It is bounded on all sides by folded ranges which have been overthrust towards the ocean. On the eastern side of the Pacific there are no island arcs but a volcanic zone and deep earthquake belt are present in South America. On the western side, right from Alaska down to New Zealand, there is a series of spectacular island arcs. One way of explaining the island arcs would be that the continent of Asia is spreading out into the Pacific along deep-seated and low dipping faults which dip from the island arcs towards the continents. The structure of these arcs have been detailed by Banioff, Gutenberg and others. They mark the so-called "Andesite line" except in the case of the Marianas. The ocean basins inside these arcs have more or less acquired the character of the continental crust, except in the Philippine basin (between the Philippines and the Marianas) which seems to be the youngest in age and has not yet evolved to the stage of acquiring continental character.

Geomagnetism

The fact that the earth behaves like a magnet and is surrounded by a magnetic field has been known for some centuries. Even though it was recognised a century ago that the observed magnetism of the earth is composed of two parts, one arising from internal causes and another of external origin, it is only during the last few years that satisfactory explanations have been put forward to account for these. The internal part is now explained as due to the interaction of an electrically conducting fluid core material in motion and a magnetic field. In simple terms, the movement of the core material due to convection in an already existing magnetic field generates electric currents in the core by the dynamo principle. The magnetic field associated with these currents supplements and modifies the existing magnetic field thus providing a self-excited, self-sustaining, dynamo under equilibrium conditions. The external field which is only a very small fraction as compared with the internal component is now known to have its seat in the upper atmosphere where it is modified by regular diurnal variations due to the tidal action of the sun and to a small extent the moon. Also, occasionally the external field is

thrown into violent, erratic fluctuations lasting for several hours due to the impact of high energy particles, cosmic rays, X-rays, ultraviolet radiation, etc., issuing from the sun. Very recent data from orbiting satellites have proved the existence of giant radiation belts around the earth (the Van Allen belts) which trap the high energy particle radiations coming from the sun and thus control the variations of the external component of earth's field.

Measurement of the earth's magnetic field at different places on the earth's surface gives us an idea of the local peculiarities in the distribution of magnetic material in the crust. Because of the fact that the basement rocks (granite and gneiss) are generally fairly magnetic in comparison with the overlying sedimentary layers which are only very weakly magnetic, mapping of the field intensity in an area can give us information as to the depth of basement surface as also the configuration of any structures in it which might act as potential reservoirs for oil or other minerals. Such magnetic surveys conducted either on the ground level or from the air by airborne magnotometers show up mineralised zones at depth in the form of strong magnetic anomalies. These anomalies when interpreted mathematically yield quantitative information on the depth, attitude and extent of magnetic ore bodies such as magnetite, hematite and certain sulphides of iron. Magnetic surveys have successfully located even non-magnetic deposits like placer gold in ancient river beds. Here the geologist locates the gold in a rather round about fashion, making use of the fact that gold and magnetite, being both heavy minerals, generally accumulate together in river beds due to the grading action of rivers. Finally, magnetic surveys do also provide data from which the delineation of and depth to the basement can be calculated to a fair degree of certainty.

Volcanology

The distribution of volcanic phenomena on the surface of the globe is closely bound up with the presence of mobile or active zones in the crust. Three major lines or zones of volcanic activity exist at the present time. They are: (1) The Circum-Pacific belt which includes the Andes mountains in South America and the whole lot of island arcs in the Western Pacific, (2) the Indonesian Archipelago and the Alpine-Himalayan belt, and (3) the crest zone of the mid-ocean

ridges. Only a very few volcanoes occur outside these major lines and they probably represent fault zones in which the crust has been disturbed, as in the Hawaii Islands in the Pacific. Volcanic activity and volcanic products give a considerable amount of information about the nature of the earth's crust and the upper mantle. Data are now available to show that magma chambers exist at a depth of 40 to 60 Km. below sea level and that subsidiary chambers can be kept active over millennia at much shallower depths. The deeper magma producing zone in the crust appears to be part of the low seismic velocity zone in the mantle, and this zone is liable to become plastic by slight variations of pressure and temperature.

It is now known that the ocean basins are underlain by olivine basalt which is distinct in composition and characters from the average basic igneous material in continental crust which generally has the composition of theoleite or andesite. It would appear that there is a complete envelope of highly basic oceanic basalt over the whole globe and that it is overlain by the less basic type in the continents. These facts are important in the growth of continents brought about by the gradual accumulation of siliceous materials differentiated from the mantle which is the ultimate source of all the rocks of the crust.

Hydrology

One of the subjects dealt with by the IUGG is Scientific Hydrology *i. e.*, the study of distribution of water on the surface and in the uppermost crust. Water is one of the important products of differentiation of the crust and, in conjunction with the atmosphere, it goes through a complete cycle from the ocean through clouds and rain, and as surface and ground water, ultimately to return to the ocean again. Much work is being done to determine the behaviour of water underground and the way of controlling and ultilising the water which is available in the sedimentary layers in the crust. Water conservation and management will be one of the major problems for scientific study in the immediate future.

Tectonophysics

This branch deals with the principles governing the evolution and development of the crust, its movements and other peculiarities. The development of the atmosphere and

of the oceans is closely bound up with that of the crust. The subsequent history includes the episodes of sedimentation, volcanism, mountain building etc. Aerial maps and aerial geophysical observations are adding a great deal of data to the fund of knowledge already available and we are now beginning to get a fairly comprehensive picture of the structure of the earth.

Applied Geophysics

Applied Geophysics is entirely utilitarian in its aims. It uses all the techniques of geophysics for studying the structure of the crust and, by inference, the possibility of occurrence of certain mineral deposits. Geological knowledge is of course fundamental in the application of these principles. The several methods used in the study of mineral deposits include gravitational, magnetic, seismic, electric, electromagnetic, and radioactive methods—all of which have a definite place in prospecting. Increasing use has been made of geophysical methods in the location of oil-fields, and the tremendous advances which have been made in the last decade or two have contributed to the better and more reliable interpretation of the data in terms of geological possibilities. Geophysical methods are used also for surveying bore-holes in order to find layers containing water, gas or oil.

Applied Geophysics has been used in ore, oil and water finding, only during a period of four decades and many spectacular results have been achieved. There is no doubt that these methods will be used more and more in the newly developing countries and in those areas which are not yet sufficiently known geologically. Man has scarcely scratched the surface of the earth in his search for minerals. The average depth of mines, over the whole world, may be of the order of 500 ft. Only in a few places are mines several thousand feet deep being exploited. There are, therefore, vast opportunities for the use of geophysical methods to bring hidden mineral deposits to light in numbers sufficient to meet the requirements of the present and future.

Instrumentation

Geophysical instruments used in former days were naturally comparatively simple. It is a far cry from the clumsy Eötvös Torsion Balance to the present Worden Gravimeter

and from the Dip needle to the present highly sensitive Proton Precession Magnetometer. Many improvements are being made to instruments which are used for measuring various properties of earth's materials. The development of electronics is naturally reflected in the development of geophysical instruments. More powerful and sensitive instruments are being manufactured which can be used on the ground, in air or in the oceans. New gravimeters have been developed for use on board ships—the Graf and the Lacoste-Ramberg Gravimeters—they are mounted on gimbals and appear to be quite reliable. Another development is the automatic recording of data on magnetic or punched tapes, which are then directly available for mathematical analysis by high speed digital electronic computors. Extremely involved computations which some years ago took many man-months of work are now done in a matter of an hour or two by these giant brains. There will doubtless be many other improvements in future.

Some Current Geophysical Work

About seven years ago, the International Council of Scientific Unions and the IUGG set up a Geophysical Committee for world wide study of certain aspects of geophysics e. g., the ionosphere, the Ozone layer, auroral activity, the phenomena characterising inter-planetary space, etc., during a period of one year which was called 'Geophysical Year'. There had, of course, been a few attempts before that for international collaboration in certain types of work. The grand success achieved by the collective efforts of many nations during the Geophysical Year has contributed much to the understanding of many aspects of nature. Part of the results of the Geophysical Year has been published and a part has yet to be studied and released. The work of Geophysical Year has actually been continued by many countries, because the importance of the data collected is such as to require further study.

A few years ago a study was made of the sun during a period of maximum activity by several countries. The results have been so good and encouraging that the IUGG recommend that the sun should be studied also during a period of its least activity (International Quiet Sun Year). That work has already been taken up by many countries and the results will be watched with great interest.

The latest geophysical aspect which has been recommended for world-wide study pertains to Hydrology. It is now widely realised that water is one of the most important mineral assets of mankind. Water is essential for life and for many industrial process. The expansion of towns and cities, the gradual destruction of forests, the intense activity in the underdeveloped nations to catch up with the very advanced nations by establishing new industries—all these have contributed to the realisation that water resources should be conserved and carefully utilised. This has now been taken up both at national and international levels. A meeting was convened under the auspices of the UNESCO a few months ago at Geneva to consider what steps should be taken to educate the less developed nations in modern science and technology. One of the important decisions taken at this meeting was to initiate a 10 year programme of study of water problems in all parts of the world under all climatic conditions. This programme will undoubtedly be of great benefit to the welfare of the human communities living all over the world.

M_2 COMPONENT OF EARTH TIDE AT HYDERABAD

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Abstract

Using the Askania Gravimeter GS-11, the earth tides have been recorded at Hyderabad. The tidal data has been analysed for the semi-diurnal principal lunar component M_2, for a few months. From this analysis the gravimetric factor G and the characteristic numbers are obtained. The variation of G with latitude is discussed. An estimate is made of the value for the rigidity of the earth at Hyderabad and its significance is discussed.

Introduction

AN Askania Gravimeter GS-11 has been used continuously over a period of three years in the Geology Department, Osmania University, Hyderabad. Data obtained with this instrument have been analysed and tentative results and conclusions have been published in earlier papers (1, 2 and 3). In this paper it is proposed to discuss the results obtained for the semi-diurnal principal lunar component M_2.

The tidal force experienced at any place is the combination of several different forces of which seven are major components which result from the interaction of the sun and moon, independently and together, with the earth. Of these, the most dominant and therefore the easiest to observe is the principal lunar component, M_2. This component, the amplitude of which forms a third part of the entire tidal force, has a period of $12^h.42$.

Observations

The experimental method of recording the values of g has been described in the earlier papers referred to above. Part of the data has been obtained manually when the value of g was read off at intervals of half hours. Later a method of photographic recording was developed. This method has been described in detail by Balakrishna (3). The variations in the value of g are continuously recorded on a drum by photographic methods and are then read off at the necessary intervals for computation. After eliminating the drift due to the instrument from these readings by a drift elimination process described earlier (3) the data are harmonically analysed for the seven components. For each such calculation, readings obtained over a period of 29 days are used. The modified Fourier analysis method described by Hayakawa and Balakrishna (1) has been used for these data. From the analysed data the amplitude of the M_2 component is obtained.

The theoretical value of the amplitude of this component is obtained using the expression.

$$Z_{M_2} = 76.0 \ \mathrm{Cos}^2\phi$$

Where ϕ is the latitude of the observing station. The latitude of Hyderabad is 17° 26′ N.

The gravimetric factor is defined as the ratio of $Z_{obs.}/Z_{th.}$ and obtained from the above values. The values have been obtained for selected nine months over the entire period under consideration and only the M_2 component has been used in these calculations.

Results

The observed values of the amplitudes of the M_2 component and the values of G obtained from them are given in Table I for the months under consideration. The amplitudes are given in milligals. In the same table the values of the characteristic numbers are also given for each month. These have been calculated using the standard relations that exist between the various constants.

TABLE - I

Tidal Constants for M_2.

Month	Exptl. Amp.	Theor. Amp.	G	h	k	l	f	D	L
July 1960	0.081	0.069	1.17	0.61	0.29	0.08	0.16	0.68	1.21
May 1961	0.080	0.069	1.16	0.60	0.28	0.07	0.16	0.69	1.20
Dec. 1961	0.083	0.069	1.20	0.71	0.34	0.09	0.20	0.63	1.25
Jan. 1962	0.082	0.069	1.18	0.64	0.31	0.08	0.17	0 67	1.22
Feb. 1962	0.081	0.069	1.17	0.61	0.29	0.08	0.16	0.68	1.21
Mar. 1962	0.067	0.069	0.97	—	—	—	—	0.96	0.96
Apl. 1962	0.083	0.069	1.20	0.71	0.34	0.09	0.20	0.63	1.25
May 1962	0.084	0.069	1.21	0.75	0.36	0.10	0.22	0.61	1.26
June 1962	0.081	0.069	1.17	0.61	0.29	0.08	0.16	0.68	1.21

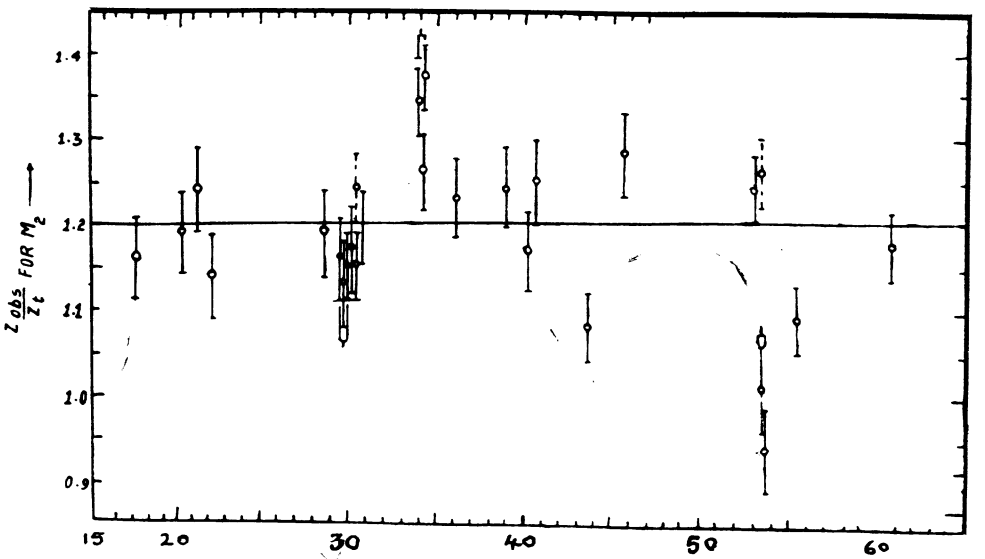

FIG. GRAVIMETRIC FACTOR FOR M_2 ACCORDING TO OBSERVATIONS AFTER 1948.

From the above table it can be seen that the value of the gravimetric factor is obtained as 1.18. The value which has been obtained for the month of March 1962 has to be discarded as there appears to be a large error. Frequent disturbances in the recording during this month probably have contributed partly to vitiate the measurements and calculations.

A set of constants for the characteristic numbers can be constructed using the above value for the gravimetric factor. These values are given below.

$h=0.64$ $\quad$ $f=0.73$

$k=0.31$ $\quad$ $D=0.67$

$l=0.08$ $\quad$ $L=1.22$

The rigidity of the earth at any point can be obtained from the relation

$$\mu = gd\rho_1/19f$$

Using the value of f obtained above and putting $d=5.52$ gms/cm, $g=981$ cm/sec^2 and $\rho_1=6371$ kms we obtain for the rigidity :—

$$\mu = 1.05 \times 10^{12} \text{ dynes/cm}^2$$

Discussion

The value of the gravimetric factor has been obtained by several workers using a variety of methods. The standard value obtained with pendulum clocks at Paris is given as 1.195 ± 0.043. Lambert (4) after a discussion of the results that are available gives a value of 1.198. The value of 1.18 obtained at this place is therefore in reasonable conformity with the observarions elsewhere. The spread of 0.03 obtained in the value during such a large period is very insignificant. In fact it is to be expected that there should be a much larger deviation according to the estimate of $\pm$ 4% suggested by Tomaschek (4). The value obtained for the month of March 1962 is however far from satisfactory and is omitted.

So far, a systematic variation of the gravimetric factor with the latitude has not been observed. The variation appears to be random. Data taken from Baars (5) along with

the present data are presented in Fig. 1. The value of G is plotted as a function of the latitude in this figure. An error of $\pm$ 4% for all values has arbitrarily been chosen as the exact errors involved in each of the measurements are not available. It is interesting to note that there are no stations south of 20° N. latitude and Hyderabad is one of the very few such stations now in operation. It can be seen that the value 1.18 fits closely with the value obtained near about these latitudes.

The rigidity value of 1.05×10^{12} dynes/cm^2 obtained from these observations conforms closely to the expectations from theoretical calculations. The significance of this particular value in connection with the geology of the local area has been discussed earlier by Johnson (6). However, in the absence of further reliable and corroborative data, no major conclusions can be drawn from this result.

Conclusions

The value of the gravimetric factor G obtained from a consideration of several months' data is 1.18. This is in conformity with other known observations at other stations. A comparison of this value with the values obtained at stations situated at other latitudes fails to suggest any systematic variation of this value with latitude. However, an apparently random spread is observed with latitude. The rigidity value obtained using this data is 1.05×10^{12} dynes/cm^2.

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THE CRUST OF THE EARTH

BY

DR. M. S. KRISHNAN

By the term *crust* we mean the thin rocky envelope around the earth exposed in the continents or covered by the ocean waters. Only a very small thickness of this crust is available for direct observation at the surface. This will be realised from the fact that the greatest depth attained by any mine is only about 11,000 feet from the surface (e. g., Kolar in India and the Rand in South Africa) and the greatest depth of any bore-hole is about 26,000 feet (in the Gulf Coast of the USA). It so happens that the deepest mines in the world are gold mines, and the deepest bore-holes are those drilled for petroleum. Even the deepest bore-hole falls very much short of the altitude of the highest mountains or the depth of the greatest ocean trenches. From information extracted from seismic records it is now known that the average thickness of the continental crust is around of 32 to 35 Km. and thatof the oceanic crust only 5 to 8 Km. The crust is underlain by the ***mantle*** which is the outer shell of the earth extending down to a depth of 2900 Km. The plane of separation between the crust and the mantle is irregular and constitutes a discontinuity recognised first in 1909 by Mohorovicic as a result of his study of an earthquake near Zagreb (Jugoslavia) in that year. He found that at stations more than 200 Km. from the epicentre of the earthquake, a type of longitudinal wave different from that arriving at nearer stations first made its appearance. He suggested that this was due to a discontinuity in the earth at a depth of about 50 Km. where there is a sudden increase in velocity. Another discontinuity was found by Conrad (1925) who recognised an additional phase of P wave in the Eastern Alps. This Conrad discontinuity occurs in the crust below the sediments or the granite shell but it is not given much importance.

The mantle is believed to consist largely of heavy ultramafic rocks having a density of about 3.2 to 3.3 g/cm^3. These rocks may be of the nature of peridotite or eclogite whose physical properties approximate to those of the mantle rocks,

judging from laboratory observations. The velocity of P and S waves in the upper mantle are respectively 8.2 and 4.7 Km./Sec. The mantle continues down to a depth of 2900 Km.

The different zones or layers recognised within the earth as a result of seismological work are shown in the accompanying table (After Bullen, 1956).

Interior Shells of the Earth

Zone	Depth (Km.)	P velocity (Km./Sec.)	
A	0- 35	2.0- 7.5	Crust
		Mohorovicic Discontinuity	
B	35- 413	8.1- 9.0	Outer mantle
		20° Discontinuity	
C	413- 984	9.0–11.4	
D'	984–2700	11.4–13.6	Inner mantle
D''	2700–2898	13.6	Inner mantle
		Core boundary	
E	2898–4982	8.1–10.4	Outer core
F	4982–5122	10.4–11.5	Transition Zone
G	5122–6371	Inner core	
		Centre	

It is now generally agreed that the core consists of a 'liquid' outer core which does not transmit shear waves and a solid inner core. The boundary of the inner core is at 5122 Km. depth and there is a transition zone about 140 Km. thick between it and the outer core (roughly between 4982 and 5122 Km.)

Figure 1 shows the variation of P and S wave velocities, gravity values, density and pressure within the earth. In the various models proposed, the density at the centre of the earth is given values between 11g/Cm^3 to 22g/Cm^3. Bullen's latest idea (1962) is that a value of 16g/Cm^3 may best fit the present data and state of knowledge based on Bolt's values of P–wave

velocity distribution in the core, in preference to 18g/Cm^3 obtained by using Jaffreys' values.

As stated already, the Mohorovicic discontinuity is a very irregular surface. In mountain regions, particularly of comparatively recent geological ages, the crust may extend down to about 70 – 75 Km. In the older peneplaned mountain ranges the crust is less thick, but not necessarily reduced to the average given above which characterises most old plateaux and plain lands. A thickness of over 45 Km. is found only in belts of folded mountains and in certain high plateaux.

Gravity Anomalies

The thickness of the crust can be estimated from gravity and magnetic measurements or more directly by seismic methods usually employed in geophysical prospecting. When the gravity is measured at any locality by a gravimeter, the measured quantities give us information on the sum total of the mass distribution at that place. For getting comparable gravity data at various places, three types of corrections have to be made: (a) the first relates to the distance from the centre of the earth to the observation point in relation to the sea level, neglecting the matter present between the two levels. The observation point is deemed to be moved from elevation h (+ if above sea level and – if below) to sea level as if only air is present between the two levels. This, known as the *free air reduction*, is given to a fair degree of accuracy by + 0.3086 h mgal where h is elevation in meters. When the locality is below sea level, the correction is negative. (b) The second is the *terrain correction* for the effect of the matter in the surrounding terrain. If there is no mass around as when the observation point is on top of a hill, the correction is negligible. If there are large masses around, as in a valley, the attraction upward will be considerable. The terrain around can be divided into zones and corrections computed in a simplified way (Garland, 1956). The terrain correction is always positive. (c) The third correction pertains to the mass present between the point of observation (h) and the sea level. One of the methods used, due to Bouguer (and hence called *Bouguer correction*) assumes the mass to be lowered below sea level. The formula to be used is $-2\pi G \rho h$, where the mass is generally assumed to have a constant density ρ, h the elevation and G the constant of gravitation (6.673×10^{-8} Cm^3/g sec.) In this

however the density of rock material in the layer concerned should be estimated reasonably well. Bouguer anomaly maps are frequently made and used.

It is generally known that any mass exposed at, and forming part of, the surface of the earth has a tendency to attain a status of balance or equilibrium akin to hydrostatic equilibrium, in course of time (may be of the order of 0.1 to 1 million years). Archdeacon Pratt (1854–55) found that the plumb line set up in North India was deflected towards the Himalayas which was naturally to be expected. But the magnitude of this deflection fell short of what was indicated by calculations for mass of the Himalaya mountains nearby. He therefore assumed that this was due to the Himalayan rocks being of smaller density than the average. Sir George Airy (1855) also used the same observational data but assumed that the mountains had roots which extended some distance down amidst the dense subcrustal rocks and that this large column of lighter rocks accounted for the smaller attraction. The upper crustal material, which made up much of the mountains, appeared to float over the denser rocks down below. This concept of equilibrium between adjacent columns of the crust was termed ISOSTASY by Dutton (1892). Even at present, all geophysicists and geologists are not agreed as to whether Pratt's or Airy's theory represents the true state, from data available on gravity anomalies in different regions. The difficulty is that one of the current hypotheses must be adopted for reduction of gravity values to sea level and then some criterion utilised to test which of the hypotheses comes nearest to the facts.

In the Pratt hypothesis the assumption is that there is *a depth of compensation at the same level or depth below sea level everywhere*, the density below which is constant, and that above this level, the density varies from place to place. The depth of compensation is to be assumed, based on observations. In the Airy hypothesis the density in the upper layer (which forms the crust) is constant, but it extends down to different depths in different places.

Many geophysicists now assume the presence of various layers of different densities in the crust and obtain their depth from seismic observations. The densities of crustal rocks have to be obtained from stratigraphic and drill-hole data. This

was suggested and adopted by Heiskanen (1927) and (1936), but involves rather tedious calculations. Hayford's method is a modification of Pratt's in that the depth of compensation is taken from the earth's surface and not from sea level. Though much theoretical work has been done to deduce crustal structure from gravity anomalies, there are several possible solutions for each case; and it is necesary to utilise other information in conjunction with gravity, in order to get reasonably reliable results.

There is now general agreement that isostasy is a reality and that most parts of the crust are in equilibrium. Except in recent mountain regions, each column of rock of the same cross section, resting at depth H below sea level has equal mass. The level of compensation which is at depth H is often taken as being at 60 or 70 Km. If h is the elevation of the column above sea level, and ρ is the density of this column; then:

$$\int_{o}^{H+h} \rho \, dz \qquad \text{is a constant}$$

In the Airy hypothesis we assume the existence of n homogeneous layers having thickness dn and densities n. As H reaches below Mohorovicic discontinuity, the mantle between H and the Moho, as well as the water column above the the rock, are to be included, then we get :

$$\Sigma_{1}^{n} \rho \, n \, d \, n \quad = \text{constant}$$

As only one discontinuity is assumed in the continental crust, we get :

$$\rho \, m \, d \, m + \rho \, c \, d \, c = \text{constant}$$

(m refers to the mantle layer between H and the Moho, and c to the crust; for oceanic areas, the water layer should also be added). When dealing with large areas of the earth ρc is taken as 2.67 to represent average value for the whole crust and ρm as 3.27 for the upper mantle below the Moho. Some authorities have used 3.30 or 3.52 as the values for the upper mantle layer. We now know that there is at least one basaltic

layer in the continental crust for which the density may be taken as having a value around 2.80 or 2.9.

The areal extent of the column which may be assumed as a unit for the operation of isostatic compensation may have a radius of 10 Km. but opinions differ and local conditions and structure must be considered. The portion in which movement actually takes place effecting compensation will be part of the uppermost mantle and a part of crust just above the Mohorovicic, which behave like plastic materials when stresses operate over an appreciable period of time.

The difference between the magnitude of gravity deduced for sea level at the point of observation and the average quantity at sea level, using the international formula given below, is called the ***gravity anomaly.***

$$\gamma_0 = 978.049\ (1 + 0.0052884\ \sin^2\phi - 0.0000059\ \sin^2 2\phi)\ \text{gal.}$$

Heiskanen (1928) obtained the gravity values from observations at many thousand stations and after reducing them isostatically to sea level, calculated the value of γ_0. The present international standard reference point for gravity value is Potsdam near Berlin. The value assumed for this point was however found to be 0.013 gal. too large. It is now generally agreed that the numerical coefficients in the above equation require revision and improvement, in view of the availability of a large amount of new data and some authorities have adopted slightly different values. Still more data are required on gravity at many other places on the earth. Heiskanen and Vening Meinesz (1959, p. 76) have discussed this question fully. They opine that errors due to the incorrectness of the above mentioned coefficients or in the gravity value adopted for Potsdam will not produce any noticeable error in general conclusions regarding the earth's crust and interior, so long as calculations are based on the same system. This is because the actual data required are the ***differences in the gravity values between station and station and not absolute values of gravity at any station.***

Bouguer anomalies are of interest especially if used in limited areas. But their utility for deducing crustal structure is not satisfactorily established. Bouguer anomalies are usually positive over ocean areas (increasing with increasing depth of water) and negative in continental areas (increasing with the

height above sea level). This indicates that, by and large, there is isostatic equilibrium in most areas of the earth. Though the Bouguer anomalies have been used for calculation of crustal thickness, there is uncertainty as to the particular method of reduction to be used to get the best fit to the actual values of gravity at sea level, as errors accumulate which may amount to as much as 10 mgals. It is therefore necessary to obtain data from other sources to check against the pure gravity data. *Isostatic anomalies* can be calculated by a variety of methods based on the hypotheses of Pratt, Airy or Heiskanen. They lead to slightly differing values. On the whole perhaps, Heiskanen's method, which uses different thicknesses and densities of crustal layers, derived from geophysical determinations, gives results which seem to approach closest to the real thickness and structure of the crust.

The largest negative isostatic anomalies occur on the convex side of Island Arcs of the Pacific Ocean, including the Indonesian Archipelago. The anomalies in some cases are greater than 200 mgals. The negative anomaly zones are generally narrow and are bordered by wider positive anomaly zones. The positive anomaly zone is generally more prominent on the continental side of the Island Arcs than on the ocean side. Positive anomalies of high value are not of the same magnitude nor do they seem concentrated in particular zones as do negative anomalies. Such zones have been found in Armenia; and in Cyprus; in southern Mindanao; in Sula and Obi islands and the Banda Sea immediately to their south etc. In these the values range from 100 to 150 and rarely to 200 mgals. These may probably be connected with zones containing intrusions of ultramafic rocks.

In comparing the results of gravity and seismic surveys, it is found that concordant results are not sometimes got in the same area. Similarly also there may not be full agreement between topography and gravity data. High topographic expression is not necessarily accompanied by a thick crust. The apparent discrepancy is due to the variation in the thickness of the different layers in the crust, the granitic layer being relatively thicker in some and the basaltic layer in others. For this reason the general assumption made that there is an average value of density for the whole crust is incorrect. A thicker basaltic layer and the greater proximity of the mantle will

produce positive anomaly, while a thicker granitic layer and a depressed Moho will give a negative anomaly, irrespective of the surface elevation. Woollard's results (1963), based on the analysis of a mass of gravitational and seismic data, supports the above general conclusions. In general, *horsts* and most large basic intrusions give rise to positive isostatic anomalies while *graben* and areas of granitic intrusions give negative anomalies.

Surface Waves and Crustal Studies

Surface waves (both Rayleigh and Love waves) have been increasingly used for crustal studies and especially for differentiating between Oceanic and Continental crusts. Rayleigh waves have motion in ellipses in a retrograde direction in the plane of wave propagation, while Love waves are shear waves in which the particles move perpendicular to the plane of propagation. Love waves in a homogeneous medium have the same velocity as transverse waves while the velocity of Rayleigh waves is slightly less (about 0.92 of shear wave velocity) depending mainly on Poisson's ratio of the medium. Early studies by Gutenberg (1924) have shown that the surface waves with periods around 20 sec. had different velocities in oceanic from Continental crusts; also that the group velocities of short Rayleigh and Love waves (periods less than 30 sec.) is higher in Oceanic than in continental areas. Waves of much longer periods are not capable of giving this differentiation. Stoneley (1948, 1953) made extensive studies on the dispersion of surface waves for different earth models. Maurice Ewing and his coworkers have more recently given much attention to these studies. In these studies a fair measure of agreement is found between seismic refraction and Rayleigh wave dispersion data in ocean basins. Oliver (1962) has constructed dispersion, group and phase velocity curves for Rayleigh and Love waves in 2 to 3000 sec. period range, the velocity in this range varying between 1 and 7.9 Km./Sec. The contrast between oceanic and continental crusts and mantle is best brought out in the range of period 20 to 130 sec. In normal ocean basin, the group velocity and the Airy phase period (maximum group velocity) have been found to be 4.05 Km./Sec. and 30 sec. respectively, while they are 3.85 Km./Sec. and 80 sec. respectively in continental paths. Waves of shorter period show more divergences in the values.

The contrast between oceanic and continental crustal paths is brought out also by Love waves of periods less than 180 sec. the largest contrast being obtained at periods around 20 sec. But the oceanic group velocity is virtually the same (4.45 Km./sec.) for periods 20 to 350 sec. Group velocity curves for Love waves in ocean basins are flat over a good range of periods, but the phase velocity rises gradually as the period increases. Earthquake studies at Suwa in Fiji Islands showed that dispersion is practically uniform for long period waves in normal ocean areas (e.g., North and Central Pacific). But lower phase velocity characterises the Easter Island Rise, Melanesia and neighbouring Island areas, showing that these basins have a different structure.

Santo's studies (1960) show that the S. W. Pacific (Micronesia, Melanesia, Polynesia areas) is more continental than oceanic. It is also found that Rayleigh waves have lower velocities when traversing volcanic island groups. Phase velocity data show that the low velocity layer in the mantle below the Pacific and in the normal parts of Atlantic and Indian Oceans is at a shallower depth or has a lower velocity than that layer under the Continents. According to Ewing et al (1962) who have summarised the present status of surface wave studies, there are, in the Pacific, a thin sedimentary layer with low shear velocity, a 5–Km. crust, and a low velocity channel between 75 and 200 Km. as shown below. Normal continental areas have a 32–Km. thick crust and a low velocity layer at about the same depth but having a higher shear velocity than that layer under the Pacific.

Normal Ocean Area

	Depth from surface (Km.)	Density g/Cm³	P wave velocity Km./sec.	S Wave Velocity Km./Sec.
Water	from 0 to 5 Km.	1.03	1.52	1.0
Sediments	" 5 to 6 Km.	2.10	2.10	2.0
Crust	" 6 to 11 Km.	2.84	6.4	3.5
Upper Mantle	" 11 to 75 Km.	3.40	7.8 to 8.2	4.55 to 4.7
Low velocity Channel	" 75 to 200 Km.	3.44	8.2	4.2

A considerable amount of information is currently being gathered in regard to the structure of the crust by seismic and other studies. The continental crust generally consists of two (or three) layers ignoring the sedimentary layers which may be present at the surface. The upper one is the Sial layer is of granitic composition (Granite, granitic gneiss and associated schists). It is 15 to 25 Km. thick. It is underlain by basalt which may consist of one or two layers. An upper layer, if present, is less dense and more siliceous than the lower. The lower portion is presumably more or less similar to the oceanic basalt which underlies the Pacific and other oceans. The basaltic layer is 15–30 Km. thick, but thicker where the crust has deep roots. These different layers have been distinguished because they are characterised by different velocities of seismic waves; the velocity of compression waves (Vp) is around 5.5 to 6 Km./Sec. in the granitic layer and 6 to 7.5 Km./Sec. in the basaltic layer. But it may be noted that a velocity of around 7.5 Km./Sec. is generally got in transitional zones where the crust grades almost imperceptibly into the mantle, as in regions of high heat flow.

Complementary to the folded mountain arcs are rifts and sunken lands quite some distance away. These would include the three major ocean areas—Atlantic, Indian and Arctic Oceans and a number of rifts of smaller dimensions. The well-known East African Rift Valleys were regarded by Bullard (1936) and some geologists as having resulted from compression, but further studies have led to the conclusion that they are really due to tension in the crust (Heiskanen and Meinesz 1958; p. 390–395). This rift system continues into the Red Sea and into Palestine (Dead Sea and Jordan Valley). A branch of this traverses the Suez canal and probably stretches into the Adriatic Sea. The Rhine graben, the White Sea-Caspian depression, the Kara Sea–Ob Valley, Lake Baikal, the Amazon Valley etc., are all regarded as tension phenomena similar to the East African Rift Valleys.

The Continental Crust

The continental crust is made up of shields, platforms, sedimentary basins and mountain belts. The shields are the most ancient areas composed of gneisses and schists with granitic and other intrusives. They contain also the root zones of ancient mountains, generally planed down, though

the harder rocks may stand up as hills. The platforms are composed mainly of well consolidated sediments of former ages. They may constitute plateaux or plains, depending on the effects of regional uplift. In general they may show slight positive isostatic anomalies.

Over the ancient basements lie sedimentary basins of various ages. In some basins the thickness of sediments may be of the order of 20,000 to 30,000 ft. As the beds are generally not horizontally disposed, the vertical thickness may be only a part of the above. The gravity anomalies in the basins are usually negative.

The youngest mountains of the world are Tertiary age. They are generally to be found at or close to the margins of the continents and are often overthrust towards the ocean basins. This implies that the continents have grown by marginal accretion. Some geologists have expressed the opinion that most of the continents are built around an ancient nucleus with younger belts added successively. This does not mean that there is symmetry in the growth, for vertical movements, erosion, sedimentation and mountain building may have destroyed any original symmetry. It is demonstrable that portions of continents have been uplifted or faulted down during the geological time, these changes obscuring their history and structure.

On a good physiographic map of the earth we see a series of mountain arcs. The most prominent of these are of Tertiary age. They occur along two major belts one being circum-Pacific and the other more or less equatorial. The circum-Pacific arcs are all convex towards the Pacific. The equatorial arcs are convex towards the former Tethys sea a remnant of which is the Mediterranean. Practically everywhere they have been formed from the sedimentary basins along the margins of the Pacific and in the Tethys sea.

Prof. Tuzo Wilson (1954) has shown that several of the Tertiary mountain systems occur as double arcs and that at the junction of each pair of arcs there is a sort of capping arc which he calls a secondary arc. So far as the writer can see, these secondary arcs, if present, have no regularity nor genetic connection with the primary arcs, at least in Asia. Transcurrent faults may however occur across the junctions of the

arcs because they are the limits of differential movements in the outer crust.

The presence of mountain roots, especially under the young mountains, has now been proved by earthquake records. Recent studies show that the crust under the Sierra Nevada (Western USA) has a granitic layer about 25 Km. thick, and a lower basaltic layer of more than usual thickness. Measurements in Central Asia show that in the Hercynian belt of Tien-Shan mountains the granitic layers are about 20. Km. thick and the basalt layers about 30 Km. Similar thicknesses have been found in several other areas. In a few cases as in West Turkmenistan it has been deduced that the granitic layer is as much as 30 Km thick, while it is 40 Km. thick in the northern part of the Pamirs. The basaltic layer in these two cases is 20 and 30 Km. thick respectively.

Oceanic Crust

For many years past it was believed that the crust of the Indian and Atlantic oceans differed from that of the Pacific Ocean and that the former contained some sial. In recent years this has not been confirmed, and all deep oceans are found to be underlain by oceanic basalt. There is however one important difference between the Pacific on the one hand and the Indian and Atlantic on the other. The Pacific ocean is on an average 3000 meters deeper than the Atlantic and the Indian oceans. It is bounded all around by folded mountains which are thrust over it. At and near the coast there are transcurrent faults running more or less parallel to the coast and having large horizontal displacements. In the symposium on fault-plane solution of earthquakes held during the 11th General Assembly of the IUGG at Toronto in 1952, St. Amand (1959) and others have stated that the relative movement is dextral, i.e., the Pacific basin as a whole appears to be rotating counter clockwise in relation to the continental masses around Ching Chang (1960) and Allen (1963) have given instances of sinistral faulting in Formosa (Taiwan) and in the Philippines. In addition to these there are also transverse fault structures like the well known Fossa Magna of Japan along which sinistral movement has taken place. Hence there is no uniform movement of the whole of the Pacific basin and the continents, but it varies in different parts of the circum-Pacific belt.

Mid-Ocean Ridges

A very important feature discovered in the oceans during last decade is the existence of a mid-ocean ridge system which, according to Maurice Ewing, Menard and others, is a continuous world-encircling feature (Menard, 1958). Starting from the mouths of the Lena river in Siberia, the Arctic ridge passes through several of the Arctic islands including Jan Mayen and Iceland. From here it can be traced unmistakably as the Mid-Atlantic Ridge right along the middle of the Atlantic ocean through Azores and other islands down to the South Atlantic where it bifurcates near Bouvet Island. One branch proceeds southwest to meet the Scotia Arc. The other branch passes mid-way between Antarctica and South Africa and joins the Mid-Indian ridge at the Reunion Island in the Indian ocean. The northern part of the Mid-Indian Ridge takes off from the mouth of the Red Sea in the Gulf of Aden as the Carlsberg ridge, and runs midway between Madagascar and India. From Reunion Island, the ridge runs to the south and southeast and enters the Pacific ocean near the Macquarie Island, south of Australia. From here it forms the East Pacific Rise (Menard, 1960), a broad dome-like feature which can be followed through Easter Island to near the Galapagos Islands and thence into the Gulf of California. The Mid-Pacific ridge of the Central and Northern Pacific is connected with the East Pacific Rise near northern end of the latter; it proceeds roughly northwest and then north through Tuomotu and Christmas Island groups and to the east of Japan and Kamchatka. The whole of this Mid-Pacific ridge system is marked by numerous sunken volcanic cones (sea-mounts and guyots) which are extinct volcanoes of the Jurassic or Cretaceous period.

The Mid-Ocean ridges are quite large features, as much as 1200 Km. or more wide, and are really large mountain ranges whose crest along the centre is marked by volcanism and high heat flow. In the Atlantic and Indian Oceans the crust shows a rift valley but not in the East Pacific Rise or the Mid-Pacific ridges. The formation of the Mid-Atlantic and Mid-Indian ridges may be explained as a long-continuing process which commenced with an initial rift in the original continent which then split up and the two sides began to drift. As the rift widened, basaltic magma rose in it from below. Each pulse in the separation would have stretched the ocean floor,

bringing up more basic magma and helping the spread of that already formed. Thus, in course of time, the central volcanic ridge must have become progressively wider and taller, the centre being occupied by newly erupted material and the sides by older and older material, depending on the distance from the crest (Krishnan 1960). More recently Prof. Tuzo Wilson (1963) has noted the existence of at least 7 parallel lines of islands in the Pacific which show progressively older rocks as one proceeds away from the central line. He believes that these island chains gradually moved away from the central line.

The northern part of the Eastern Pacific has been found in recent years to be crossed in a E–W direction by several major faults along which the bottom has been let down as much as 2 Km. in some cases. Two ar three others further south have cut across the East Pacific Rise. These faults show steep scarps on their northern or southern sides depending on which block has moved down relatively to the next. It is also known that considerable horizontal movements have taken place along the fault planes and in one case a movement of about 200 Km. has been inferred from the magnetic anomaly map of both sides of the fault. Only one or two of these faults are observed to continue on the surface of the continent. The others may possibly be present at some depth unless obliterated by the post-Jurassic orogeny near the continental margin. Though it is not known when they were formed, it is surmised that they may be Cretaceous.

The Pacific Ocean basin does not contain any sediments older than the Cretaceous; in several cases where bore-holes have been put down, the earliest sediments obtained were of Cretaceous age, as far as is known at present.

The absence of lower Mesozoic sediments does not mean that the Pacific Ocean itself is young. In fact there is no evidence that the Pacific was ever occupied by a continent since the Archaean times. This would only mean that, whatever sediments were accumulated in the Pacific basin before the Jurassic were assimilated by vast eruptions of oceanic basalt that welled up from below. Similarly the Indian and Atlantic oceans do not contain sediments older than early Cretaceous, except in small areas as in the Mozambique Channel which is known to have been formed initially in the Per-

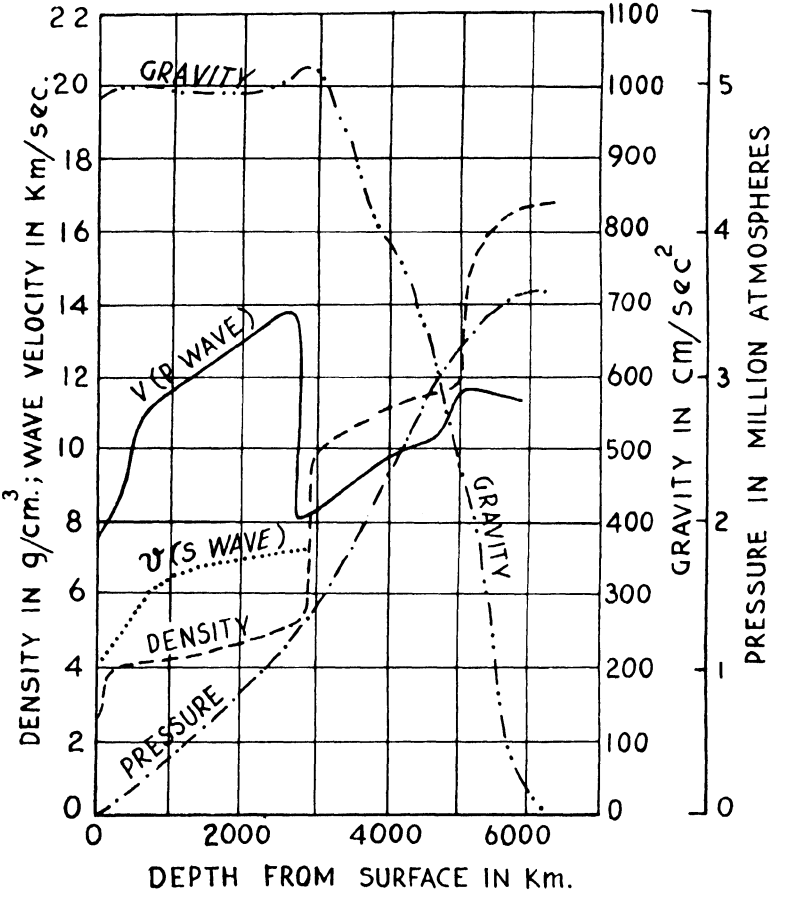
GRAVITY
V (P WAVE)
v (S WAVE)
DENSITY
PRESSURE
GRAVITY
DENSITY IN g/cm³; WAVE VELOCITY IN Km/sec.
GRAVITY IN cm/sec²
PRESSURE IN MILLION ATMOSPHERES
DEPTH FROM SURFACE IN Km.
0
2000
4000
6000
22
20
18
16
14
12
10
8
6
4
2
0
1100
1000
900
800
700
600
500
400
300
200
100
0
5
4
3
2
1
0

Figure (1)

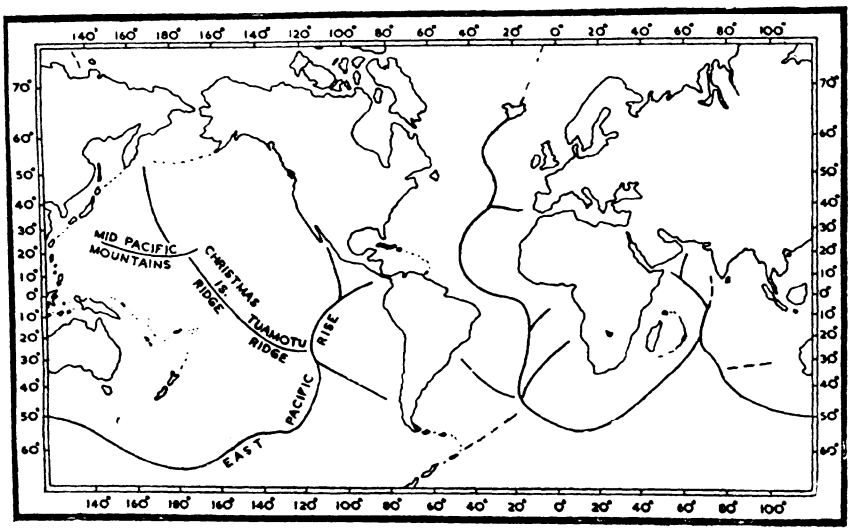
MID PACIFIC MOUNTAINS
CHRISTMAS IS. RIDGE
TUAMOTU RIDGE
EAST PACIFIC RISE

Figure (2)

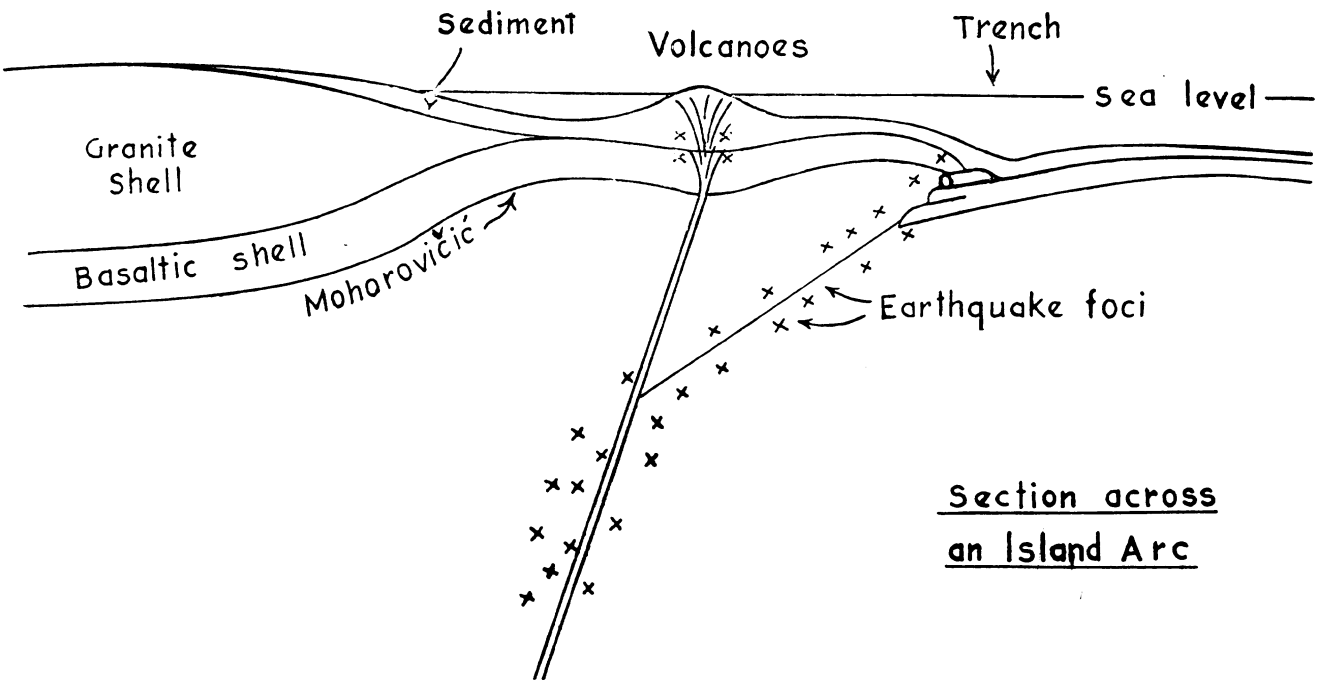
Sediment
Volcanoes
Trench
sea level
Granite
Shell
Basaltic shell
Mohorovičić
Earthquake foci
Section across
an Island Arc

Figure (3)

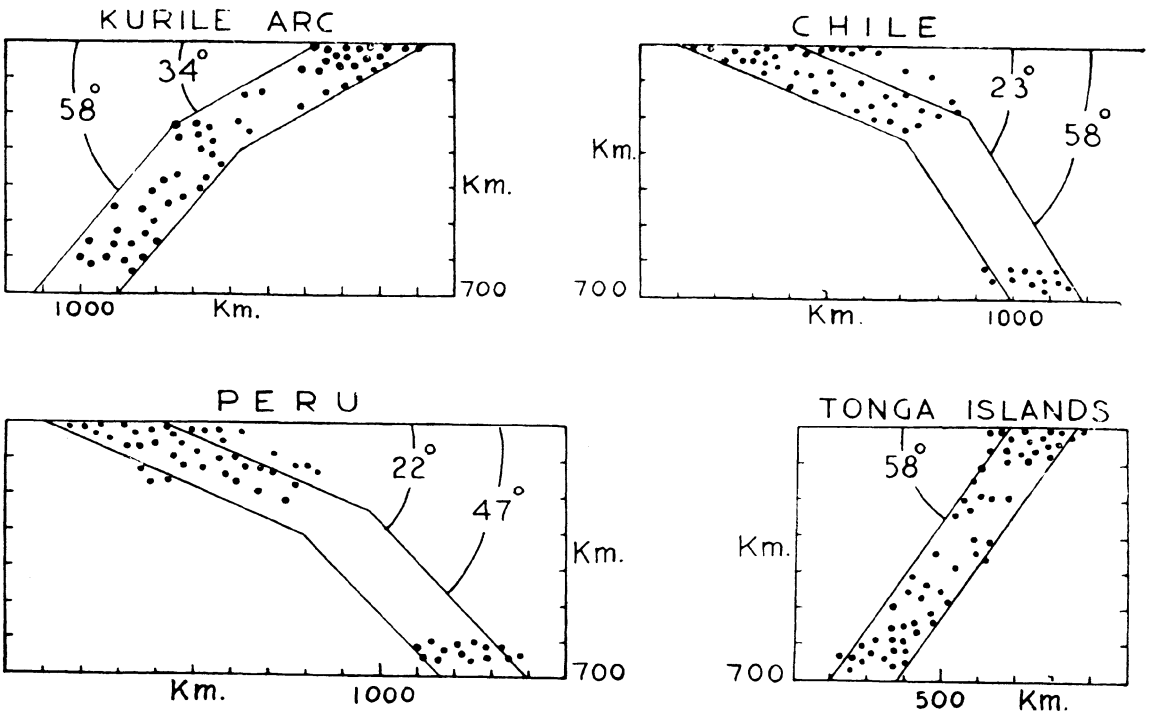
KURILE ARC
58°
34°
Km.
700
1000
Km.
CHILE
Km.
23°
58°
700
Km.
1000
PERU
22°
47°
Km.
700
Km.
1000
TONGA ISLANDS
58°
Km.
700
500
Km.

Figure (4)

mian times. The absence of earlier Mesozoic sediments in these two oceans can of course be easily explained, as in accordance with the theory of continental drift, these oceans were formed only in the early Cretaceous period.

Island Arcs

The Pacific is marked, on its western margin, by a series of Island Arcs from the Aleutian Islands in the north to New Zealand in the south. The various arcs are of different dimensions and curvatures except the Tonga-Kermdec strip which is virtually straight. They are all convex towards the Pacific Ocean. The fact that they are connected with land-ward dipping planes which contain the loci of earthquakes can be construed as indicating that continental matter is being thrust towards and over the Pacific ocean along the above mentioned planes.

As is now well known, Island Arc structure comprises several zones. The outermost, on the convex side, is a deep Oceanic trench, a long narrow and very deep trough. Behind this rises a ridge which may be above or below water level. Its outer flank is marked by large negative gravity anomalies (—100 to—200 mgals), and by shallow earthquakes. This ridge constitutes a nonvolcanic zone but is actively rising. Behind this comes the zone of positive gravity anomalies often with active or recently extinct volcanoes. The earthquake foci beneath this zone are at 60 to 100 Km. deep. Further behind, there is often a second arc with older volcanic rocks, with a small or no gravity anomalies, and with earthquake foci at intermediate depths (200 — 250 Km.). Lastly comes a somewhat wider zone containing deep focus earthquakes (at depths of 300 to 700 Km.). This is in some cases a submerged area covered by a shallow sea. It is not unlikely that the depression of this last zone is due to the withdrawal of continental material from below and its movement upward along the plane of earthquake foci which ends at the surface in the active island arc. The total width of the Island Arc structure including the deep earthquake zone is of the order of 600 Km. at the surface. Within this general structure, minor variations are found in the different arcs in size, curvature, distinctness of zones etc.

Central and South America also show these structural characteristics though the zones have been welded on to the

Continent in South America. There are no similar structures on the eastern margin of the Pacific while such structures, if originally present are not easily recognisable now in the Rocky mountains and Coastal region of North America. The Banda-Sunda-Andaman arc is of this type and parts of the Island Arc structure can be deciphered along the Alpine-Himalayan belt though largely obliterated in large stretches because of the direct clash of Eurasia and Gondwana Continents against each other.

Benioff's studies (1954) of Island Arcs and associated seismic zones have led him to decipher a multiple fault system in which the surface fault appears to become steeper at some depth of the order of 25 or 30 Km. The distribution of earthquake foci shows that the shallow portion of the "fault" has a dip (towards the continental mass) of about 30° and that the deeper portion has a steeper dip of around 60°. The latter is recognised in arcs which have a deep focus seismic zone present, and extends down to 700 Km. Some variation in the dip and width of this zone is to be expected. Benioff thinks that the change in dip of the zone at around 300 Km. depth marks a tectonic discontinuity which may be the boundary of Continental masses. But, as mountain roots do not extend below 70 or 80 Km. at the most, and as isostatic compensation is also operative at that depth, a continental crust cannot be deemed to extend to 300 Km. depth. It may however represent the lower boundary of a shell or a zone in which the physical properties and temperature-pressure conditions of the upper mantle rocks are different from those of the deeper zone.

The Andesite Line

The Island Arcs of the western margin of the Pacific delineate the 'Andesite line' of Marshall (1912). This boundary has tectonic significance as the boundary of Continental areas in the Pacific. It marks also the active volcanic and earthquake belt. On the American side, the continental boundary (including the coastal islands) may be taken as representing this line. The andesitic lavas, especially those exposed in the Island Arcs, may be considered to have originated from partial assimilation of the sialic crust by the basaltic magma or by a process of differentiation of the mantle rocks by partial fusion (Jacobs et al. p. 63–64). It is interesting that andesite has such a close association with continental areas. In and

on the landward side of the Island Arcs, andesite, dacite and acid lavas are common amongst the volcanic materials, whereas outside the arcs in the main oceans, andesite is absent and only Olivine basalts (and alkali-Olivine basalts) are present. That is to say, while andesite and more silicic rocks are very common in continental areas, the deeper oceans including the Pacific, Atlantic and Indian, are devoided of acid and intermediate lavas. There appears to be one exception to the occurrence of an island are inside the Andesite Line, *viz.*, The Marianas-Yap-Palau arc which contains calc-alkalic rocks, though a distance away from the continental margin. The Philippine Sea behind it has an oceanic crust and is thus part of the Pacific (Macdonald, 1960).

The Mid-Ocean ridges are now generally thought to have been formed above the junction zone of ascending currents from two adjacent convection cells. Such a junction zone will be one of tension as the currents will flow away sideways at the top. On the other hand, the continental margins would mark a strip along which the convection currents from adjacent cells descend down. Here the currents would produce compression and therefore folding and overthrust phenomena should be conspicuous near the edges of continents. The rift valleys and deep sags in the continents can also be explained as due to the presence of similar convection cells below. It is possible that, during the history of the earth, the position and dimensions of the convection cells may have changed many times and that these determined the major tension and Compression zones. As there is likely to be some degree of symmetry in the arrangement of these cells and as they may not operate below certain minimum size, it would be irrational to try and explain every fold and fault zone by invoking the action of convection cells as some have attempted to do.

Zone of Deep Earthquakes

Seismologists have generally treated the strain release responsible for earthquakes in the upper mantle (down to 700 Km. depth) as due to faulting, as will be evident from the series of papers in the symposium on fault-plane solution of earthquake motion (Hodgson et al. 1957) presented at the Toronto Assembly of the IUGG. It is most improbable that any fault planes (as we envisage them at the surface) exist at those depths. All irregularities would be smoothed down

at the isostatic level of compensation, say at 70 Km. Magma chambers from which most present volcanoes ultimatley derive their materials exist at depths of 40 to 60 Km. (Eaton, 1962) so that much of the adjustment of crustal strains takes place at depths of 40 to 70 Km. Below that is the low velocity channel down to 200 Km. in which the effects of temperature are dominant and the rocks are presumably in a condition of incipient fusion. In the deep focus earthquake zone of 300 to 700 Km. movements may be set up as a result of relief of pressure which crustal movement involves. Pressure changes would produce phase change of the mantle material from a dense to less dense state. The location of these changes along the continental margins of the Pacific may have some connection with the temperature distribution in the mantle, as between the continental and oceanic mantle. The Mohorovicic discontinuity under the Pacific, which is at a depth of 5 to 8 Km. beneath the ocean bottom, may be a few hundred degrees centigrade lower in temperature than the adjacent continental crust at the same level. An appreciable, though gradually diminishing, temperature difference between the sub-continental and sub-oceanic mantle may persist to some depth, certainly into the zone of intermediate earthquakes and even into the deep earthquake zone. The border zone, between these two, which would show a temperature gradient, would become subject to phase change and as a result the less dense material produced there would rise along the zone into the Island Arc at the surface. It has also been suggested by F. Birch and others that the mantle down to 700 or 800 Km. depth possesses chemical inhomogeneity and this may induce phase changes and movements near the margins of the Continents which may also be the junction of descending convection currents from adjacent cells in the mantle.

Below the continental margin of the Pacific, therefore, active changes are taking place whereby the mantle rocks are reconstituted and perhaps also differentiated into fractions of both andesitic and ultrabasic character. This should be the area of continental spread and continental accretion.

In conclusion we may state that the earth's crust shows different characters in continental and ocean areas. The former is some 35 Km. thick on an average and consists of a granitic shell about 15 to 20 Km. thick (P velocity 5.5 to 6 Km./Sec. and a basaltic shell below (P velocity 6.5 to 7.4

Km./Sec.). The latter may sometimes show a double layer. The Oceanic crust on the other hand is normally only 5 to 7 Km. thick (6.5 to 7.5 Km./Sec.) and is composed of olivine basalt or gabbroid material. The mid-ocean ridges and Island Arcs are transitional in character, the former being entirely basaltic while the latter contain andesitic material also. The latter may be considered as continental crust in the making. There are indications that the continents have been gradually growing through a process of differentiation of the crust and the mantle, though at the same time other parts of the crust may have been reincorporated in the simatic crust.

Crustal Thickness in Various Regions

(After Gutenberg (1959) and other sources)

Area	Thickness Sial (Km.)	Vp (Km./Sec.)	Thickness Sima (Km.)	Vp (Km./Sec.)	Depth to Moho (Km.)
CONTINENTAL AREAS					
Black Forest Germany	20	6.0	10	6.5	30
Southern Alps	35	5.7	10-15	6.6	45–50
Po Valley, Italy	14	5.1	18	6.5	32
Hungary	9	5.6	26	6.2	35
N. E. India	25	5.6	21	6.6	46
Kyoto, Japan	22	5.8	10	7.0	32
Near Lake Issik Kul	15	5.5	30	6.4	55
Alai Range	35	—	30	—	65
South of Lake Balkash	18–20	5.5	20	6.4	35–40
Kura, Caucasus	15	5.7	34	6.7	49
Kola Peninsula	19–21	5.6	30	—	49–54
Central Appalachian	15	6.0	25	6.5	40
Pennsylvania	32	6.1	3	—	35
Arkansas Plains	12	5.5	31	6 9	40–43
Sierra Nevada (USA)	—	—	—	—	50–55
Michigan Peninsula	1.5	4.7	35	6.3	35–37
Canadian Shield	30	6.2	7	7.1	37
Mexican Plateau (Durango)	4	4.9	29 11	6.0 7.5	34
Peru, High Plateau	4(Sedim) 21.2	5.3 6.2	39.6	6.7	61–65
Chuquicamata mine, Chile	6	5.5	28.4 35.9	6.3 7.0	65–70
New Zealand	10	6.0	23.29	6.5	33–39
West Australia	—	6.0	—	—	36
Johannesburg (South Africa)	—	6.2	—	—	34

Area	Thickness water (Km.)	Thickness Basaltic layers (Km.)	Vp (Km./Sec.)	Depth to Moho below sea bottom (*below sea level)
OCEANIC AREAS				
Arctic Basin	3.5	11 to 12	—	11 to 12
West Atlantic	4 to 5	8 + 3	6.7	11
Atlantic off N. California	3.5	4 + 5	6.5	9
Deep central Pacific	6 to 7	4 to 6	6.5	4 to 6
Pacific Ocean	5 to 6	7 + 5	6.8	12
West Indian Ocean	4 to 5	7 to 8	—	7 to 8
Pacific, off Central America	4 to 5	6 + 6	6.8	12
E. of Tonga trench	6	8 + 4	6.5	12
Tonga Trench	9	12 + 8	6.5	20
Puerto Rico Trench	6 to 7	8 + 4	6.3	12
Easter Island Rise	3	1 4 to 5	6.5 7.5	* 5 to 6
Mid-Atlantic Ridge	1	4 to 5 20	5.5 to 6.5	*23 to 25
Iceland	—	2.5 15.0 10.0	4.0 6.7 7.2	*26 to 28
Hawaii Islands	—	0 to 4 4 to 9 9 to 14	3.9 5.0 6.8	*14
Eniwetok Islands	—	10 + 7	6.9	*17

NOTE : Where the sign + is used, two layers are present with the thicknesses shown.

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LOCAL GRAVITY ANOMALIES AND GEOLOGICAL STRUCTURE OF RUDNY ALTAY

BY

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GRAVITY survey has great significance in the study of tectonic structures of regions bearing ore deposits. Knowledge of tectonic structures of these regions is one of the main factors that determines successful prospecting for useful materials. One might show the meaning of gravity maps in relation to tectonic features by discussing the gravity map of Rudny Altay. For some years a gravity survey was carried out in the district of Rudny Altay and Bouguer anomaly map was plotted. On that map it is noted that the gravity field gradually decreases in the south-east direction and on a background of gradually decreasing gravity field, the territory of Rudny Altay is distinguished by relative increase of gravity field. Progressive decrease of gravity field in the south east direction is connected with the behaviour of Mohorovicic's boundary which increases in depth in that direction. To be able to interpret gravity anomalies aroused by geological structures situated above Mohorovicic boundary, it is necessary to eliminate gravity effect of the very boundary. That is, from the net gravity field, local gravity anomalies connected with the geological structures are to be picked out from the regional anomalies caused by the relief of Mohorovicic boundary. Because of some smoothness of regional anomalies one may use a method of average. In the present case, a square grid was used with a length of side of square equal to 100 Km. The size of the square was chosen experimentally. Using this grid, the map of local gravity anomalies was prepared which is the subject of the present discussion.

The gravity map of Rudny Altay and adjacent regions as a whole shows a characteristic north-west trend of anomalies which also coincides with the direction of the main structural elements of the region. There are some deviations from this general picture, which may be explained in terms of the

deviations in the strike of the corresponding structures of the region.

In north-west part of Rudny Altay, near the town Rubsovsk, there is intensive positive anomaly with strike very close to the latitude. To south-east of Rubsovsk gravity maximum, on the territory of Rudny Altay, between the villages Solotuha and Bolshe-Narim, there is positive anomaly with two maxima. The first maximum is on the south-east of Aleysky anticlinorium the top of which is situated on the north-west part of the maximum. The second maximum has north-west strike and is situated in Ziryanovsko-Buchtarminsky region. This stretches in the south-east direction upto the valley of the river Narim where it disappears. When continued to the South Altay, there are positive gravity anomalies of north-east strike, the central part of which is situated in the region of metamorphic schists.

To the south-west of the positive anomalies of Rudny Altay, there is a region of negative gravity anomalies with north-west trend and is situated on the Kalba synclinorium area. The lowest values of negative anomalies are observed above the exposures of the massive Kalba granites.

The region of Gorny Altay is mainly characterised by negative gravity anomalies of north-west strike. Most of the positive anomalies are noticed in the south-east of Terektinsky and to the west of Katunsky mountain ridges. The main geological structures are characterised by their own anomalies. Above the Talisky anticlinorium, there is a positive anomaly and the Tigereksky synclinorium is characterised by negative anomaly and so on.

Hence, from the above review one may visualise and understand the connection between the main structural units and the behaviour of the gravity field. Geologically differrent regions of Rudny Altay, Kalba and Gorny Altay are characterised by differrent values of gravity field. The main anomalies correspond to the main geological structures of the said regions. For more detailed characteristics of gravity field and its relation to geological structures, let us consider the gravity traverses crossing the territory of Rudny Altay and Kalba in their central part. Along this traverses in the Kalba region,

there is negative gravity field and on the background of this there is negative gravity anomaly above Kalba granites. Between the town Ust-Kamenogorsk and the village Butakovo, there is intensive positive anomalies with maximum values located above the exposures of Zmeinogorsk granites. Near the village Butakovo, the gravity field decreases very quickly and we have a quiet behaviour of the field till the village Poperechnoe, where there is abrupt decrease in the field again above the region where the Kalba granites are distributed. So gravity traverses help to make concrete the general picture of the gravity field of Rudny Altay and adjacent regions and to find out some of the details.

Considerable intensities of the main anomalies and a relatively small gradient of the field together with the absence of visual connections of the anomalies with rock types, show us a large depth of the sources giving rise to these anomalies. Display of causes of these anomalies is different in different parts of the region and one may judge about it on the basis of the differences in the gravity field. These differences may be observed in the regions of Verh-Ubinka and Ziranovsk gravity maxima. The region of the first maximum is wider and gravity gradients are much less than in Ziranovsk region. On the background of large local gravity anomalies there are positive and negative anomalies which may be due to the definite complex of rocks (Kalba granites of negative anomalies; Zmeinogorsk granite of positive anomalies; Lower palaeozoic rocks of positive anomalies and so on). These anomalies are characterised by abrupt gradients which indicates the shallow depth of the sources causing them. So it could be said that the local gravity field contains two types of anomalies : (1) Local anomalies of the first order, reflecting the distribution of rock density in great volumes and occupying considerable areas and also commensurable with the main structural units of the territory in question (Rudny Altay, Kalba and Gorny Altay) and (2) Local anomalies of the second order which in the most cases may be explained directly by geological causes so far as they reflect composition and structures of rocks in the vicinity of a earth's surface. Above established connection of gravity field with the pecualiarities of geological structures of the region shows importance of gravity investigations for accurate determination of tectonic scheme and internal structure of the discussed territory. To solve these problems correctly and to use the data of gravimetric investigations, it

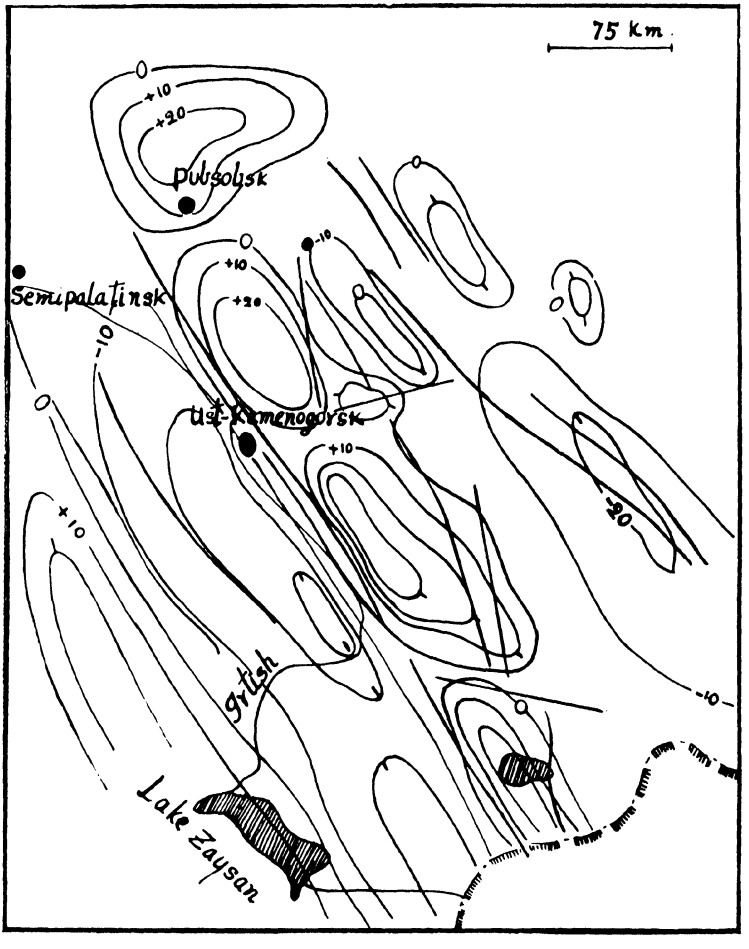
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Figure (1)

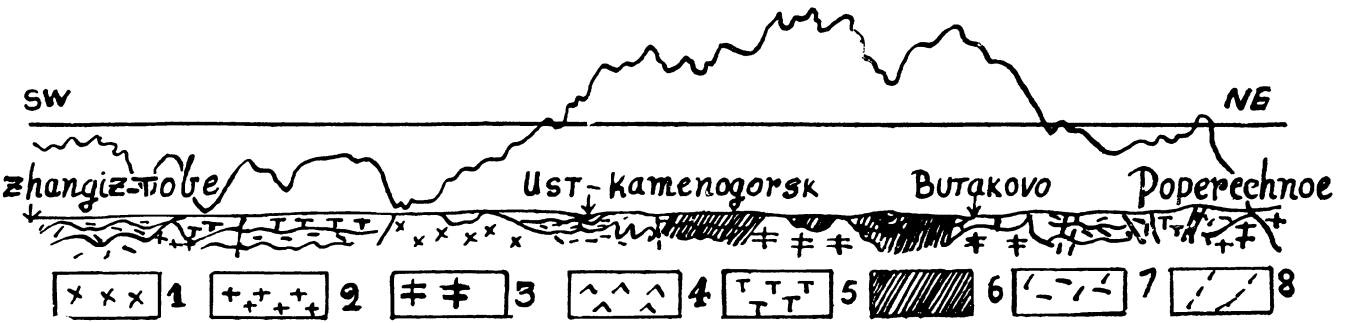
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Figure (2)

is necessary to find out the factors influencing the observed gravity anomalies.

At present the problem of interpretation of gravity anomalies of the first order apprently cannot be solved simply because of insufficiency and contradictoriness of the existing data. But, at any rate, one must try to compare the base factors in relation to the problem at hand and work out corresponding conclusions.

In general, the data about the density of rocks has a great importance from the point of view of the determinations of causes of gravity anomalies even though they fail to explain the anomalies of the first order, so these do not characterise the distribution of rock density at large depths, to say nothing about the data of rock density for the region under study being meagre. Besides, in solving the problem of the nature of gravity anomalies, it is necessary to take into account the specific features of gravity field and known geological facts and regularities. Comparitive study of the geological and gravity maps of the said areas shows territory coincidence of many positive anomalies with the regions of distributions of Zmeinogorsky granites and negative ones with the regions of distribution of Kalba granites. This coincidence is confirmed by a further comparitive study with magnetic data. The average density of Zmeinogorsky granites can be 0.07 to 0.2 gm./cm^3. more than the average density of the Devonian rocks. In order to explain the observed anomalies, it is necessary to have the thickness of granite massive about 7 to 10 Km. and also the massive must be submerged into the Devonian rocks till this depth. It is possible to have such a thickness of granites, but it is impossible to have Devonian rocks of this thickness, in contact with the granites. If the thickness of the Devonian rocks is less than this thickness, then the Zmeinogorsky granites will not have positive, but will have negative effective density difference of the order 0.05 to 0.2 gm./cm.^{3} and the observed anomalies cannot be explained. However, it is possible to explain the observed gravity anomalies as a result of a probable increase in the depth of their base and consequently with increase in density with depth. But this assumption is very artificial and cannot be right from geological point of view.

Kalba granites must have almost the same thickness so that their effective density is negative by about 0.1 gm./Cm^3,

if one wants to explain the existence of negative gravity anomalies as a result of the influence of these granites. For such a situation, strictly speaking, it is necessary to add that there is no exact coincidence between gravity field and regions of distribution of this or that rock complex, when anomalies of the first order are discussed. Regions of distribution of negative anomalies in the Kalba are very large and Kalba granites occupy only 20 to 30% of that territory. The same may be said to be true of the distribution of positive anomalies and region of Zmeinogorsky granites. From the foregoing arguments, it may be concluded that igneous rocks cannot be the main factor of great gravity anomalies of the first order.

However, in the regions of postive gravity anomalies of Rudny Altay, there are exposures of lower Palaeozoic rocks some of which are situated in the region of gravity maxima of the first order. In Kalba, where the lower Palaeozoic rocks are in the depth, there are negative gravity anomalies. The effective density of the Devonian rocks is 0.1 to 0.2 gm./Cm^3. and a little more than the density of Zmeinogorsky granites. So it would be possible to explain the observed gravity anomalies in terms of the influence of the depth of the Caledonian Basement. But there are some factors that contradict such an explanation. For instance in the region of the village Shemonaiha and the north-west of it, the lower Palaeozoic rocks are close to the earth's surface and even bear some exposures. These exposures are situated on the core of the Aleysky anticlinorium and are located not in the centre, but to the north-west of Verh-Ubinka maximum. In the Ziranovsko-Buhtarminsky region where the most intensive gravity anomalies are observed, there are no lower Palaeozoic rocks at all. In the region of Rubsovsky maximum, lower Palaeozoic rocks are unknown. In the region of Gorny Altay, the Caledonian basement is exposed on a large territory, but no intensive positive gravity anomalies are noticed there. Besides that having taken the relief of Caledonian basement as the main factor of gravity anomalies of the first order, it is necessary to assume a great variation of its depth from place to place. For a difference of densities of the order 0.1 to 0.2 gm./Cm^3., the difference of the depth of the lower Palaeozoic rocks in Rudny Altay and Kalba will not be less than 8 to 16 Km. But such differences in the depth are impossible for many parts of that region. All the facts mentioned above indicates the source of gravity anomalies in the deeper horizons of the

ancient basement. The possible connection of gravity anomalies with objects at great depths shows the kind of anomalies to be expected as : great intensity, small gradients and large territory of distribution.

Under the known lower Palaeozoic rocks at Rudny Altay, there are more ancient and perhaps more metomorphosed rocks with greater density. This fact was not taken into consideration earlier and it is now felt that only on account of this unsatisfactory interpretations were made for the discussed territory. Metamorphic rocks are very heterogeneous with respect to their density and one may judge about this on the grounds of the investigations carried out in Karelia, Urals and other regions. As long as 1937, it was shown that the change of density of the ancient crystalline rocks connected with change of their composition, was the main factor in the cause of great gravity anomalies of Baltic Shield and the Northern part of the Russian Platform.

There are all grounds to assume the existence of such a heterogeneity of ancient rocks over the territory of our investigation because of different lithological composition of ancient rocks in different parts of Rudny Altay. Heterogeneity of rocks of pre–hercynian basement containing rocks more ancient than lower Palaeozoic, is more possible, so the geological history of different parts of the discussed territory in a large measure was different. Hence there are grounds to consider that a density heterogeneity of rocks of pre-hercynian basement combined with difference of their composition and the degree of metamorphism as one of the main causes of local gravity anomalies of the first order. Besides, gravity anomalies reflect in some degree the influence of its depth also. Thus it is seen that igneous rocks also have some meaning.

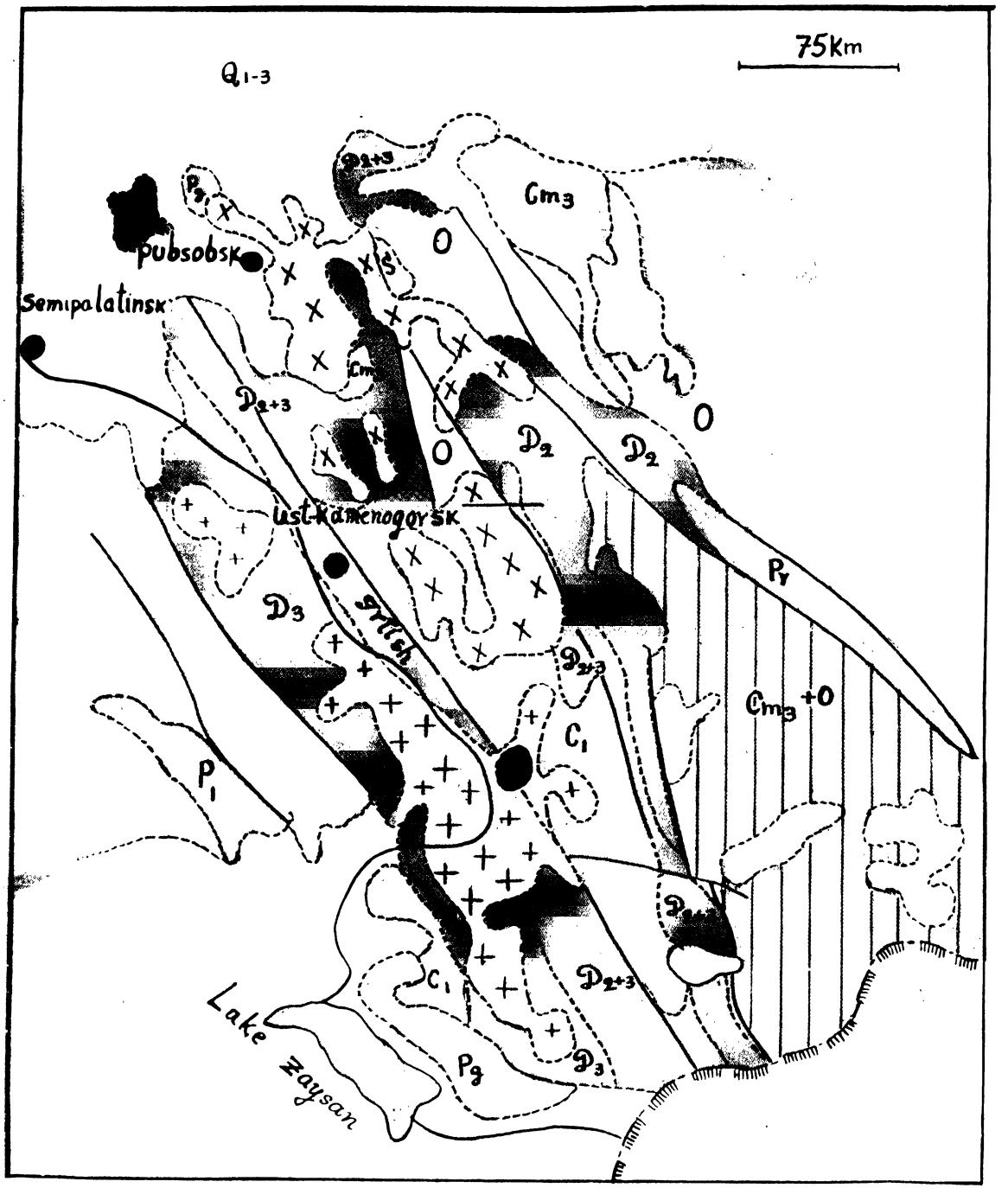
The two causes, just pointed out, not being the main ones for gravity anomalies of the first order, nevertheless are important in the creation of gravity anomalies of the second and third order. The problem of concrete matter of basement heterogeneity in different parts of the territory may be the subject of special investigations.

Coming to the Rudny Altay, one might affirm that on its territory, the pre-hercynian basement rocks are more rigid

than in the Gorny Altay and Kalba. In the light of this, the most intensive gravity maximum of Rudny Altay-Ziranovsko-Buhtarminsky, shows that there are the most rigid rocks composing the basement of that region. For the relatively large gravity gradients of that maximum, one may suppose a shallower depth of basement.

Negative gravity anomaly of Kalba territory completely coincides with the central zone of Zaysan geosyncline. For that region from the gravimetric and Paleogeographical data, one may suppose the greatest depth for the pre-Hercynian Basement. In addition to this, the gravity field behaviour is influenced by Kalba granites situated at the lowest part of negative anomaly. Negative gravity anomalies of Gorny Altay, observed over the territory, where the pre-Hercynian Basement is on the very surface, seems to be a contradiction with present idea of "horst" nature of the Gorny Altay mainly composed of lower palaeozoic rocks. But negative anomalies of Gorny Altay reflect the existence of rocks of decreased density occurring within considerable interval of depth. In this respect, Gorny Altay is like any other mountaneous region, especially the Middle Asia where the uplifting of rocks on high level is accompanied by abrupt decrease in the gravity field. A group of processes is possible which might arise negative anomalies in Gorny Altay and in Middle Asia. That group simultaneously shows difference in the geological history of Rudny and Gorny Altay. This difference seems to consist in the more development of the processes in the Gorny Altay arousing decrease in the density of deeper masses.

Tectonic zones of Rudny Altay on the gravity map are situated in the regions of transition from positive anomalies to the negative ones. Such a feature of the anomalies can be caused by an existence of a fault. Apparently, Irtish and North-East tectonic zones are ruptures of the pre-Hercynian basement along which displacement took place in Rudny Altay relative to Gorny Altay and Kalba. On the basis of gravimetric data, confirmed by aeromagnetic surveys, the Irtish tectonic zone can be traced in Kulundinskaya steppe, preserving its north-west extension. But the North–East tectonic zone does not continue into the Kulundinskaya steppe and ends in the region of the village Kurya. So gravimetric data enables one to draw out some conclusions of significance in the right understanding of the structure of Rudny Altay.



Q1-3

Pg

P1

C1

D2+3

S

O

Cm3

Pr

a)

(2)

In addition to the use of gravity maps for tectonics, it is interesting to discuss them also from the point of view of their significance in the prospecting. The background for that is offered by the relation between regions of distribution of ore deposits and some peculiarities of the gravity field.

When the local gravity map is compared with the map of ore belts of Altay, one might notice that the polymetallic belt of Rudny Altay, limited by Irtish and the North-East tectonic zones, is on the zone of positive gravity anomalies. The rare metallic belt of Kalba is tied to the narrow negative anomaly stretching along the left bank of the Irtish and Irtish tectonic zone. The main part of the rare metallic belt where the majority of big rare metallic deposits are located, is situated on the eastern part of negative anomaly. Gold belt situated to the west of the rare metallic one and also parallel to it, is characterised by an increase of gravity field and situated on north-east part of the increased value of the gravity field zone. This zone stretches from the lake Zaysan to north-west of it. Such a distribution of ore belts and the relative peculiarities of gravity field has lots of value in controlling our direction of prospecting in locating the deposits. At the same time that shows existence of some connections between the deep structures arising gravity anomalies and distribution of zones of mineralizations. At present, the western and the eastern boundaries of the polymetallic belt are known definitely. The question of north-west and south-east boundaries of Rudny Altay is open. That is, the question of the behaviour of the polymetallic belt along the extension of the geological structures.

In direct continuation of Rudny Altay to the north-west in the region of the town Rubsovsk, there is positive anomaly similar to that of Verh–Ubinka and Ziranovsk ones, around which polymetallic deposits are grouped. As a result of that, in the region of Rubsovsk, it is necessary to assume a possible continuation of polymetallic belt in the north–west direction also. In this case, the polymetallic deposits, situated to the north–east from the North–East tectonic zone, have a natural explanation. The occurrence of these have been held to be exceptions to the general rule (straight extension of polymetallic belt in north–west direction) by some geologists. These deposits are situated along eastern part of Rubsovsk anomaly. Most probably, the north–east tectonic zone does not continue fur-

ther to the north–west, but ends in the region of the village Kurya and the polymetallic deposits of the river Charish basin are controlled by a structure arising the Rubsovsk gravity anomaly.

It is evident from a consideration of the character of gravity field, that the South Altay must be a direct continuation of the polymetallic belt. So in the light of gravity evidence, polymetallic belt is a single whole beginning from the State boundary through the territory South Altay, Rudny Altay until the town Rubsovsk where it is covered by Meso-cainozoic sediments of Kulundinskaya steppe. The western boundary of this, forming the Irtish tectonic zone, continues into Kulundinskaya steppe. The eastern boundary forming the North-East tectonic zone ends on the latitude of Verh–Aleyskoe–Tretyaki and the polymetallic belt has a branch in the basin of the river Charish. From the results of the regional gravity survey detailed so far, one might draw these following conclusions:

1. The direct cause of local gravity anomalies of the first order is heterogeneity and different depth of pre-Hercynian basement.

2. On the basis of the gravimetric data, the continuation of Irtish tectonic zone and the general structure of Rudny Altay could be confirmed.

3. Connection of Ore belts of Rudny Altay and Kalba with the structural peculiarities of the region are reflected on the gravity map.

A REGIONAL GRAVITY STUDY OF PENINSULAR INDIA SOUTH OF LATITUDE 16°

BY

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Abstract

Using the published Bouguer Anomaly values of Survey of India a Bouguer Map, a Downward Continued Map and a Ground Level Second Derivative Map are presented for the peninsular India south of latitude 16°. Five anomalous features are discussed in the light of known surface geology of the region. One of the most prominent features is a linear belt of NE—SW strike extending from around Madras city to the vicinity of Mangalore on the west coast with two intense peaks, one near Coimbatore-Ootacamund and another to the south near Thekkadi in Kerala. This belt is seen to correlate very well with the known Charnockite exposures of Madras, Salem-Shevaroys, the Nilgiris, the Anaimalais and the Palni Hills. A large, broad anomaly centred around Chikmagalur in Mysore State does not show any correlation with the Dharwars of the area. The Cuddappah Basin shows only a weak expression in the Bouguer picture. However to the east of the basin are seen a series of small anomalous patches, brought out only under the higher resolving power of Second Derivative Map. The authors believe that this string of anomalies might be the expression of isolated Charnockite masses forming the 'backbone' of the Eastern Ghats. To the south of Madras, the Downward Continued Map shows an anomalous belt which swings out into the sea with a tendency for closure in the sea off Karaikkal. This has been identified with the 'Karaikkal Structure' first pointed out and extensively studied by Kailasam. On the whole the study seems to delineate satisfactorily the boundaries of the Charnockite region in the peninsula as given by Fermor and Pascoe.

THE peninsular shield of India offers a special interest both to the geologist and the geophysicist for a variety of reasons. For instance it had no sedimentary history since the

Cambrian till probably the Cretaceous times when large thicknesses of sediments were deposited along the coastal areas. The shield contains the type areas of two very famous rock groups, the Charnockites and the Dharwars. From the geodetic point of view the geoid over the southern part of the shield is found to be depressed below the Spheroid all the way down to the land's end in the south. Thus any regional geophysical study of the peninsula is bound to throw valuable light on the structure and tectonics of the shield. The present authors have attempted a regional gravity study of the peninsula south of latitude 16° using the available gravity data published by the Survey of India with a view to examine how far the gravity picture can be tied to the surface geology and also how much can be gleaned about sub-surface structure from the regional gravity picture.

Fig. 1 gives a contoured map of the ordinary Bouguer Anomaly (from Survey of India data). It may be pointed out here that these Bouguer values represent the Bouguer Anomaly upto a distance of 104 miles taking into account the orographic correction and not the so-called 'Modified Bouguer Anomaly' which is computed on the assumption of no compensation within the lettered zones (that is upto a radius of 104 miles from each station) and Hayford type compensation outside. According to Gulatee[1] the variations of these two types of Bouguer Anomalies are the same in a limited region though they may vary considerably over vast regions like a whole continent. The original Survey of India Bouguer values have been deliberately biassed by the addition of –60 mgals for computational convenience as this makes all the values over the peninsular appear in one sign.

The following anomalous features stand out prominently in the Bouguer Map (Fig. 1) :

1. A negative high of about 50 mgals amplitude centred around Chikmagalur in Mysore state.

2. A weak anomaly of about 15 mgals centred around Gidalur in Andhra Pradesh whose eastern flank is banded by a tight bunch of contours running parallel to the east coast.

3. A strong elongate negative anomaly of about 30 mgals

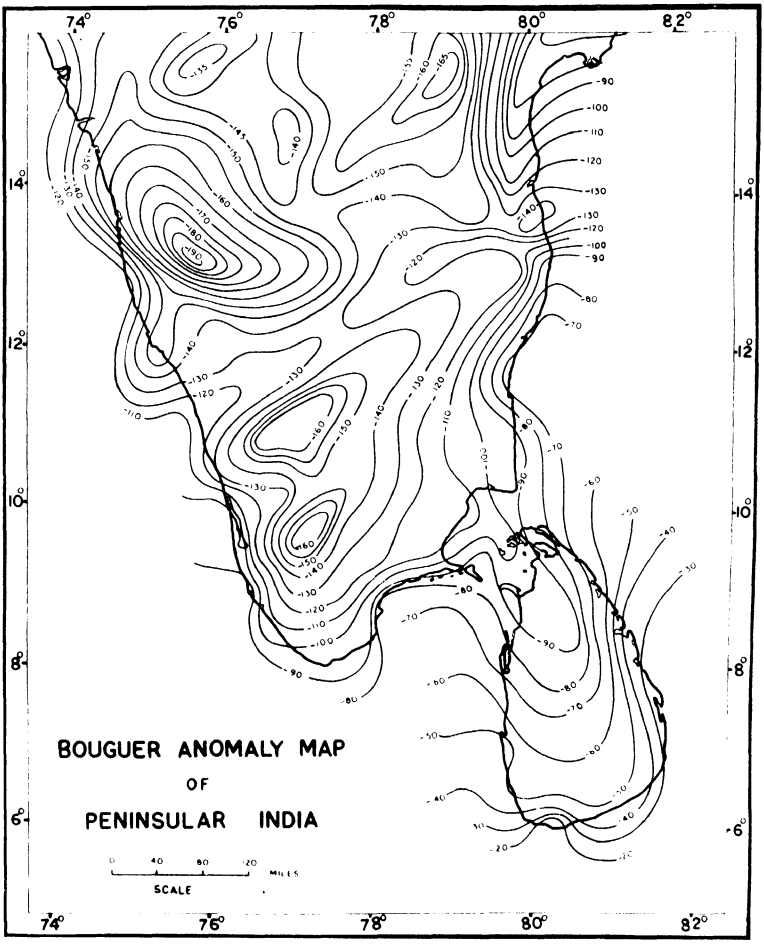

Figure (1)

Bouguer Anomaly Map of Peninsular India south of lat. 16° (from Survey of India data).

Contour interval = 10 mgals.

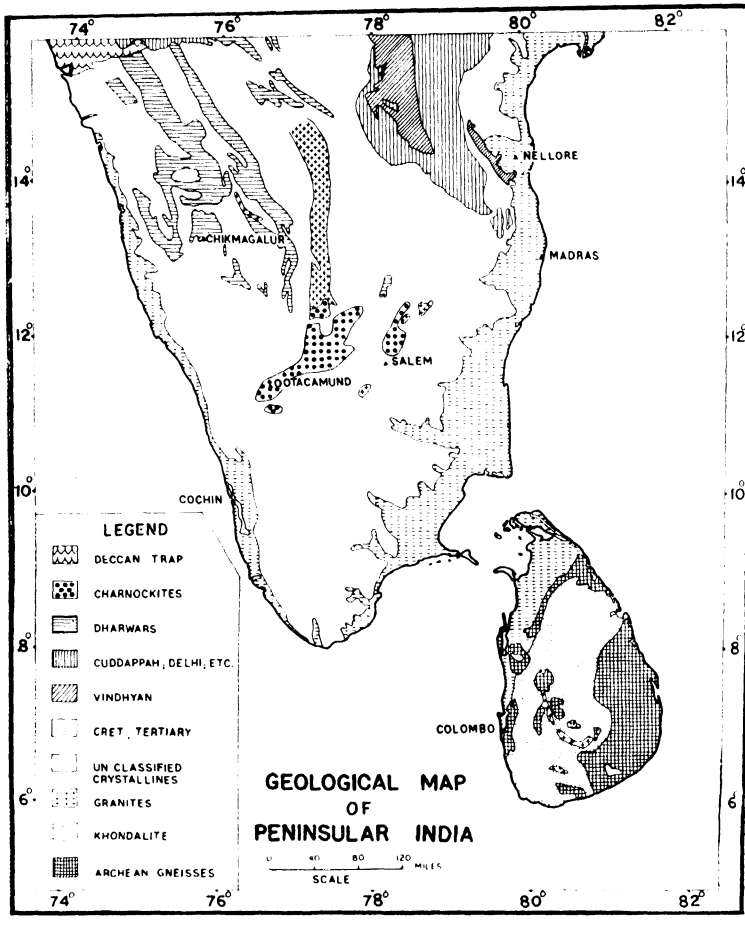

Figure (2)

Simplified Geologic Map of Peninsular India South of lat. 16°.

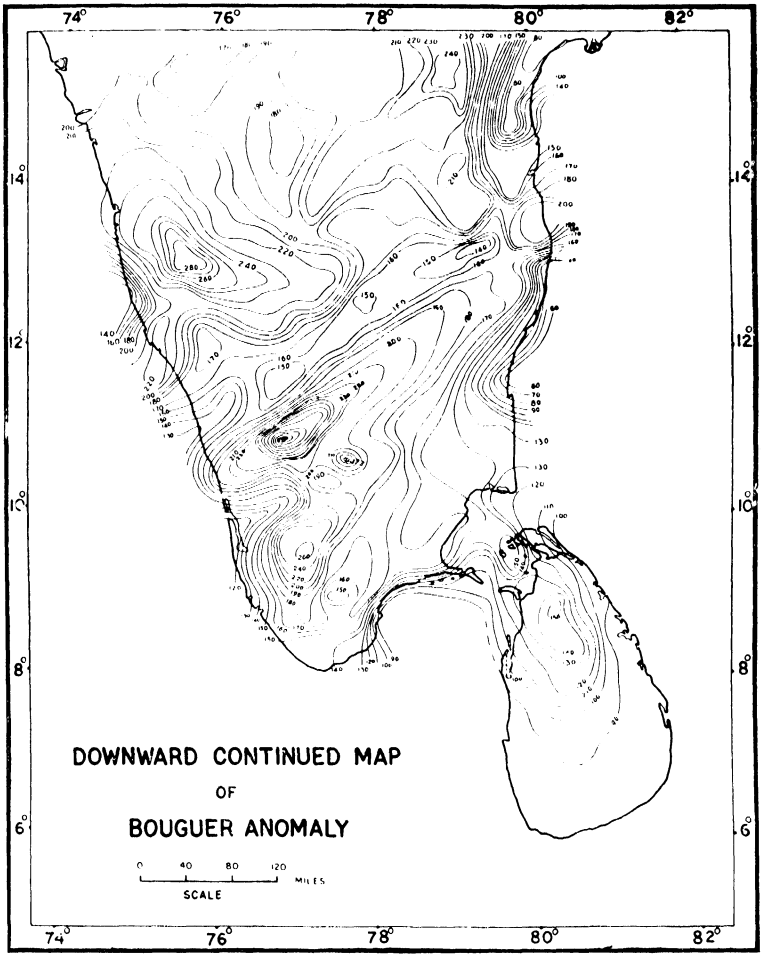

Figure (3a)

Downward Continued Bouguer Map of Peninsular India (analytical continuation to a depth of 10 miles). Contour interval = 10 mgals.

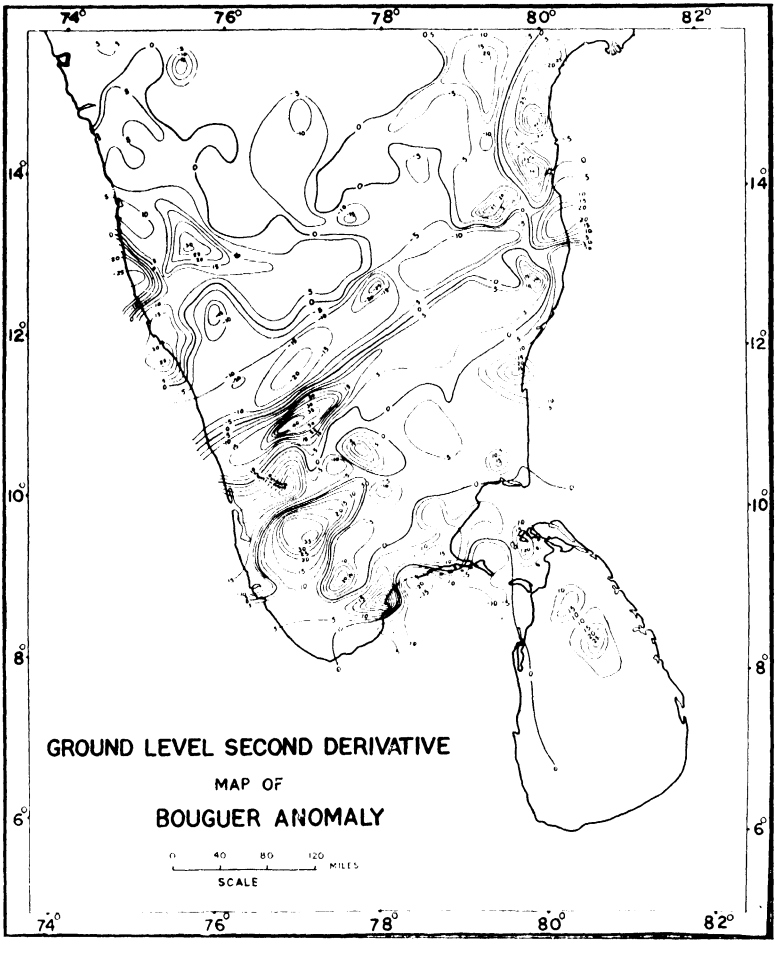

Figure (3b)

Ground Level Second Derivative
Map of Bouguer Anomaly over Peninsular India.
Contour Interval = 5 Units.

having a strike approximately N. E.–S. W. centred around Coimbatore in Madras State.

4. A similar anomaly of about the same strike and amplitude just to the south centred around Thekkadi in Kerala State.

5. A prominent nosing of contours in the southeast end of the peninsula, continuing into Ceylon.

Fig. (2) is a simplified map of surface geology for the region under study.

Fig. (3) presents two high resolution maps derived from the original Bouguer Map (Fig. 1)— (a) a Downward Continued Map where the field has been projected down to a depth of about 10 miles using the 1960 coefficients of Henderson[2]; (b) A ground Level Second Derivative Map using the 1960 coefficients of Henderson[2].

Discussion of Results

The Charnockite belt.

Both the high resolution maps in Fig. (3) show a long, linear anomalous belt of strike N. E.—S. W. running from a little north of Madras City to the vicinity of Cochin on the west coast. A comparison with the map of surface geology (Fig. 2) shows this anomalous belt to coincide with the known exposures of charnockite. It is interesting to observe that this strike is also in excellent agreement with A. P. Subramaniam's observations[3,4] in the charnockite type area at Pallavaram near Madras City. He reports that the foliation trends of these rocks in that area are generally N. E.—S. W. His observation that the rocks seem to have very steep dips is also confirmed in a qualitative way by the tightness of the flanking contours on the anomalous belt.

According to Krishnan[5] Charnockite type of rocks may be formed under deep-seated (kata-zone) conditions and may behave as igneous rocks. They were probably intruded into the country rocks at considerable depths so that the contact phenomena are not as prominent as in the case of hot magmas at shallow depths. Their presence at the surface as prominent hill masses may be due to uplift in post-Archaean times.

L. L. Fermor[6] in discussing the structural relations of the Charnockite region of the peninsula with respect to the Non-Charnockite region puts the age of their uplift as possibly between Post-Cuddappah and Pre-Gondwana. The uplift itself according to him could be visualized as having been brought about by either of two different mechanisms :- (a) by a rise of the south and southeast coast of the peninsula by several thousand feet as compared with the north-western part, that is a relative uplift of land without application of active stresses; or (b) by a vertical uplift with active lifting forces, along a belt of weakness or fault lines or zones along the junction between the Charnockite and Non-Charnockite regions. Wadia[7] points out that the Charnockite massifs of south India stand out bounded by steep scarps above the general level of the Mysore Plateau and other hills of the south. Fermor's concept of a fault zone or line does seem to have some supporting evidence in the Second Derivative Map (Fig. 3b) of the present study where a sharp belt of contours stand out trending N. E.—S. W. from near Madras to a little north of Cochin. This would also support the field evidence quoted by Wadia.

Pascoe[8] and Subramaniam [3,4] describe the Charnockites of South India as Acidic to Intermediate in composition for which the average density has been given by Washington as 2.77. This is only very slightly different from the generally assumed average crustal density of 2.67 and it is surprising that such a small density differential should give rise to the strong Bouguer anomalies observed in the present study. However, one possible explanation might be that these hill masses might have undergone differentiation into a layeriform complex with the dense material at the deeper levels. With such a distribution of density the observed magnitude of Bouguer anomalies could be accounted for. While there has not been any petrological evidence in support of this thesis as yet the possibility exists that Charnockites might behave like true magmatic intrusives and belong to the class of the famous layeriform complexes like those of Bushveld in Africa or Stillwater in Montana or Skaergaard in Greenland.

Lack of Correlation with Dharwars.

The large intense anomaly centred around Chikmagalur, Mysore State does not show any correlation with the Dharwar trends which are essentially elongate patches of highly metamorphosed material striking nearly NNW–SSE. Two reasons

could be thought of to account for the apparent lack of correlation with surface geology. For one thing the spacing of the sampling points in this region is far too great in comparison with the average width dimensions of the Dharwar bands. Secondly the original synclines in which the Dharwarian material was contained have been extensively eroded out so as to leave only shallow relict troughs of the material which cannot be expected to have much of an expression in the gravity picture. This large anomaly presents another puzzling feature. A comparison between the original Bouguer picture (Fig. 1) and the two high resolution maps (Figs. 3, a and b) shows that while the downward continued map presents the anomaly essentially unaltered in shape and extent the Second Derivative Map shows the feature as an insignificant small anomaly comprised of a few contours tightly bunched up in the centre. The existing land elevations in the area are nowhere near those needed to account for such an intense negative anomaly. A possible explanation might be that associated with the Mysore plateau there is probably a pronounced subsurface mass deficit. Even this deficit appears to be concentrated into a small area corresponding to the apex of the anomaly since the counterpart of the anomaly in the Second Derivative picture shows only very small spatial extent in comparison with the spread of the original anomaly or the downward continued picture of it.

Coming to the North-Eastern corner of the map area the eastern flank of the Cuddappah Basin finds expression in the form of a tightly packed trend of contours in the original Bouguer map (Fig.1). However the western flank of the basin does not find any clear expression in the gravity picture. The strip along the east coast from Madras through Nellore upto Godavari Delta shows strong, compact, small anomalies in the Second Derivative Map (Fig. 3 b) Surface geology shows unclassified crystallines and Cretaceous-Tertiary sediments in this area. However in this belt there are many spotty exposures of Charnockites. In fact according to Pascoe[8] a belt of Charnockites runs from Madras northward through the Godavari Delta, on to the Mahanadi valley. It seems very probable that these small, lumped-up anomalies seen only under the high resolution of Second Derivative may be due to a belt of uplifted Charnockite masses representing the backbone of the Eastern Ghats, though at the present time the surface expression of the Ghats appears only as a series of disconnected 'relict' hills.

Another anomalous trend of contours similar to the one along the Madras-Nellore coast is seen running from Madras southward along the coast and swinging sharply into the sea off Karaikkal, brought out clearly in the Downward Continued Map (Fig. 3 a). This anomaly was first pointed out by Kailasam[9] who has made a detailed study of the feature through gravity, magnetic and seismic work. According to him the gravity 'high' over this structure-designated by him as the 'Karaikkal Structure' coincides with a magnetic high and shows a definite closure out into the sea. Seismic shots in the area give a thickness of about 9000 ft. of sediments according to Kailasam. Another prominent gravity anomaly has been located by Kailasam about 30 miles southwest of Karaikkal between Mannargudi and Pattukottai. This feature does not find an expression in the original Bouguer map (Fig. 1) or the Downward Continued Map (Fig. 3 a). However a vague indication is seen in the Second Derivative Map (Fig. 3 b) in the form of a small closure of contours.

Lastly the original Bouguer map (Fig. 1) and the Downward Continued map (Fig. 3 a) show a sharp nosing of contours entering Ceylon from the southeast end of the peninsula and going deep into the island. This correlates fairly well with the postulated synclinorium running approximately NNW–SSE through the island. According to Krishnan[5] a belt of Charnockites and khondalites forms this central synclinorium which separates the southeastern area of Bintenne gneisses from the northwestern areas of Wanni gneisses.

Conclusions

From the present generalized regional study it appears that the main Charnockite belt of South India trending in a NE–SW direction finds clear expression in the gravity picture. In fact the boundary of the Charnockite region in the peninsula, postulated by Fermor as running roughly from Mangalore on the west coast through Bangalore to Madras and then parallel to the east coast all the way to the Mahanadi valley is also delineated satisfactorily by the present study. The high resolution picture seems to lend support to the view expressed by Fermor and the field evidence quoted by Wadia that the main Charnockite belt might have been uplifted vertically along linear fault zones. The Dharwar bands do not find a clear

expression in the gravity picture, the whole area being encompassed by one large, broad negative anomaly. It appears difficult to account for this intense negative high in the light of the present physiography or known surface geology of the region. The well known basin structures like the Cuddapah and Cauvery basins are not clearly brought out by the gravity picture of the present study. This is probably due to insufficient density of spatial coverage in the gravity sampling available for the study. The eastern coast north of Madras, while not showing any feature in particular except a tight bunching of contours on the original Bouguer map, does show a string of small anomalies in the high resolution Second Derivative Map. This may reflect a belt of small uplifted Charnockite masses and may be the expression of the 'backbone' of the Eastern Ghats which at the present time appear only as a discontinuous chain of small 'relict' hills.

Acknowledgement

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ROCK MAGNETISM AND CONTINENTAL DRIFT

BY

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FRANCIS BACON first suggested that continental drift had occurred when he noticed the similarity of the Atlantic coast lines of South Africa and South America. Later Wegener inferred the occurrence of continental drift from the information he gathered from palaeoclimates, structural geology and paleontology. But unfortunately, this information could hardly appear decisive to the scientists in other fields as most of the arguments put forward were essentially qualitative and some of the pre-suppositions were open to criticism. The suggested explanations of continental drift were shown by Jeffreys and others to be incompatible with the inferences drawn from the study of the earth's interior.

Quite unintentionally, the recent studies in Paleomagnetism seems to have revived this old controversy. Curiously enough, palaeomagnetic results provide very strong evidence in favour of this hypothesis. Though the Paleomagnetic results are not yet quite conclusive, it is clear from these results that certain land masses have experienced both translatory and rotatory motions in the geological past.

The possibility that the magnetisation of rocks could be used in the investigation of polar-wandering and continental drift has long been recognised. The magnetic field of the earth can be looked upon as the vectorial sum of two components of magnetic field *viz.*, the dipole field and the other the non-dipole field, which is essentially of an oscillatory nature. If we view the origin of the earth's magnetism as being due to the effect of both electro-dynamic and hydro-dynamic effects occuring in the earth's fluid core, the secular variation of geomagnetism as well as the reversals of the geomagnetic field can be explained. However, averaged over a period of, say, a thousand years, the magnetism of the earth can be conveniently represented by a magnetic dipole at the centre of the earth with its axis coinciding with the axis of rotation.

Now, if we can measure the mean direction of magnetisation in a rock series and if these show a different direction with respect to, and at a different angular distance from, the axis of rotation of the earth at the present time, it can be assumed that the rock series were deposited when the land masses were at different positions with respect to the poles. A series of such results on rocks of different geological ages from the same area give us the various positions of the land masses in different geological epochs. Similarly if measurements are made from the rocks correlated in time but occuring in different continents, the relative movements between these continents can be known. However, a series of practical difficulties arise before we can safely process the paleomagnetic data. Before going into these details, it is worth while to consider the physical processes under which rocks acquire magnetism.

Broadly speaking, the magnetism of a rock *in situ* is the vectorial sum of the induced and remanent magnetism. Induced magnetisation is the magnetism acquired by the rock due to the induction of the present earth's field and is not relevant in the discussion of continental drift. Remanent magnetism is the permanent magnetism possessed by the rock and is either thermo-remanent magnetism or isothermal remanent magnetism or both, and is liable to decay with time (magnetic instability) and may vary with the alteration of chemical composition, pressure, etc.!

Magnetism of a rock, as far as we are concerned, is essentially ferromagnetic in character and depends not only on magnetite but also on its solid solutions with (FeO) Tio_2, or more complex solid solutions among Fe_3O_4, Fe_2O_3, $FeO.Tio_2$, and sometimes the ferromagnetic Fe_2O_3 might also contribute to the magnetism of the rocks. For instance the basaltic lava flows, on which much of the present paleomagnetic data are based, contain usually the members of the magnetite-ulvospinel solid solution series. Their Curie point is a maximum (575°C) for pure magnetite and decreases with increasing titanium content. Such lavas and other igneous rocks acquire a magnetism known as thermo-remanent magnetism when they cool from their Curie points in the earth's field. The direction of this field is generally that of the ambient field even though in certain cases it is found that the rocks acquire magnetism in

the opposite direction. These cases have been considered by Neel, who has explained theoretically four possibilities under which a rock may acquire a reversed magnetism. Only two of these cases have been so far found to occur in nature.

After the rocks are cooled they are naturally acted upon by the magnetism of the earth. It is also possible that these rocks may attain some more magnetism in the direction of the earth's field. Such magnetism is known as isothermal remanent magnetism. This is, of course, very small in magnitude compared to the thermo-remanent magnetism.

Apart from these factors, it is supposed that the geomagnetic field has, every few millions of years, reversed its polarity. Though this has not been conclusively proved, strong evidence exists to prove that such reversals are quite possible. Now the rocks in such a reversed field will slowly reverse their directions and acquire magnetism of the then magnetic field. Measurement of the direction of the magnetism of lavas have shown that certain rock and certain flows often record a reversed polarity compared to the present direction of field. As already stated, the explanation of the reversed polarity of these rocks may be due to the reversal of geomagnetic polarity or due to one or more of the processes described by Neel, or both. (At present we do not have a method of knowing which of the rocks acquired their inverse magnetism due to the reversal of geomagnetic polarity and which of these are due to internal physical or chemical processes.) Though this is one of the unsolved major problems in rock-magnetism, fortunately this has not much to do with polar wandering or continental drift; because whatever the polarity of the rock under investigation may be, the axis of magnetisation is the same and on this depends wherefrom this particular landmass in which the rocks occur, has drifted.

Paleomagnetic data on sedimentary rocks is still more complicated as the processes of magnetisation in these rocks is different from those of igneous rocks. Small grains of magnetic material such as magnetite, when deposited in shallow rivers, lakes and seas along with the other detrital materials derived from the weathering of the older igneous rocks, tend to orient themselves in earth's field, while the sediment is still wet and uncompressed. Later the material may become relatively hard rock by compression and cementation due to the

weight of overlying material. Thus under favourable conditions, the sedimentary rocks may give us the direction axis at the time of deposition. This is the case of clays and other sedimentary rocks derived from an original igneous body. In the case of red sandstones which are often preferred for paleomagnetic work because of their stability, the iron oxide solution percolates into the already formed pores of the sandstone and later crystallises. The direction of magnetism in these crystals will be that of the earth's field at the time of crystallisation of these grains.

Now in the case of clays, errors in the then direction of magnetisation may at times occur as described below: At the time of deposition relatively calm conditions may not be present and the particles may be acted upon by the water current in addition to the magnetic force; and as a result they align themselves midway between the directions of these two forces. Further, when the magnetic particles are not needle-shaped, (say, pebble-shaped) the tendency of the particles when settling under gravity will be such that their smaller axis is vertical. If the magnetism is not along the long axis, then the particles align themselves in a slightly different direction with respect to the direction of the magnetic field.

Again in the case of red sandstones, if the percolation of iron oxides and its crystallisation have taken place long after the deposition of the sandstones, the direction of magnetisation of these will be that at the time of crystallisation of the iron oxides and not of that when the sandstones were deposited. Further we have to consider the question of magnetic stability of these sedimentary rocks before we can interpret their data reliably. As already pointed out, the magnetism acquired by a rock decays with time and changes with change in chemical composition. So, at any time after deposition, the unstable component in the magnetic intensity may vanish and/or a new component along the direction of the new magnetic field set up at any intermediate time i. e., intermediate to the time of deposition and now. Let us consider a hypothetical proposition. Let three magnetic grains be present in a sedimentary rock side by side separated by a few millimeters and let us suppose that water is percolating slowly from one direction and effecting a chemical change slowly. Suppose at any moment the first particle has changed its composition such that

under this chemical change a self-reversal of the magnetic field has occured. When this chemical change is proceeding towards the second particle it is under three .simultaneous influences : (i) the chemical change trying to reverse the direction of magnetism, (ii) the first particle inducing a component in one direction and (iii) the third in the opposite direction. This effect is equivalent to a magnetic couple and if the chemical change stops at that moment the second particle acquires a magnetism in a direction which is the resultant of both of these forces. If this process is extended over a series of particles, it is possible to visualise that the rock as a whole shows a direction of magnetisation entirely different from the direction at the time of deposition as well as that of to-day. Of course, this process may be hypothetical and may not actually occur. But the fact remains that unless the physical, chemical and other mechanisms affecting the magnetisation of mineral particles are known with greater certainty, we cannot with definiteness exclude these possibilities. We may recall in this connection the significant statement of Nagata : "One of the main reasons for this difficulty (meaning a systematic description of the magnetic behaviour of rocks based on the physics of the magnetic matter) may be due to the incompleteness of our basic knowledge of the magnetism of metallic oxides and other compounds of metallic and non-metallic elements, which are the constituents of most magnetic materials and consequently of most rocks". Added to these complications are the sources of secondary magnetisation like lightning effects, magnetostriction etc.

However, all these local phenomena of self-reversals and magnetic instability may not effect our findings as long as the results are applied for interpreting continental drift; but they serve as useful guides to tell us not to conclude hastily and in some cases to discard results with "improper" rocks. That is why perhaps the results of the paleomagnetic measurements are interpreted statistically after measurements are carried out on a great number of samples in a rock series and on several rock series of the same age. However, it is worthwhile considering the following points :

(i) For igneous rocks, the samples should not be altered and weathered and no major chemical change should have occurred since the time of their formation. Doubtful rock series in which self-reversals are prevalent (for instance– Nagata's pumice type) should be avoided.

(ii) Sedimentary rocks should be tested for their magnetic stability. Graham's test is often recommended for this. By finding pebbles in a conglomerate bed which were derived from the rock formation under study and determining the directions of magnetisation which they have at present, information about the stability of the rocks since the conglomerate was formed can be obtained. In the case of red sandstones, Runcorn opines that even though some of them are not proved completely stable, still they can be used for paleomagnetic measurements. Under these circumstances the rocks acquire a component of intensity varying from specimen to specimen directed along the mean geomagnetic field in recent times which is known to be that of a dipole oriented along the present axis of rotation of the earth, thus the resultant directions of magnetisation of the samples from such a formation form a streak rather than a grouped set in a plane containing the present dipole direction and the direction of the field at the time of deposition. Some information about this type can therefore be obtained even from slightly unstable rocks.

The second test to be carried out for sedimentary rocks is to find out whether they were deposited in calm conditions or not. For this Johnson, Griffiths and others conducted some experiments by dispersing the clays etc., and re-depositing them in the laboratory under controlled field directions. Thus inclination errors, if any, can be removed.

Of course, rocks which have undergone folding, and other structural deformations cannot be used for paleomagnetic work unless one fully knows the exact time and nature of the various geological processes involved.

In spite of these facts, the result of the paleomagnetic data have been found to give useful results regarding continental drift. The results on some of the landmasses may now be enumerated :

(i) England has been found to be oriented some 10°W of north 450 million years ago and that this westerly orientation increased slowly and possibly irregularly by an anti-clockwise rotation, till it reached a maximum of 34° in triassic times, 150 million years ago; after which it rotated steadily clockwise to reach its present position.

(ii) United States and Britain have been found to move only a little relatively to each other, but markedly relatively to the poles. However, there is a certain discrepancy between the pole positions given by the British and American rocks. These results are re-interpreted by Graham, Runcorn and Carey. Carey conclusively proved that by altering the position and orientation of the United States and England, the relative change in position of the poles can be eliminated. There is much evidence in favour of this from geological and other considerations. This finding supports the theory of continental drift and polar wandering and conclusively supports the use of paleomagnetic data for continental drift interpretation.

(iii) In the southern hemisphere a close fit between South America and south Africa is found. Australia has been found to wander into various positions and so is the Indian landmass, though the paleomagnetic data on the latter are not sufficient to warrant such a conclusion. Some geologists are of the opinion that the available data on South Africa, India and Australia should be re-interpreted and the various pole positions deducted from the rocks of these landmasses. Such re-interpretation with adequate adjustment of the position of these landmasses may conclusively prove a sort of close fit between them as has been found in the case of North America, Greenland, England and the Scandinavian countries. As there is a lot of evidence otherwise also for this conclusion, it can be hoped that such a re-interpretation of the paleomagnetic data may conclusively support this theory.

In conclusion, the significant statement of Prof. Blackett may be quoted here : "There can be no doubt that rock magnetic measurements already made very strongly support the view that there have been, during geological times, very large movements of land masses relative both to each other and relative to the geographic poles. Thus polar-wandering and continental drift have both occurred."

AN OUTLINE OF THE MAGNETISATION OF DECCAN TRAPS OF THE LOWER GODAVARI VALLEY

BY

V. BHASKARA RAO AND P. SITAPATI RAO

Abstract

Results of a comprehensive study of the remanent magnetisation of the Deccan traps of the lower Godavary valley are reported. Five sampling sites were chosen in an area of 10 square miles and about 70 specimens were studied for their magnetic polarisations. The results obtained show a broad spectrum in their remanent intensities from 0.3 to 20×10^{-3} E. M. U., and the average intensity is 4 times greater than the present earth's magnetic intensity. In some cases the isothermal remanent magnetisation is predominent over the natural remanent magnetism. The mean remanent magnetic dip and declination were found to be 45° and 32° East of North. This indicates the possible drift of the peninsular India from Southern Latitudes to the present position. The results were compared with those of earlier workers. The ancient pole positions for the site were calculated and presented along with the available Indian data. The Deccan trap patch at the mouth of Godavari river, far removed from the main Deccan trap land, was correlated for the age and eruptive activity with the main mass.

DURING the magnetic field surveys it was observed that the Deccan traps of the West Godavari District were possibly polarised in a different direction to that of the present Earth's magnetic field. The earlier investigations on Deccan traps of India mainly by the group of workers of Tata Institute of Fundamental Research, Bombay, have lent support in part to the above conclusion.

From the investigations of Koenigsberger (1938), the conditions under which a rock can retain its magnetism at the time of its first formation were that its curie temperature should be greater than 300° C and it should not have been subjected to mechanical disturbances. The intensity of the

natural remanent magnetism depends again on the grain size and composition of ferromagnetic minerals—especially magnetite—in the rock. The Deccan traps containing a small percentage of ferromagnetic oxides (magnetite or titanomagnetite) acquire, during cooling through the Curie temperatures of these minerals, thermoremanance in the direction of the then earth's field. These fine grained basalts having large coercivity retain this magnetisation over long periods. Thus, Deccan traps could show a permanent direction of polarisation different from the present direction of the earth's field.

Previous Research

In recent years, evidence for continental drift and large scale polar-movements prior to the Miooene period have been adduced from the results of palaeomagnetic measurements of several investigators. The volume of data collected has been so large and the inferences drawn so varied that an attempt to discuss the results in detail would be beyond the scope of the present work. However a brief survey of the work of groups of workers in England, America, Australia and India is presented below. Creer, Irving and Runcorn (1954–1957) from their measurements on rocks of various geological periods dating back to Precambrian era, plotted the North pole locations on a path reaching as far South as the equator. A number of surveys carried out in North America by Graham (1955–1956), Doel (1955), Howell and Martinez (1957) had yielded pole positions generally within 20° of those from the results of British investigators on formations of corresponding periods. This discrepancy had been ascribed tentatively to relative drift between Britain and North America. Studies on Tasmanian dolerites, basalts and volcanic tuffs by Almond, Clegg and Jaegar (1956) indicated that a relative movement had occurred between the land mass of Tasmania and the geographical poles since the early part of the Tertiary period. Results of investigations on Indian formations by Clegg, Deutsch and Griffiths (1956), and Deutsch, Murthy and Sahasrabudhe (1959), showed that India had drifted northward though 50° of latitude and rotated though 25° in an anti-clockwise direction within the last 70 million years. The remanence measurements, apart from their contribution to continental drift and Polar wandering, gave also information regarding the "Reversals of the Earth's field" (Roche 1950, Hospers 1951, 1953, 1954). Certain cases of magnetic self-reversal have been observed in nature (Nagata

1951; Balsey and Buddington, 1954) and they are explained on the basis of one of the four mechanisms first theoretically postulated by Neel (1949, 1952).

Measurement of NRM.

The Deccan trap outliers of the West Godavari District are removed by about 650 Km. from the main mass of Deccan trap and overlie the Gondwana formations. The problems of their origin and age, besides the magnetic anomalies encountered in the field surveys, are intimately connected with the NRM studies. The results of NRM measurements on the Deccan traps are presented and discussed here.

Seventeen samples of rock were collected from five sampling sites, two near Pangadi, one at Duddukur and two near Lakshmipuram, all of these being within 15 miles of Rajahmundry in a NNW direction. From the 17 rock samples, 70 specimens were prepared averaging over 4 specimens from each rock with a maximum of 6 and a minimum of 2 from a rock. The specimens were in the form of cylinders of about 2 cm. diameter and 1.5 cm. length.

The laboratory measurements presented in this section were carried out by the authors at the rock magnetism laboratories of Tata Institute of Fundamental Research, Bombay, by their kind permission. The astatic magnetometer used in these measurements is of Blackett (1952) type with a simple two magnet system and a sensitivity of 10^{-5} E. M. U., which was quite sufficient in view of the fairly large intensities of the Deccan traps as will be seen later. The direction and intensity of magnetisation of each specimen were measured employing the standard procedures used by Clegg, Almond and Stubbs (1954) and Deutsch, Murthy and Sahasrabudhe (1959).

Discussion of Results

(a) Remanent magnetic intensity:

The remanent intensities have a wide range of variation from 0.3×10^{-3} E. M. U. to 18.7×10^{-3} E. M. U. Figure (1) gives the intensity spectrum of the 70 specimens. It could also be seen that the intensity varies among specimens from the same sample. Grouping the measurements into 10 kinds, the intensities were represented in a histogram in Fig. 1. A

maximum number of the specimens show intensities in the range 3 to 7×10^{-3} E.M.U., having an average value of 5×10^{-3} E. M. U. The frequency of intensity average 5×10^{-3} E.M.U. is 1 in 4. The specimens of the top flow, which were subjected to weathering, show intensities lesser than the bottom flows. The black parts shown in Fig. 2 represent specimens from top flow.

Thus the wide range of remanent intensities and their changes among specimens of the same sample lead one to expect large, fluctuating magnetic anomalies in the field. The magnetic mineral content, which is a controlling factor in the intensity and anomaly measurements, would also exhibit corresponding variations. The remanence would, however, further depend on the demagnetization effects from the time of solidification of the lavas to the present date.

(b) Remanent magnetic Dip and Declination :

The declination (θ) of the NRM obtained for the seventy specimens show uniformity and consistency within the limits of sampling and experimental errors. There are, however, a few noticeable deviations from the general run. A histogram constructed for the declinations of the NRM is shown in Fig. 2 (top). The maximum number of the specimens fall in the range of 270° to 20° reckoned from magnetic north to east in clockwise direction. A few specimens show reversal in azimuth direction. Few sporadic specimens fall in the region of 90° to 190° azimuth. But in general a consistency for the azimuth angles was maintained. The frequency for declination angles between 300° and 330° is 1 in 3. The specimens from the top flow are shown in black in the histogram.

The dip angles of NRM show a wide range of variation having both positive (Dip downwards) and negative (Dip upwards) values. Grouping them into 9 kinds in 10° steps starting from 0° dip, a histogram was constructed and shown in Fig. 2 (bottom). The majority of specimens show upward dip. About 16 out of a total of 70 specimens indicate a downward dip. A third of those with downward dip are from the top flow. The specimens from the top flow are represented by black parts in the histogram. The number of specimens in the upward dip range of 20° to 60° is maximum. The frequency of specimens with 40° dip is 1 in 5. The top flows generally show a low dip with both upward and downward directions.

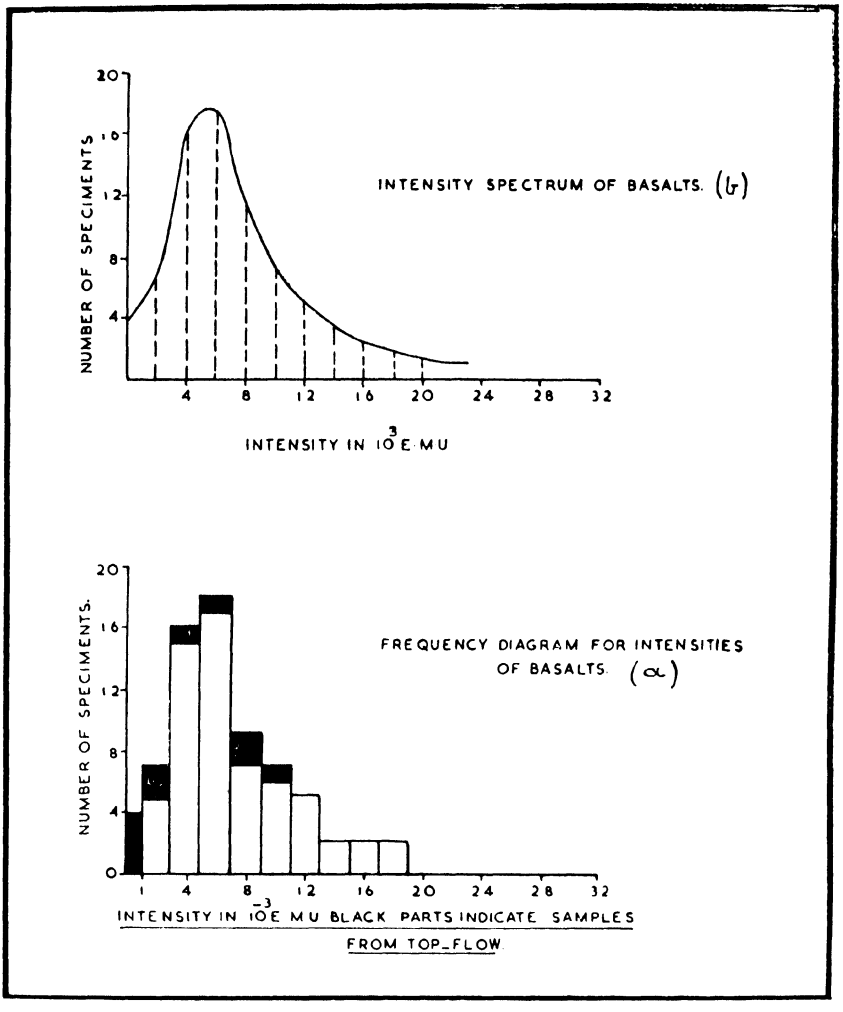
NUMBER OF SPECIMENTS
20
16
12
8
4
4
8
12
16
20
24
28
32
INTENSITY IN 10^{3} E·MU
INTENSITY SPECTRUM OF BASALTS. (b)
NUMBER OF SPECIMENTS.
20
16
12
8
4
0
1
4
8
12
16
20
24
28
32
INTENSITY IN 10^{-3} E MU BLACK PARTS INDICATE SAMPLES FROM TOP-FLOW
FREQUENCY DIAGRAM FOR INTENSITIES OF BASALTS. (a)

Figure (1)

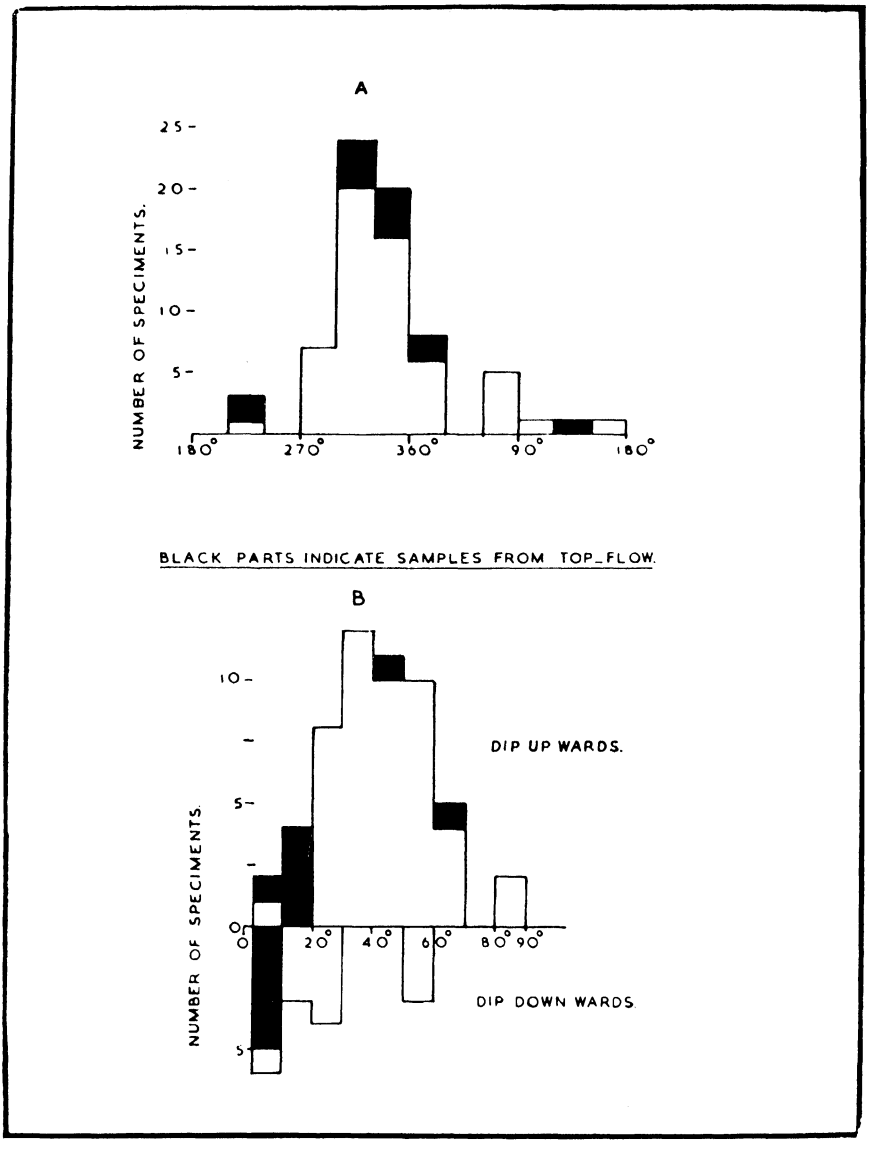
A
25
20
15
10
5
NUMBER OF SPECIMENTS.
180°
270°
360°
90°
180°
BLACK PARTS INDICATE SAMPLES FROM TOP-FLOW.
B
10
5
NUMBER OF SPECIMENTS.
0
0
20°
40°
60°
80°
90°
DIP UP WARDS.
DIP DOWN WARDS.
5

Figure (2)

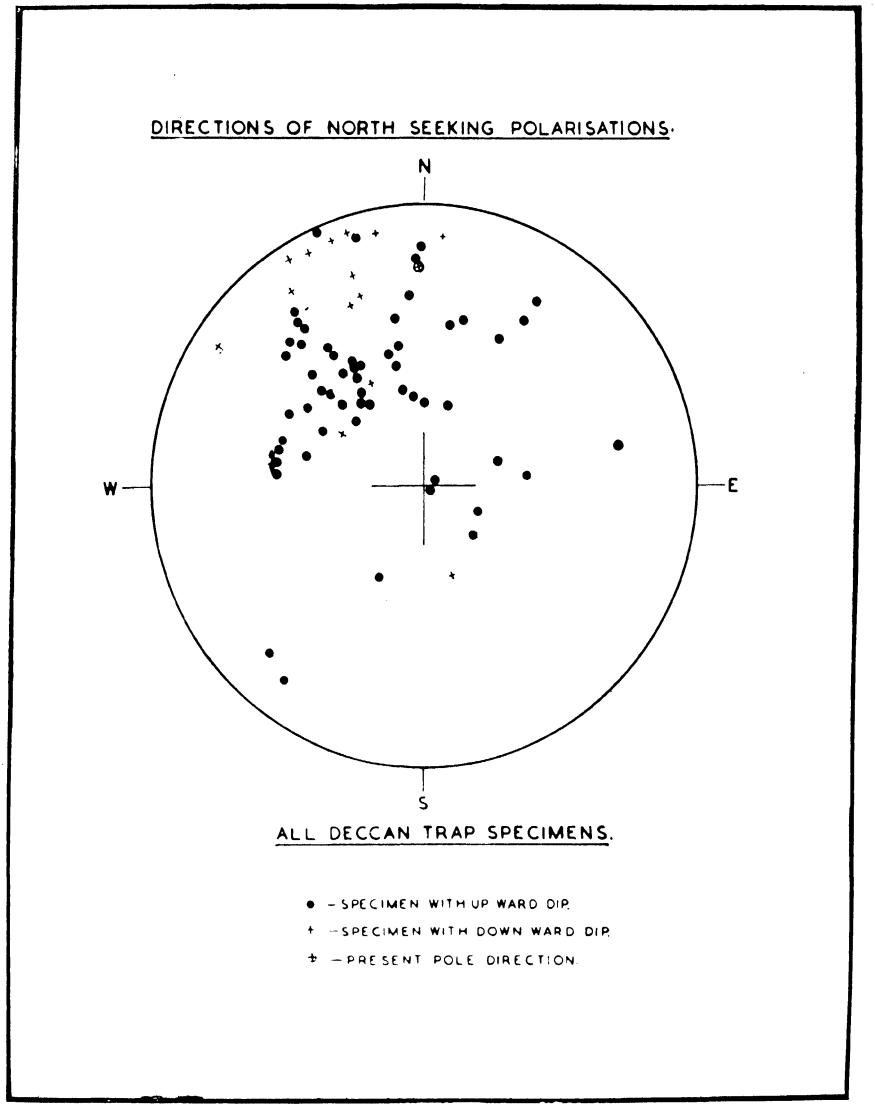
DIRECTIONS OF NORTH SEEKING POLARISATIONS.
N
W
E
S
ALL DECCAN TRAP SPECIMENS.
● – SPECIMEN WITH UP WARD DIP.
+ – SPECIMEN WITH DOWN WARD DIP.
± – PRESENT POLE DIRECTION.

Figure (3)

The remanent vertical component, which is involved in calculations of dip, might have been superimposed by the soft component, especially for the samples collected from the top flows. The predominant soft component, acquired by the samples from the top flow, which are subjected to weathering, influence the Z-component resulting in a downward dip. It was, therefore, considered necessary to test for the stability of the specimens and the results of such tests are presented elsewhere.

(*c*) *Mean magnetic dip and declination* :

The remanent dip and declination data presented on a Schmidt's equal area projection are shown in Fig. 3. Even though the samples were collected from five localities separated by 4 to 5 miles, the total area covering these localities forms a very small part of the main Deccan trap land. Areawise it would, therefore, be proper to consider that all the 17 samples as from one spot. On this basis and applying Fisher (1953) analysis, the mean dip (D_m) and the mean declination (θ_m) for all samples were computed and given below.

$$D_m = 45°\text{ (upward) and } \theta_m = 327°\text{ E. of N.,}$$

for 8° cone of confidence with the dispersion factor 12.94.

Palaeomagnetic Results of Pangadi Traps

The present Palaeomagnetic investigations on the Deccan traps of the West Godavari District help in correlating the traps in age with the main land. In the following pages, the remanent magnetic dip and declination are compared with the results of Deutsch, Murty and Sahasrabudhe (1959) and the position of these far removed outliers is fixed with respect to the main land of Deccan traps.

(*a*) *Palaeontological evidence* :

A knowledge of the fossils associated with infratrappean and intertrappean limestones would greatly help in fixing the age of the traps. The fossiliferous intertrappean bed, exposed on either side of the Godavari river underlies the traps. The fauna (on the western side of the river Godavari) of the Duddukur Infratrappeans consists of both marine and fresh water species (Nautilus, Lamellibranches and Gastropods). The Turritella species (gastropod) is the only ones that can be compared with

Trichinopoly Cretaceous fossils. On the other hand, the fauna, from the Infratrappeans of the eastern side of Godavari river (Kateru, near Rajahmundry) indicate fresh water species. Oldham (Krishnan, 1960) states that on the whole the Infratrappeans have perhaps more affinity with the Cretaceous than with the Tertiary. Das Gupta (1933), who claimed to have found *Cardita beaumonti* from Duddukur beds, supports this view. In their studies of fossils from Kateru area, Rama Rao (1936) reported *Chara* fruits, while Narayana Rao and Sripada Rao (1936) thought the fossils were of Tertiary age.

The Intertrappeans also contain, in several places, animal and plant remains which should prove to be valuable in the determination of the age of these beds and incidentally of the associated traps. These are fluviatile and lacustrine deposits and intercalated with the lava flows. They have been found in other parts of India as in Chindwara, Nagpur and Jabalpur.

It may be mentioned the trap flows of the area of the present investigation and those in the main exposure have not yet been correlated. Opinions were divided whether they are uppermost Cretaceous to lower Eocene or entirely Eocene. If the infratrappeans are of Cretaceous age, then the associated traps, in all likelihood, are of Eocene age.

(*b*) *Palaeomagnetic evidence* :

It has been deduced from the results of Deutsch et al (1959) that the Deccan traps above 2000 ft. m. s. l. are normally magnetised with dip upwards, whereas the lower parts show reversed magnetisation with downward dip. The Rajamahal traps of Bengal, which are also far removed from the main Deccan trap area, show (Clegg, Murthy and Sahasrabudhe, 1958) normal magnetisation.

The question arises whether the traps under investigation belong to main Deccan trap or to the Rajamahals. The latter case has no support since Rajamahal traps have given definite indication on fossil evidence suggesting that they belong to upper Jurassic age. Therefore, there is age difference between the Deccan traps and Rajamahal traps. The question regarding the Deccan traps of West Godavari district was only whether they are upper Cretaceous or Tertiary (Eocene).

The main Deccan traps are divided into three groups (Krishnan, 1960) — upper, middle and lower—with the Infra-trappean beds or lametas as their base. The majority of these upper traps are polarised 'normally'. The demarcation of the upper traps from the inter-trappean bands (by specification of height) is not very clear from the work of Deutsch et al (1959). The present investigations indicate normal polarisation of these rocks. Therefore, it is thought that the Deccan trap outliers of West Godavari district are of the same age as those of the upper traps of the main mass. It may be stated that evidence, which has been gathered and put forward in recent years, shows that a good part of the traps may have been erupted in early Eocene. It may be concluded that the outliers under survey belong to early Eocene similar to top-flows of the main mass. That is to say, these traps may be correlated with the upper traps at Mahabaleswar, Amba, Gargoti and Ajra (Deutsch et al 1959). But at some places of the upper traps (Igatpuri, Khandala) reported by Deutsch et al show reversed magnetisation. It may be emphasised that one should carefully ascertain whether these upper traps of the above areas showing 'reversals' are not from the latest phase of the activity as Krishnan (1960) pointed out that 'the latest phases of the activity found in Bombay and Saurashtra are distinctly later than the main mass'. It may be that the traps of Godavari district originated from independent eruptive centres somewhere near Rajahmundry, during the Main Deccan trap (upper) period.

The Magnetic Axis

The general direction of magnetic axis of Pangadi traps is along N. W. to S. E. dipping towards South. This is in broad agreement with the earlier results of Irving (1956), Clegg, Deutsch and Griffiths (1956) and Deutsch et al (1959) and supports the suggestion that India moved northwards across the equator relative to the Earth's geographical axis, and rotated in an anti-clockwise direction, since the rocks were laid down. The period of time over which the Deccan traps were erupted is likely to have exceeded the period of the secular variation by a large factor and so it can reasonably be expected that the mean direction will correspond to a dipole assumed to be coaxial with the geographic axis of the earth. The relationship between the mean dip D_m and the ancient magnetic latitude, λ is given by

$$\tan\lambda = \tfrac{1}{2} \tan D_m$$

It is of interest to compare the mean direction of the area with the results of the previous investigators already refered to. The palaeomagnetic results of various investigators on Deccan traps are shown summarised in Table I.

TABLE I.

	θ_m	D_m	λ
1. All reversed sites. (Deccan traps)	156	+56	37 S
2. All normal sites. (Deccan traps)	341	—24	13 S
3. Rajamahal traps.	328	—64	46 S
4. Present site. (Pangadi traps)	327	—45	27 S

The ancient magnetic latitude of the area under investigation lies in between the latitudes obtained for normal and reversed rocks of the main Deccan traps. This would indicate that the postulated northward movement of India across the equator has involved about 44° of latitude.

Deutsch et al from their results pointed out this movement involved a maximum of about 56° of latitude. The mean declination obtained for the area suggests that this translations movement was accompanied by an anti-clockwise rotation of 33°; whereas the Bombay main traps show a translatory rotation of 24°. There is a discrepancy of about 9°, and the longitude difference between Bombay and Pangadi is about 9°. This indicates that the Pangadi traps have further drifted by about 9° from the main Deccan trap mass in an anti-clockwise direction to the present position provided that the assumption, that this small patch at the mouth of Godavari river owes its origin to main traps is correct.

Pole Positions

It is postulated that the mean magnetic field for each period is a geocentric dipole field. The pole position in terms of latitude (θ_p) and longitude (φ_p) for that period using present geographical co-ordinates of the site is given by (Creer, Irving and Runcorn, 1957), which has been adopted widely in palaeomagnetic investigations by various workers. The north

pole position obtained from the above consideration, with respect to Pangadi region is

$$\theta_p = 36°N$$
$$\varphi_p = 61°W$$

The results when compared with that of the earlier workers on main Deccan trap land already referred to, support their view in regard to relative movement of India with respect to other land masses.

Conclusions

Studies on natural remanent magnetisation were carried out on Deccan traps. The intensity of NRM varies over a wide range for the 70 specimens. All the different flows were polarised in the same direction. They show a mean declination of 327°E of N and 45° dip upward. The results are in conformity with the palaeomagnetic observations made earlier on Deccan traps. The pole positions of the Pangadi traps are deduced te be 27°S latitude.

Acknowledgements.

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ANALYSIS OF THE MAGNETIC ANOMALIES IN RELATION TO GEOLOGY AND STRUCTURE OF THE LOWER GODAVARI VALLEY

BY

P. SITAPATI RAO AND V. BHASKARA RAO

Abstract

Systematic magnetic surveys were conducted over an area of 1,000 square miles on the Gondwana, Deccan Trap and Tertiary formations of the Lower Godavari valley. An analysis of the magnetic anomalies obtained in the surveys enables the demarcation of the various geological formations by the 'Characteristic anomalies'. Further, intrusive bodies and Deccan traps amidst the Gondwana formations were clearly brought in the magnetic picture. The results indicate that the sediments attained maximum thickness in the Western part rather than in the eastern part of the valley surveyed. This was borne out also by the resolution obtained in the residual magnetic anomalies employing grid methods and polynomials of the first order to compute the regional. The magnetic anomalies obtained in the detailed surveys over Deccan Traps show rapid fluctuations which are possibly due to their magnetisation being different from the present earth's magnetic field and due to intense weathering resulting in exfoliations particularly of the top layers.

Introduction

THE Geophysics Department of Andhra University has, as a long-range project, undertaken to investigate the coal field areas of the Godavari Valley, which extend from the Chanda District in the north-west to the West Godavari District in the south-east. The project envisages a close network of gravity and magnetic stations over the entire region. As a first step, a limited project of carrying out magnetic and gravity investigations of the areas in the West Godavari District was undertaken and this has been supported financially by the Council of Scientific and Industrial Research of India. The authors carried out magnetic investigations reported here on a part of the West Godavari District.

Though this area holds considerable interest owing to its coal potentialities, no systematic geophysical investigations have so far been undertaken. The area has been geologically mapped and some information is also available as a result of drilling (Krishnan, 1949). Comprehensive geophysical surveys are expected to yield valuable information about the structure and coal bearing formations of the region.

Results of Regional Magnetic surveys, such as are reported here, do not lend themselves to easy interpretation in so far as they represent a composite effect of (i) subsurface and near surface geology and (ii) the basement structure and other deep seated bodies with accompanying variations of magnetic polarisation. In some cases, however, the geology seems to be better correlated with the magnetic data than the gravity data. In part, this may be ascribed to the comparatively large effect of local magnetic susceptibility changes on magnetic data and also the comparative insensitivity of magnetic observations to various local factors like elevation or density. Calculations by Wollard (1948) of the relative gravity and magnetic effects illustrate this point well. A change in elevation by 16 feet at a gravity station has the same gravitation effect of one milligal as 160 feet of material with a density contrast of about 0.5 gm./cc., whereas a change of one or two percent of magnetite content of a rock formation is sufficient to produce a very considerable change in magnetic readings. However, this apparent advantage is outweighed by other factors.

In the present investigations, the observed anomalies of the regional and detailed surveys have been analysed and discussed. A comparative study of the residual anomalies computed by different methods has also been made.

Magnetic anomalies and their general interpretation

Most magnetic interpretations, initially, are largely qualitative, consisting of delineating the areas of magnetic highs and lows and ascertaining ideas about the general trends of magnetic variations in the area.

Generally, the spacing of contours in an isoanomaly map is a rough indicator of the possible subsurface geological structure. The closer the contours, the shallower, in general, is the source. Sudden changes in contour spacing over appreciable

distances in an area might indicate a possible discontinuity at depth. On such considerations, it is sometimes possible to demarcate the boundaries of sedimentary basins and large scale faults, if any. The deepest parts of the basin in such cases generally correspond to the minimum magnetic gradients.

Further, the magnetic properties of geological formations especially of igneous and metamorphic rocks, are normally subject to lateral and vertical changes depending on the thermal and mechanical stresses undergone by the formations. It is possible to ascribe the observed magnetic anomalies, especially in areas with only a thick alluvial cover, to the characteristics of the basement complex. Even in such cases, the anomaly would be the total effect of variations in relief and of magnitude and direction of magnetic polarisation of the basement. However, in normal cases the directions of induced and remanent polarisations are assumed to be the same, the total effect being considered as due to induced polarisation. But in clear cases of reverse polarisations, both the directions and relative proporations of the contributions of the induced and remanent polarisations have to be taken into account for an accurate quantitative interpretation of the observed anomalies.

In the present regional investigations, attempts have been made to remove the regional magnetic trends on the assumption that the latter, arising due to large scale inhomogeneities in the crust, are regional, broad and uniform with low gradients and possibly large amplitudes.

Analysis of the Magnetic anomalies of the Godavari Valley

A general discussion of the magnetic anomalies relative to the regional geology and the plan and procedure of the survey over 550 sq. miles was presented earlier to N. I. S. Symposium by the authors (1961). Later, the magnetic surveys were extended to a larger area of 1,000 square miles and the density of magnetic stations was also increased. As a result, the magnetic picture was little modified over the earlier, already referred to. The magnetic vertical intensity isoanomaly map with contours at 50 gamma intervals over the area is shown in Figure 1.

It can be seen that the area covered by alluvium, which extends along and the adjacent to the Godavari river and ranging

in width from 1 to 6 miles, is approximately enclosed by the zero anomaly contour. Inside this area, there are a few small pockets of positive anomalies ranging from 50 to 200 gammas, probably arising from local magnetic disturbances. The distortion of the zero anomaly contour noticeable near Pangadi may be associated with the effect of Deccan traps in the region. The zero anomaly contour in the south-eastern part of the area closely follows and demarcates the alluvial area east of a line approximately joining Pangadi and Nidadavol. Except for the above, there is no other prominent zero anomaly contour in the area. In the west central part of the area limited by Zangareddigudem and Koyyalagudem in the north, Nallajarla and Telikicherla in the south and Ernagudem and Gopalapuram in the east, magnetic anomalies of the order of −100 to −150 gammas seem to be typical of the basin covered by the sedimentary Gondwanas.

Intense positive and negative anomalies varying from +600 to −500 gammas characterise the area between Devarapalle and Pangadi where Deccan traps are present. From the distribution of the anomalies it can be seen that they are limited in extent and their sources are comparatively shallow. Similar fluctuations on Deccan traps have been observed elsewhere by Banerjee and others (West, 1950).

Another interesting feature is the area of positive anomaly rising to about 600 gammas near Prakkilanka, which is covered by Alluvium. One possible cause considered for this anomaly is that the Deccan traps might extend into this area and also the eastern side of the Godavari river after crossing underneath the river. From the detailed magnetic investigations conducted in this area it appeared that the anomaly may be the result of the presence of pegmatite or charnockite intrusions with concentrations of magnetite. Earlier reports of Ramachandra Raju (1952) and Apparao (1950) indicate the existence of such intrusions in the area. Detailed discussions of the quantitative estimates of the source of these anomalies are presented elsewhere. Near Dondapudi evidences of another intrusion of possibly similar nature are found. The magnetic anomaly in this region, however, is only of the order of +50 gammas.

Low magnetic anomalies ranging from −50 to −100 gammas are representative of the area covered by Archean Khondalites. A small region of positive anomalies inside the zero anomaly

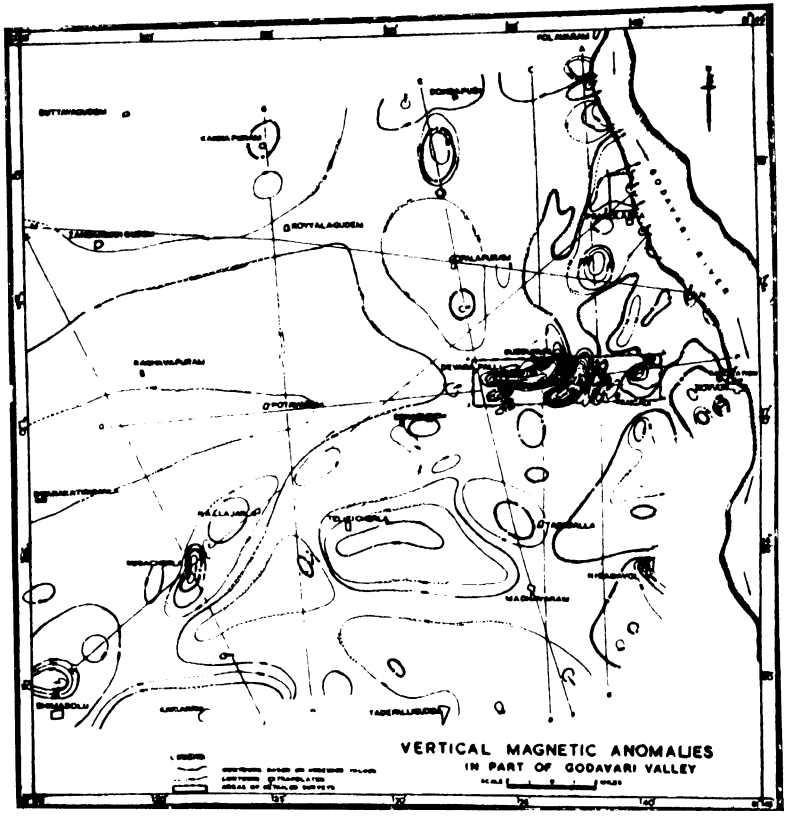

Figure (1)

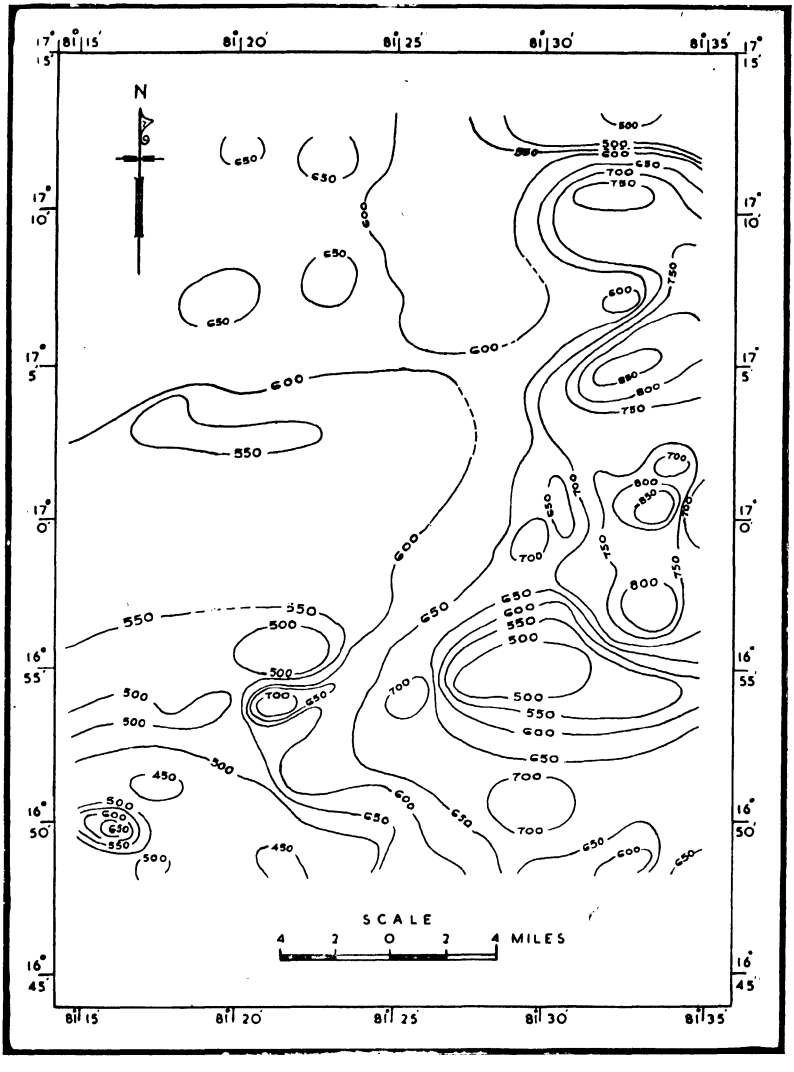
81° 15'
81° 20'
81° 25'
81° 30'
81° 35'
17° 15'
17° 10'
17° 5'
17° 0'
16° 55'
16° 50'
16° 45'
N
SCALE
4 2 0 2 4 MILES

Figure (3)

contour near Kannapuram is considered to be the result of linear bands of charnockite. It is not possible to distinguish between the Archeans and Gondwanas from the magnetic anomalies, as the magnetic contrast is expected to be low. However, the –50 gammas contour in the Zangareddigudem and Koyyalagudem area in the north-west appears to follow the boundary (but somewhat to the south of it) between the Archeans and the Gondwanas. South of this –50 gamma contour the magnetic anomalies gradually decrease towards Nallajarla and Dubacherla and Bhimadolu in the south west to about –200 gammas. In the west central part covered by the Gondwanas, the magnetic contours are wide apart and exhibit low gradients indicating maximum thickness of sediments in this region. This seems to be in conformity with the earlier geological observations (Krishnan, 1949). As pointed out earlier the rocks of the Tirupati stage of the Upper Gondwanas are normally more ferruginous in the eastern than in the western part of the formation. Positive anomalies of the order of +50 gammas south of Gopalapuram and the comparatively large anomalies of about +200 gammas at stations 244, 245 and 246 seem to reflect this ferruginous character of the Tirupati sandstones. The presence of a fairly ferruginous clay band known to exist in the shales near Raghavapuram is not indicated in the magnetic anomalies.

In the south, the area roughly enclosed by Nallajarla, Telikicherla, Madhavaram, Tadepalligudem, Kaikaram and Bhimadolu and covered by Tertiary Rajahmundry Sandstones, the magnetic anomalies range from –50 to –200 gammas. There are few pockets of local positive magnetic anomalies of about +50 gammas or less. At Dubacherla, a hard band of ferruginous Rajahmundry Sandstones is indicated by a positive anomaly. Weak positive anomalies are observed on a line joining Nallajarla and Tadepalligudem. Two miles south-east of Nallajarla, the gradual increase of the anomaly to positive values, from about –150 gammas, may probably be ascribed to a thin sheet of Deccan Traps. The negative anomaly region enclosed by Madhavaram, Tadepalligudem and Telikicherla gradually decreasing to the –200 gamma anomaly contour off Telikicherla points to the thickening of the sedimentary section. At this stage, it is desirable to investigate the magnetic polarisation of these Tertiary Sandstones as they often give rise to broad negative anomalies which might sometimes happen due to the Natural Remanent magnetisation different from the

present earth's field. Attempts by the authors to find out the magnetic polarisation of this tertiary strata were unsuccessful as the specimens picked up sporadic magnetisation during drilling, resulting in inconsistent directions.

In general, contour trends indicate broadly that the maximum sedimentary thickness is attained in the west central part of the area rather than in the eastern part. The magnetic anomalies are considerably disturbed by the presence of the Deccan Trap outliers in the east central part of the area. Within limits, it has been thus possible to outline the different geological formations by characteristic magnetic anomalies.

Analysis of the magnetic anomalies on Deccan Traps

Figure 2 shows the magnetic anomalies on the Deccan Trap area between Pangadi and Devarapalle, drawn at 100 gammas contour intervals from closely spaced observations in the area. It can be seen that the area is intensely disturbed magnetically, exhibiting large fluctuations in magnetic anomalies of both signs within short distances. The contours close locally and are roughly aligned in the east-west direction corresponding to the general strike of the Deccan traps in the area. Anomalies ranging from ± 200 to ± 500 gammas are characteristic of the area, though spot values of larger magnitude, as indicated in Figure 2 by the letters A, B, C, etc., with the anomalies, are observed. Most anomalies in the region may be interpreted by approximating the sources to a series of single magnetic poles at shallow depth. The contour trends seem to indicate the trend of the Traps rather strikingly. The Deccan Traps are marked by a number of fractures and joints and are affected by spheroidal weathering as a result of the percolation of rain water through the fractures and joints and consequent leaching and probable concentrations of magnetite and ilmenite locally. Thus it can be seen that there are series of discontinuities in the magnetic characteristics of the traps in the region as reflected by the fluctuating and discontinuous anomalies. The anomalies may, therefore, be viewed as arising from discontinuous sheets of magnetic poles of both signs.

The isoanomaly map points to the possibility that the direction of polarisation of these Cretaceous Eocene basalts does not conform with direction of present earth's field. From

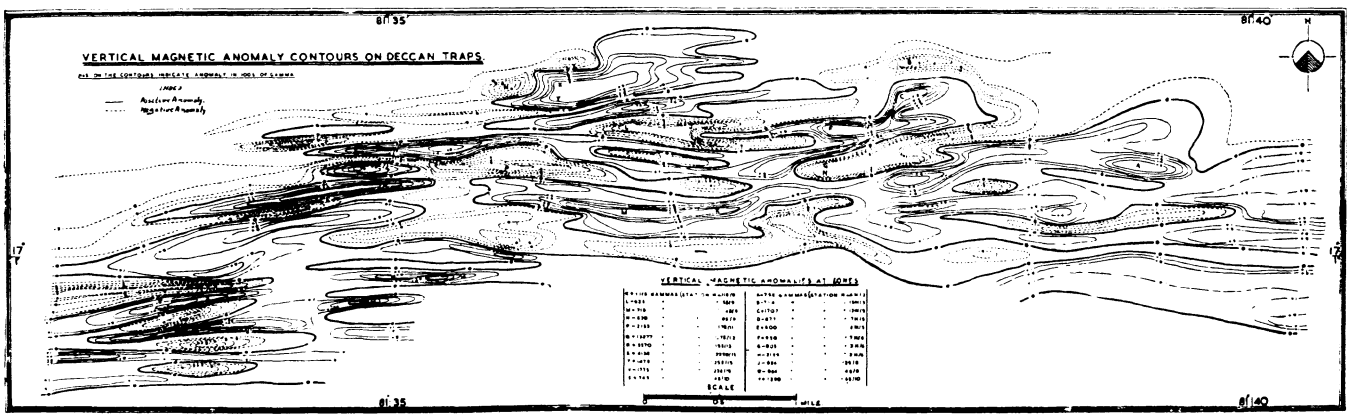
VERTICAL MAGNETIC ANOMALY CONTOURS ON DECCAN TRAPS
81°35'
81°40'
17°
VERTICAL MAGNETIC ANOMALIES AT BOMBS
SCALE
MILE

Figure (2)

the palaeomagnetic measurements made on about 70 specimens of basalt from the top and bottom flows in the present area of investigation, it was found that both the flows were normally polarised with magnetic dip upwards. The resultant direction for the declination is 327° East of North and the dip is –45° (upwards). The natural remanent magnetic intensity was found to vary from 0.4×10^{-3} to 18.7×10^{-3} E. M. U. The range of magnetic susceptibilities at earth's field determined by a prototype of Mooney's induction bridge was 1280×10^{-6} to 5244×10^{-6} C. G. S. units. Average values for percentage of magnetite and ilmenite contents of these basalts from the analyses of Venkayya (1949) and Vemban (1947) were 6.5 and 5.7 respectively. It may also be pointed out that in rocks with comparatively high coercive force and over long periods of subjection to the present earth's field, it is possible that the soft component may have a dominant influence over the remanent magnetism. The thickness of the flows also seems to affect the distribution of the magnetic anomalies. This may be noticed in the western part of the area where the Traps thin out and are subjected to more severe weathering than on eastern side and this is perhaps reflected by increased fluctuations in the western part. The phenomenal magnetic variations in this region are, therefore, to be viewed as the combined effect of the natural remanent and induced magnetisations, and their directions, the changes in magnetic susceptibilities, the peculiar weathering and the mineralogical and petrological characteristics of the Deccan traps. It has not been possible, in the present studies, to investigate all the above aspects. However, measurements of remanent magnetisation and magnetic susceptibilities were made for 70 specimens of the trap basalts and the results are discussed in greater detail elsewhere.

Residual anomalies of a part of Godavari Valley

The isoanomaly charts of the measured gravity or magnetic fields include effects due to deep seated sources, which usually, are not of geological interest in prospecting. To resolve the observed magnetic picture for better interpretation in terms of the geological structures of interest in prospecting, various methods of removing the regional field and deducing the residual field have been developed over the years by a number of investigators. Though the different methods contained elements of controversy from one point of view or the other, it was generally recognised that a residual field picture affords resolu-

tion of the anomalies and is amenable for better interpretation in terms of the geological structures being sought to be located. Nettleton (1954) discussed in detail the principles of most of the available methods of computing the residuals with their possibilities and limitations for application. Due to the inherent ambiguity in arriving at a unique solution of source for a given anomaly, it is, however, difficult to define exactly the regional except in a practical way as given by Grant (1954), *viz.*, that "a regional anomaly is defined as a field that is too broad to suggest the object of exploration and it is generally assumed to be smooth and regular, suggesting characteristically the field due to deep-seated disturbance." It, therefore, follows that the residual anomaly is the residue or the remainder that one obtains by substracting an estimated value of the regional anomaly.

In recent years, literature on the subject of regionals and residuals has grown considerably. Maps variously known as residual maps, derived maps or second derivative maps have been in vogue. The techniques to prepare such residual maps were by (1) smoothingof profiles or contour maps (Vajk, 1932, 1951, Woollard, 1948, 1949; Rao and Narain 1956 etc.) and (2) grid methods (Griffin, 1949). Applying the potential field theory to the grid methods practical schemes of calculation of derivates were evolved out employing averages over circles of different radii from a central point, by various workers (Peters, 1949, and Elkins, 1951 etc.).

In 1951, Agocs advocated a method by employing least squares to estimate the regional. Assuming that a plane would fit the regional variations, the regional anomaly, Z may be expressed as a first order polynomial

$$Z=f(x,y)=C_{oo}+C_{10}x+C_{01}y=ax+by+c \qquad ...(1)$$

By previous definition, the residual anomaly, R, can then be put down as

$$R=\gamma-Z=\gamma-(ax+by+c) \qquad ...(2)$$

where γ is the observed anomaly.

Fulfilling the minimum conditions for the residuals, the constants a, b and c are evaluated by a set of normalising equations.

Equation (1) thus represents a first order surface. This method was claimed that it practically eliminates the personal judgment inherent in the graphical method and approximations and emperical weighting factors in derivative maps, as the regional plane is determined purely by the observed data. This method was developed more recently by Simpson (1954), Oldham and Sutherland (1955) by using higher order and orthogonal polynomials respectively. Polynomials were also applied by Grant (1957) to estimate the regional. Zbigniew Fajklewicz (1959) employed cracovians—a variant on matrices, which do not appear to have been much used outside Poland—in the application of least squares method to estimate the regional gravity.

The observed vertical magnetic intensities of a part of Godavari valley, excluding the area east of longitude 81°35′, were taken up for computing the residual anomalies. The contour map of the intensities shown in Fig. 3 is almost the same as the isoanomaly map (Fig. 1), except for the order of anomalies. The residuals for this area obtained by two techniques, viz., (i) graphical method and (ii) least squares method and the resolution of anomalies obtained is discussed here, without bringing in any derivative maps.

The residual anomalies obtained by the first method are shown in Fig. 4. The broad regional anomalies observed in Fig. 3 disappear and result in localised positive and negative anomalies specially in the north-eastern part of the area. The areas of negative residual anomalies, though isolated, may indicate the regions of increased sedimentary thickness. In the central and western parts, it is seen that there are few isolated zero anomaly contours, though it might be expected that these would merge into a single zero anomaly contour. This may be due to insufficiency of data in the region. However, the area, west of the + 50 gamma contour line, indicated by isolated zero residual anomaly contours has perhaps attained a maximum thickness in its sedimentary cover. As can be seen, the anomalies gradually increase from west to east up to + 100 gammas and with isolated patches of + 200 and + 250 gammas on the extreme eastern side. The anomalies in the south-eastern part are broad starting from + 50 gammas to — 100 gammas where as in the iso-intensity map, (Fig. 3), there is gradual decrease in their intensities. In general, there is a gradual decrease of anomalies from east to west suggesting possible thickening of the sediments in this direction. The region

enclosed by the + 100 gamma contour in the southern part corresponds quite well with the Deccan trap cover in the area. The local anomalies at Dubacherla discussed earlier are clearly isolated by the + 200 gamma contour.

The residual anomalies obtained by the least squares method are shown contoured in Fig. 5. The constants a, b and c are obtained by solving the normalising equations with the observed data on 373 stations and the regional plane is given by

$$6.5\,x + 1.2\,y + 516 = Z \qquad \ldots \quad (3)$$

From the above equation, the values of Z for all the stations are computed and subtracted from the observed values to give the residual anomalies shown in (Fig. 5).

The residual anomalies obtained by this method proved advantageous when compared with the residual anomalies obtained by graphical method (Fig. 4). In the graphical method some details of the anomalies are not clearly brought out specially in the south west corner because of the ambiguity involved in smoothing out the existing anomalies. On the contrary, in the case of the least squares method, the magnetic intensity observations themselves determine the residuals obtained and thus provide greater scope for all the possible details to be shown up in the residual anomaly picture. It can be seen from the anomalies a prominent valley-like region bounded broadly by the two long zero contours running in the N. E. to S.W. direction is demarcated. This area corresponds with the area of maximum sedimentary thickness and is clearly brought out by least squares method. It may be pointed out that the north-western part bounded by –50 gamma contour consists of metamorphic rocks. On the eastern side of the valley-like region, thin layers of Deccan traps and other disturbing layers are encountered. The metamorphics lie north of –50 contour line in the north-eastern part also. In the eastern side anomalies of + 250, + 100 and — 50 gammas are some of the local features. In the south eastern part, the anomalies decrease to — 150 gammas indicating alluvial thickening. The area enclosed by + 50 contour in the southern part consists of a thin Deccan trap layer, as indicated by the residuals from the graphical method also. In general, the sedimentary, metamorphics, trap areas are demarcated with greater resolution by the least squares method than by the others.

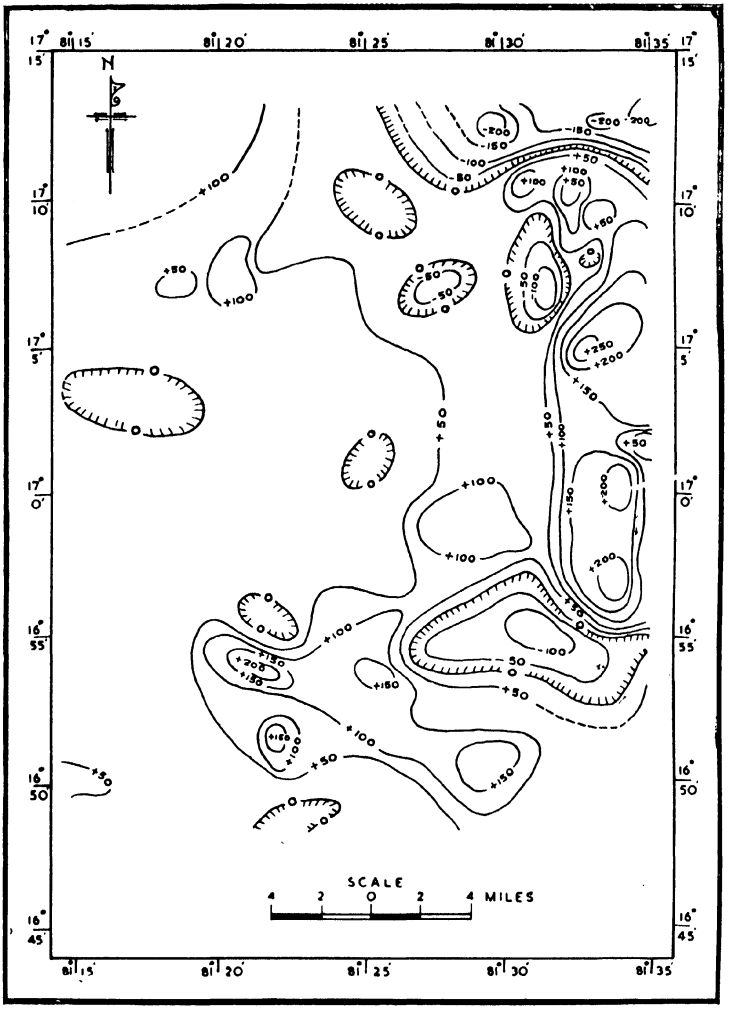

Figure (4)

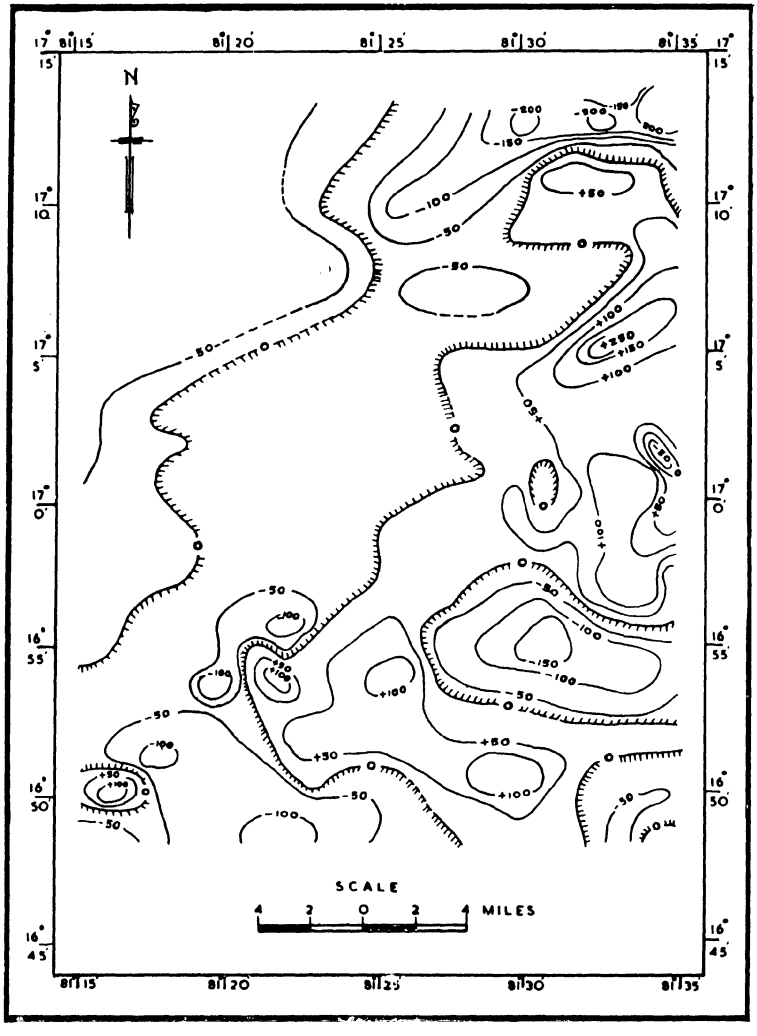

Figure (5)

Conclusions

In conclusion, the results of the field surveys may be stated as :

(i) An area of about 1,000 square miles in the southern part of the Godavari valley was covered with 550 magnetic stations on a regional basis.

(ii) The magnetic relief from the anomalies justifies possible demarcation of the geological boundaries. The magnetically flat area corresponds to the broad outlines of the alluvial cover.

(iii) The problem of anomalies on Deccan traps is complicated by a number of factors effecting the nature of anomalies. The results yielded valuable information with regard to magnetisation of Deccan traps and other phenomenon.

(iv) Attempts were made to obtain residual anomalies by two techniques on part of the Godavari valley. The least squares method indicated greater resolution in magnetic anomalies than the other.

Acknowledgements

The authors are thankful to Council of Scientific and Industrial Research of India for their financial assistance to carry out this project. The authors' sincere thanks are due to Prof. M. S. Krishnan, for his keen interest and guidance throughout the work. The junior author (P. S. Rao) is thankful to the C. S. I. R., for the award of a Senior Research Fellowship to prosecute these studies.

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ANALYSIS OF MAGNETIC ANOMALIES ON GRANITES OF HYDERABAD

BY

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Abstract

An area of 8 sq. miles has been surveyed with a magnetometer. There are mainly two types of granites namely the pink and the grey granites. There is another variety which can be called leuco-granite having little or no mafic minerals. Vertical and horizontal magnetic intensities were measured on a square grid with an interval of 200 meters. The anomaly maps reveal a complex distribution of magnetic field. Certain distinct trends could be located from both the anomaly maps and these are attributed to certain relict features present in the granites. Analytical methods like second derivative methods, upward and downward continuation of the magnetic field have been employed in getting a better picture of the magnetic properties of the area.

Introduction

MAGNETIC studies on granites of Hyderabad have been reported earlier by Balakrishna and others (1962). Data for the same area with some additions have been subjected to analytical methods of interpretation and are presented in this paper. There are mainly two types of granites in the area under consideration, namely pink and grey granites. The present work is an attempt to understand the magnetic expression of these rocks.

An area of 8 sq. miles included between the latitudes 17° 23′ 48″ N–17° 25′ 42″ N and longitudes 78° 31′ E–78° 35′ 48″ E has been surveyed for magnetic and geological data. A geological map has been prepared and is presented in fig. 1. The pink and grey granites are closely associated and are greatly admixed. At places, the grey granites are found to be enclosed by the pinks and at other places the pinks are enclosed by the greys. The contacts are mostly gradational and it is often

difficult to separate the two. However, dominantly pink and dominantly grey granite areas have been demarcated. Pink granites occupy the central and northern parts while the grey granites occupy eastern and western parts of the area. Another type of granite having little or no mafic minerals is found in the eastern part of the area lying between the pink and the grey granites. Dark basic material, consisting of hornblende and biotite, is present in both the granites but with greater frequency and dimensions in the greys. Dolerite dykes are present in the area with east-west trends. There is a quartz reef extending over a distance of nearly two miles in a NE–SW direction. Trends of banding, lineation, major axes of basic enclaves and foliation are NNW–SSE and are represented in the map 'as flow lines'.

The pink granites are coarse to fine grained with red to light pink in colour; at times more basic varieties are also present which are dark in appearance. Porphyritic varieties are also present showing sub-parallel arrangement of microcline laths. The grey granites are also coarse to fine grained, with grey to greasy grey colours. They are vaguely foliated and at times pass into gneiss.

Magnetic Survey

About 600 stations have been fixed in the area on a square grid with an interval of 200 meters. Vertical and horizontal magnetic intensities have been measured using Askania Schmidt magnetometer. After applying the usual corrections, the data are presented as anomaly maps given in figs. 2 and 3. These maps reveal a complex distribution of magnetic intensities. Taking into consideration the trends of the magnetic anomalies, the area can be divided into two parts, along the line connecting Regional Research Laboratory and Elugu Gutta as shown in Fig. 1. In the western portion prominent NE–SW trends are present and in the eastern portion E–W trends are noticed. The anomalies follow the boundary of grey granites to some extent in the western part of the area. Even though, the grey granites are present in the eastern part of the area, such type of anomalies are not noticeable. Some anomalies with such amplitudes are also found over the pink granites.

Second Derivative Method

In the interpretation of the magnetic anomalies, the second derivative of the field has been recognised as an effective means

GEOLOGICAL & STRUCTURAL MAP

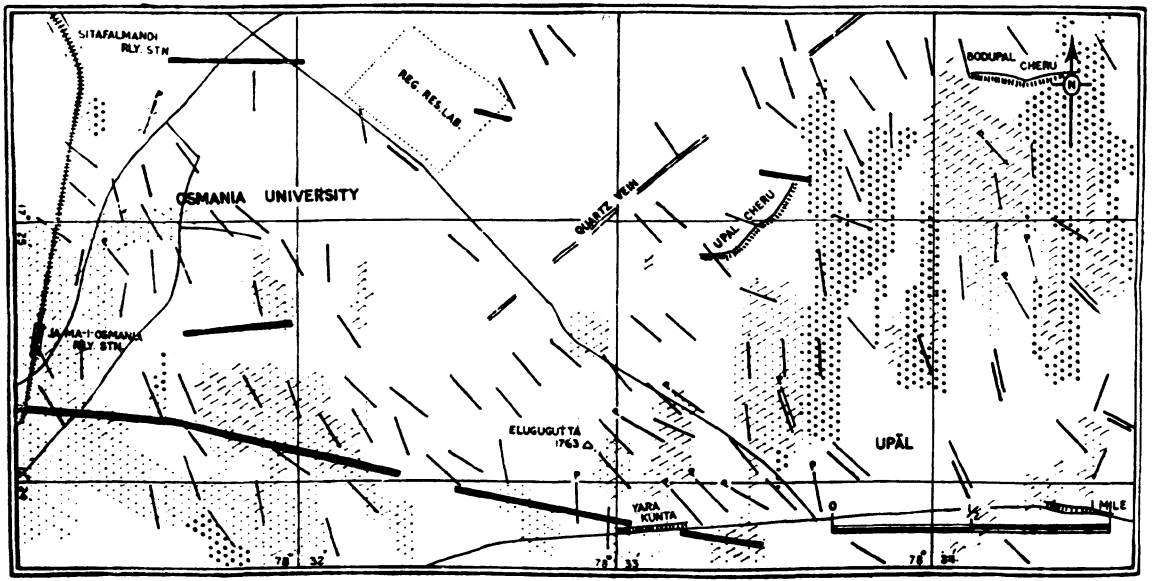


Figure (1)

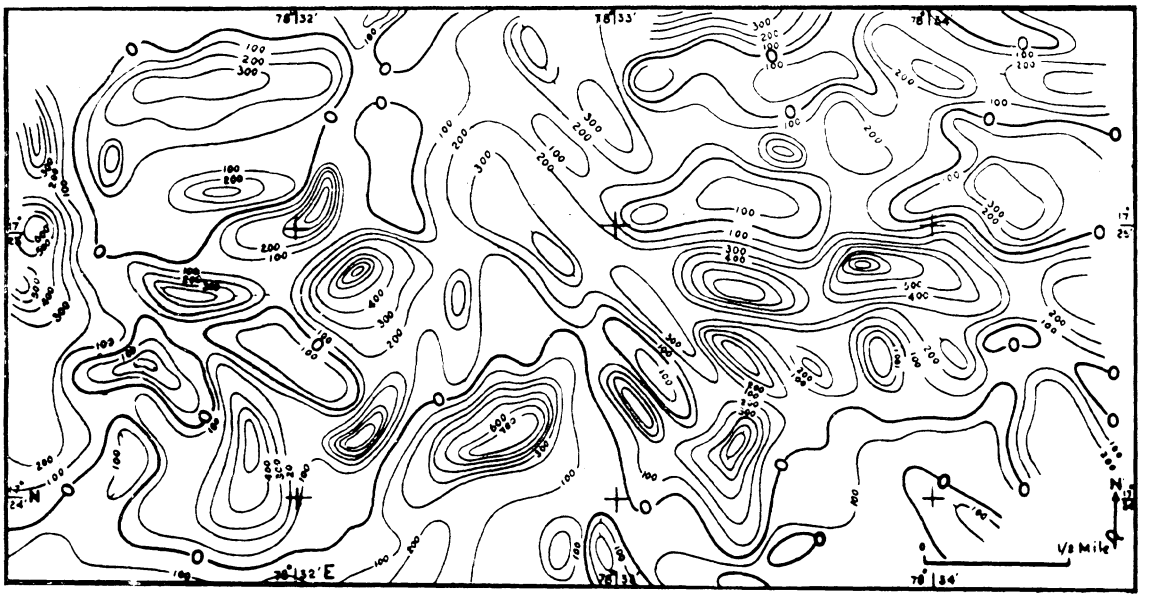


Figure (2)

Vertical Magnetic Anomaly Map

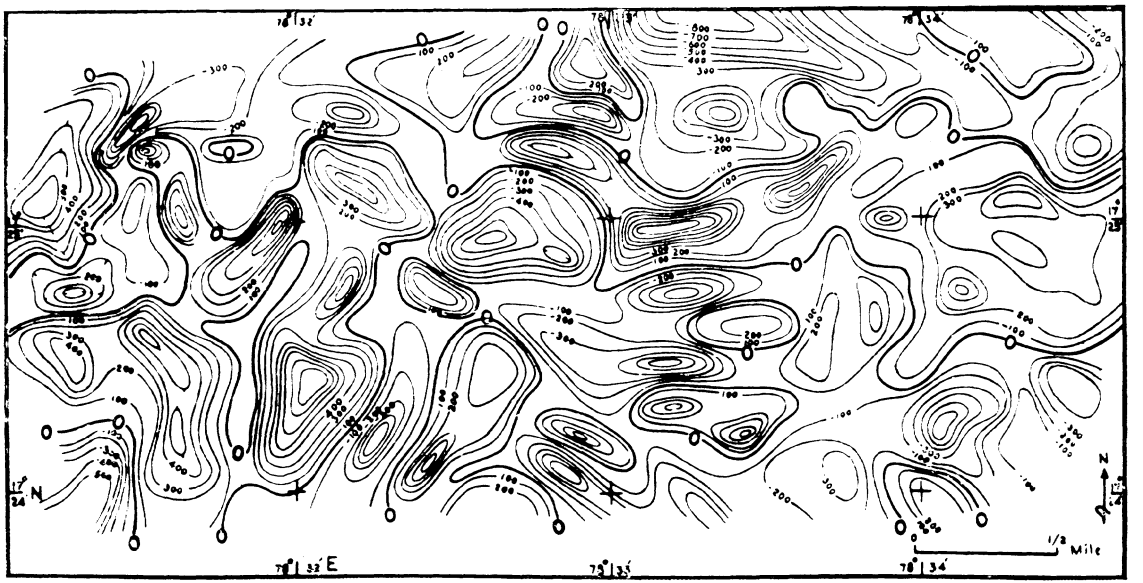
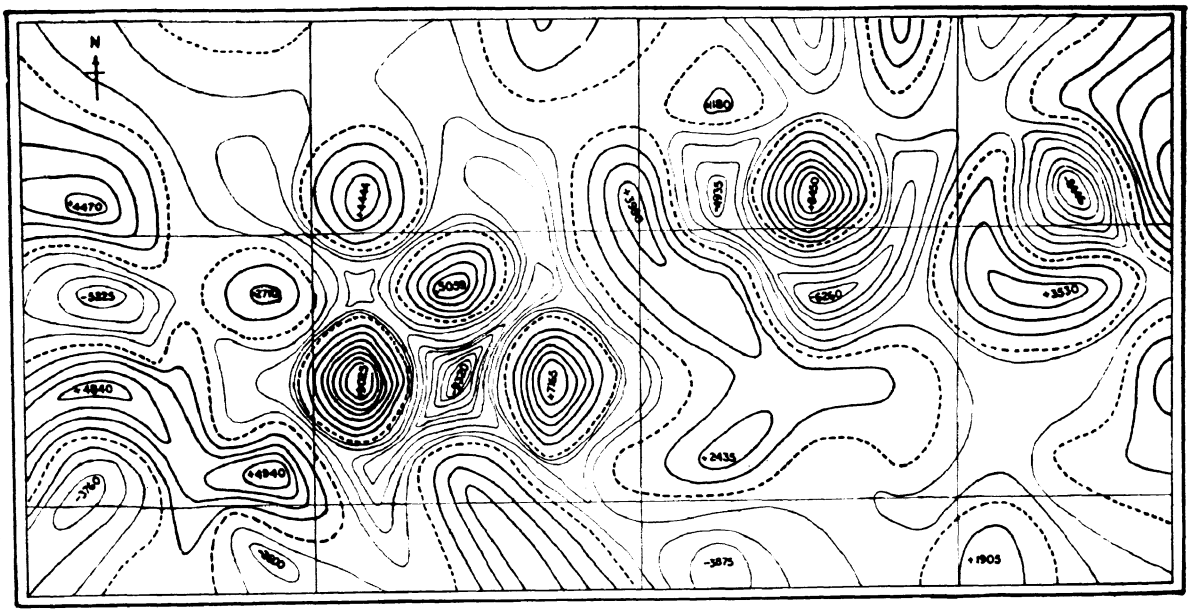


Figure (3)

Horizontal Magnetic Anomaly Map

SECOND VERTICAL DERIVATIVE MAP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+4180
+4470
+4344
-3825
-3718
+5038
+4840
+4840
+4840
+4760
+4760
+4760

of bringing into focus the diagnostic features of the area. This method helps in locating some anomalies which are obscure on the intensity map with large gradients.

For calculating the second derivative at any point, a grid is superimposed on the anomaly map and intensity values at each grid intersection is interpolated and recorded. Eight intensity values about a centre point T_o are used in the computation. They are A through H and are as illustrated as below:

A B C

D T_o E

F G H

The second derivative is found by the means of the relation

$$0.5\ (12T_o - 4T_1 + T_2)$$

where $T_1 = D+E+B+G$ $T_2 = A+C+F+H$

The second derivative of the vertical intensity is presented in Fig. 4. It was found suitable to use a grid with an interval of 500 meters. It can be seen that 'noise' or unwanted intensities which are a result of small magnetic concentrations at shallow depth are eliminated. One more advantage in this method is that the zero contour follows the upper surface of the anomaly producing body.

The two regions which have been recognised in the intensity maps are brought out more clearly by this method. It can be observed that there are circular contours in the western region whereas in the eastern part of the area irregular shaped contours are present. The region dividing these two regions is represented by contours having NW–SE trend. In the present case the anomalies are found to be well resolved.

Analytical Continuation

It is known that the anomalies in the magnetic field are produced by lateral changes in the magnetic susceptibility in the rocks and also due to the underground structure. When the field is calculated at the level of the anomaly producing body, the relief of the magnetic field over sharp structures is

greatly increased while the increasing relief over broad susceptibility changes but little. As the anomalies would be separated more clearly by this method, the study of individual anomalies becomes more easier.

The upward or downward continuation of the magnetic field can be calculated at any point by using a grid with unit interval. A circle is drawn with unit radius around that point. Four magnetic values of the grid will fall on this circle and the average for these values are found. Another circle is drawn with radius $\sqrt{2}$. Four more intensity values fall on this circle and the average value is found. In the same manner, a third circle is drawn with radius $\sqrt{5}$ and the average is found.

Once the average for these circles is found, they can be used for calculating the field at a height or depth of one grid interval by using proper constants. For the present purpose constants given by Roland G. Henderson (1960) have been used. It has been found to be sufficient to use only three circles even though the constants have been given for ten circles. The continuation value $\triangle\phi$ at any point can be obtained by using the following expression :

$$\triangle\phi = A\,\triangle\bar{\phi}(o) + B\,\triangle\bar{\phi}(1) + C\,\triangle\bar{\phi}(\sqrt{2}) + D\,\triangle\bar{\phi}(\sqrt{5}) + \ldots\ldots$$

where A, B.....are constants for the various circles, $\triangle\bar{\phi}$ is the average value of intensities over a circle.

The upward and downward continuation maps are presented in figs. 5 and 6. Some interesting features are revealed in the upward continuation of the horizontal intensities. A big anomaly covering a large area can be seen in the western region where grey granites are present. This has a roughly E–W trend and it turns to NE–SW. In the eastern part also such an anomaly is present over a small area. From the south-eastern corner to the centre of the area anomalies with low values are found having NW–SE trends. This map has been computed for the magnetic field at a height of 1630 feet above the ground surface.

The downward continued map shows many similarities with the second derivative map. Here the anomalies are less resolved as compared with the results of the second derivative method. The downward continued map has been computed to a depth of 1630 feet below the ground level.

UPWARD CONTINUATION OF HORIZONTAL ANOMALIES

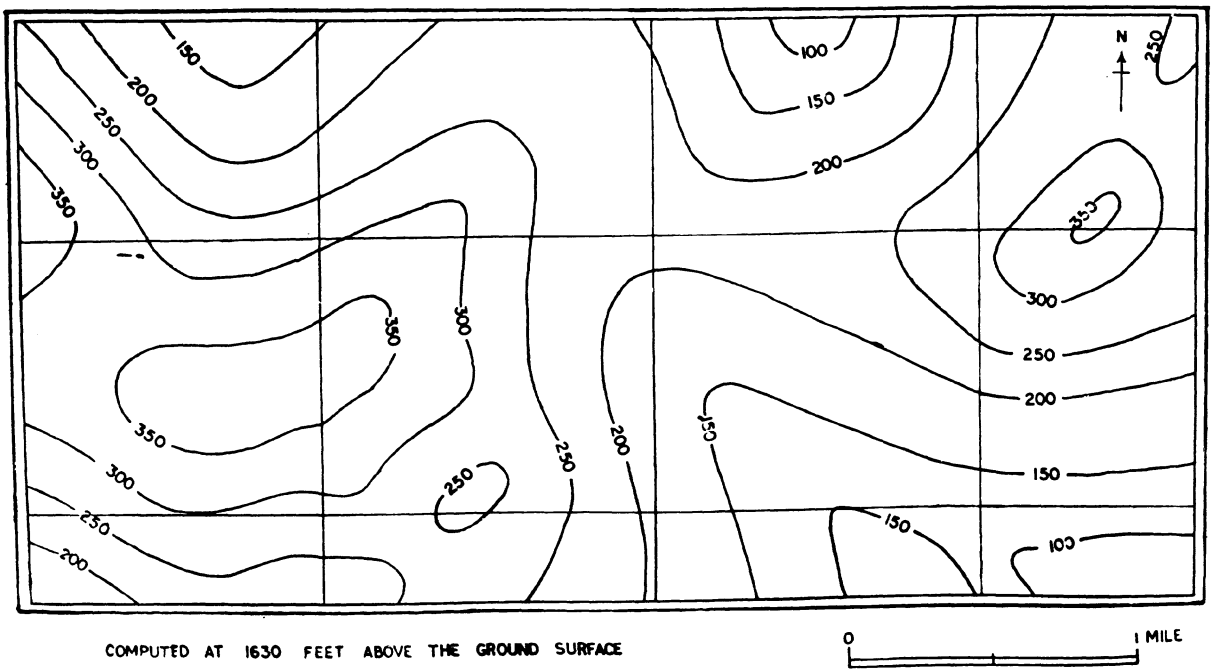
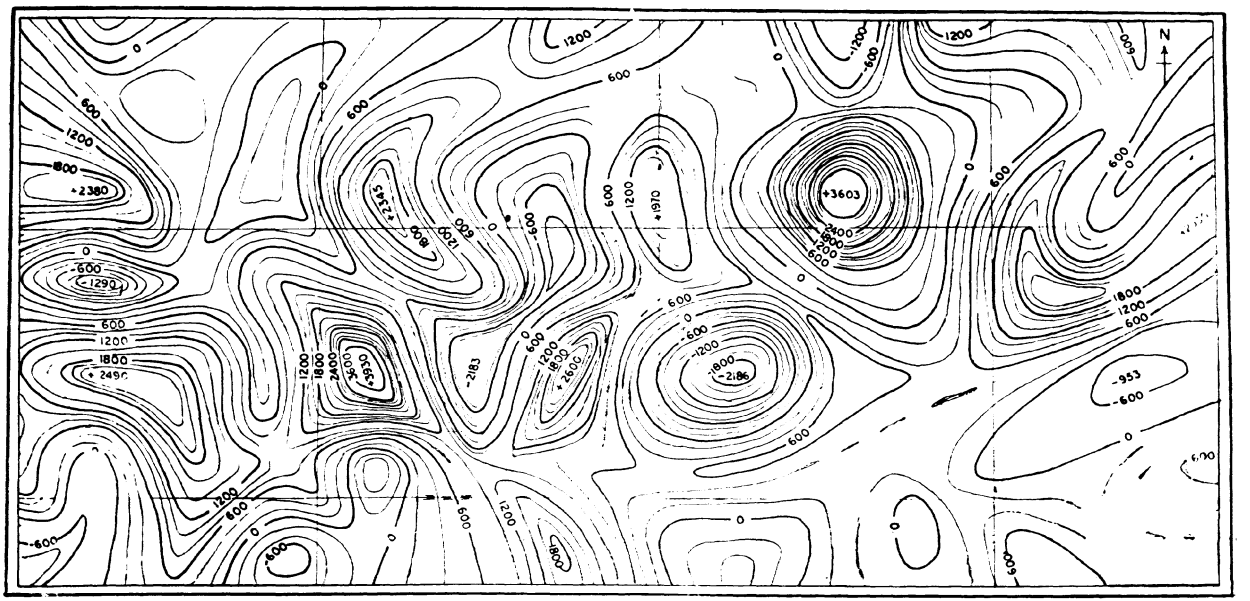


Figure (5)

DOWNWARD CONTINUATION OF HORIZONTAL ANOMALIES



COMPUTED AT 1630 FEET BELOW THE GROUND SURFACE

CONTOUR INTERVAL -- 200 GAMMAS

0 1 MILE

Figure (6)

Discussion

The complexity of the magnetic field is because of the fact that the measurements are made directly on the crystalline rock and so also because of the heterogeneity present in the granites. The magnetite contents of the pink and grey granites range from 0.1 to 1.97 percent by volume. From the laboratory measurements it has been found that the magnetic susceptibility for the pink granites ranges from $260–1040^{-6}$ cgs/cc and for the grey granites it is $540–1640^{-6}$ cgs/cc measured in a field of 1 oe. It is because of the fact that the grey granites are having higher susceptibility a few anomalies may be attributed to them, particularly in the western part of the area where anomalies roughly follow the boundary of the grey granites. Even though grey granite patches are present in the eastern part of the area such type of anomalies are not observed. This suggests greater dimensions for the grey granite bodies in the western part of the area.

It can be seen that prominent anomalies are present over the pink granites also. In order to test whether they are due to lateral changes of susceptibility in the pink granite itself or due to some body with higher susceptibility at depth, measurement of intensities have been made at very close interval of 30 to 50 feet across some prominent anomalies. It is seen that these major anomalies are made up of small anomalies with sharp gradients. The gradient of these small anomalies suggests a shallow depth, may be due to local concentration of magnetite. But the major anomalies are thought to be due to some other source because the trends do not coincide either with the structure or the distribution of different rock types. These features may be due to certain relict features present in the granites which are closely related to their petrogenetic history.

Acknowledgements.

The author is thankful to Council of Scientific and Industrial Research for providing grants to carry out the project, and to Dr. S. Balakrishna, Head of the Geology Department, Osmania University, for guidance and help throughout this work. He is also thankful to Dr. P. V. Sanker Narayan of National Geophysical Research Institute, Hyderabad for many useful discussions and help.

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MAGNETIC STORMS AT HYDERABAD

BY

S. RAMAKRISHNA AND A. PATTABHI RAMA RAO

(Defence Electronics Research Laboratory, Hyderabad)

Abstract

An Askania Magnetometer has been used at the Osmania University to continuously monitor the magnetic activity. The Horizontal component has been recorded throughout the year 1962. Data regarding the 35 magnetic storms observed during the year is presented here. Data obtained at this station is compared with the storm data of Alibag, Annamalainagar, Kodaikanal and Trivandrum. A good degree of correlation is observed. The storms are correlated with flare activity.

Introduction

AN Askania H–component magnetometer was put into continuous operation from December 1961 in the R & D Cell, Geology Department, for measuring the variations in the earth's magnetic field. These variations were recorded by means of an Askania Magnetic Recorder. The principle and a brief description of this instrument is given below.

The magnetometer operates on the principle of balancing the forces of earth's magnetism and gravity. Initially the torque of gravity is so adjusted that the longitudinal magnetic axis runs in a horizontal or vertical direction as required. If the torque of gravity is then kept constant, an inclination of the magnetic system can be produced only by a variation of magnetic intensity.

The magnetic system consists of two gold plated magnetic bars of tungsten or cobalt steel fastened together by a cube–shaped structural membrane made of aluminium. A quartz knife edge is fastened to the block at right angles to the long axis of the magnets. The quartz knife–edge rests on two semi-cylindrical quartz bearings and supports the moving system. In order to provide for temperature correction, two thermometers are fastened inside the case. The magnetometer is clamped on an adjustable tripod, its graduated rotational head

being levelled by means of a central bubble and three levelling screws. Fastened to the underside of the tripod is an extension tube holder for an auxiliary magnet.

A photo-electric attachment mounted on the field balance reads the deflections of the magnetic system as current variations. These are recorded on a strip-chart recorder with a speed of 20 mm per hour.

Results

29 magnetic storms and 6 sudden impulses were recorded in the year 1962. The maximum initial amplitude recorded is about 60 gammas. The maximum range observed is more than 280 gammas while the minimum range is 60 gammas. Table I gives a consolidated list of all the magnetic storms. The storms have been classified as moderate, moderately severe and severe. This classification has to be normally based on the magnitude of the total field. But in the absence of the vertical component and the declination, the classification shown in the table is based only on the value of the H-component and hence is only tentative. It must be noted that the range given in table I also includes partly the effects due to the Solar, Lunar and Secular Variations, which have not been corrected for.

A graph was drawn between the number of storms and the ranges grouped in intervals of 50 gammas (Fig. I). It can be seen that the maximum number of storms were recorded in the range 50 to 150 gammas while the minimum number of storms are in the range 200 to 250 gammas.

In Table II a comparison is given between the starting times at Osmania University and the other Indian Observatories. The data for other observatories is taken from the Indian Journal of Meteorology and Geophysics. Only storms for which corresponding disturbances are noticed in other observatories are taken. A good correlation between the starting times of other observatories and this observatory can be observed. There is a difference of a few minutes in certain cases. This is mainly because no accurate time marking is available for our records. Storms recorded here but not recorded in other Indian Observatories have been reported from foreign observatories notably Huancayo and Honolulu. The implications of this are being studied.

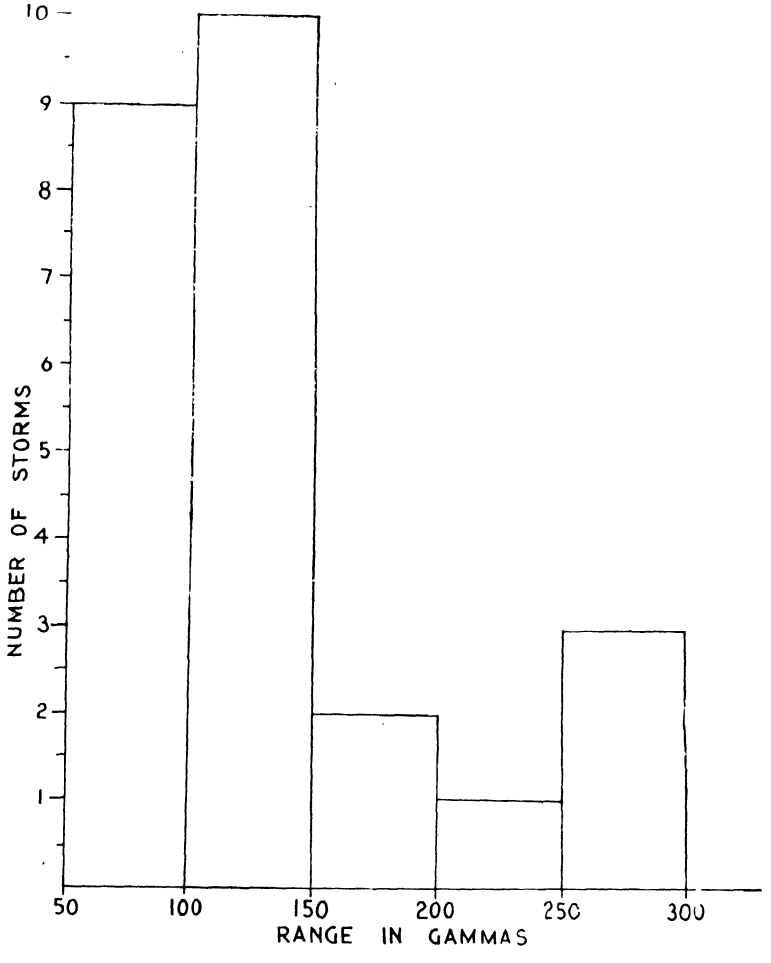
10
9
8
7
6
5
4
3
2
1
NUMBER OF STORMS
50
100
150
200
250
300
RANGE IN GAMMAS

Figure (1)

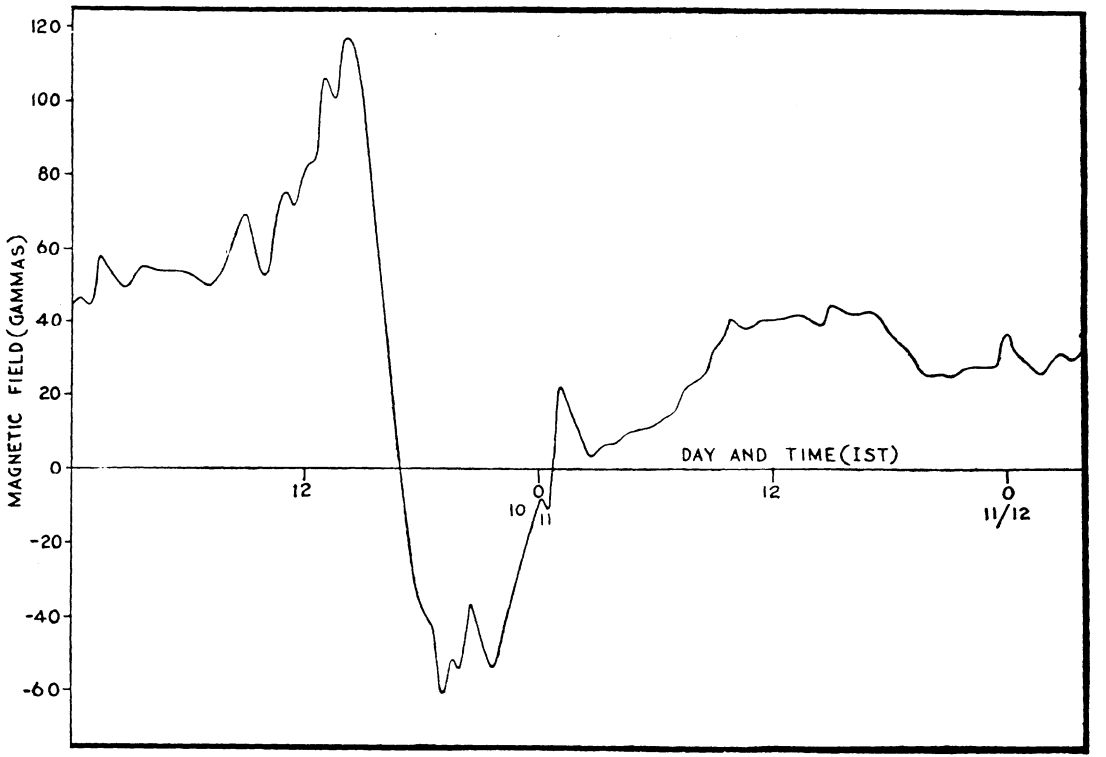
120
100
80
60
40
20
0
-20
-40
-60
MAGNETIC FIELD (GAMMAS)
DAY AND TIME (IST)
12
0
10
11
12
0
11/12

Figure (2)

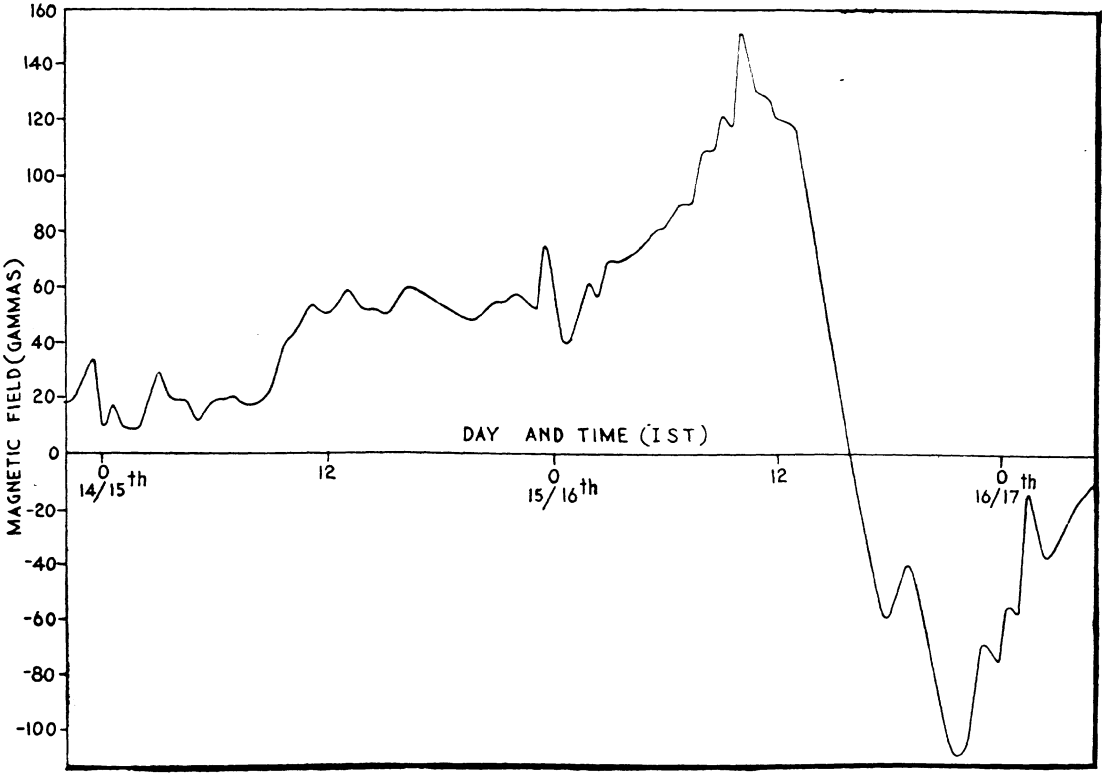
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
MAGNETIC FIELD (GAMMAS)
DAY AND TIME (IST)
0
14/15th
12
0
15/16th
12
0
16/17th

Figure (3)

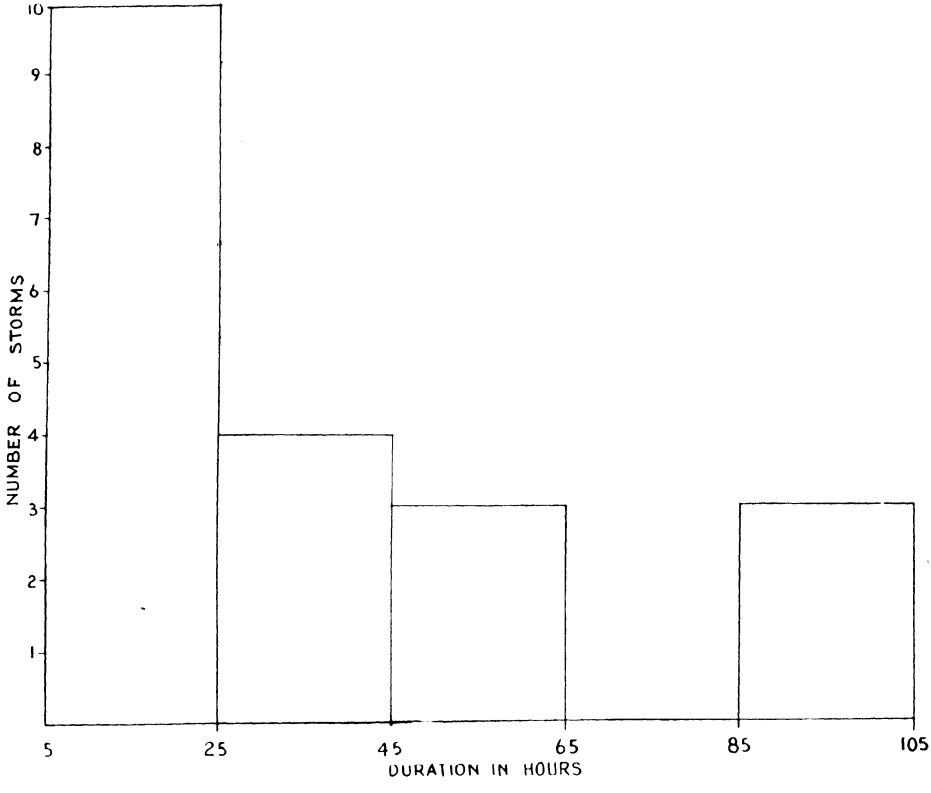
NUMBER OF STORMS
10
9
8
7
6
5
4
3
2
1
5
25
45
65
85
105
DURATION IN HOURS

Figure (4)

In figures II and III two typical magnetic storms recorded here are shown. The starting time of the first storm is 0215 hrs. on 10th January 1962. The maximum variation is between 0630 hrs. to 1030 hrs. while the minimum value recorded is between 1130 hrs. to 1430 hrs. The storm lasted for about one day. The second storm occurred at 1145 hrs. on 14th February 1962 and ended at 2130 hrs. on 16th February, 1962. It has been observed that a prolonged quiet period occurred after these two storms. The ranges of these two storms are 240 gammas and 270 gammas respectively.

Histograms have been drawn for the duration of storms versus the number of storms (Fig. IV). The interval taken into account is 20 hrs. About 50% of the storms occurred with a duration of 5 to 25 hrs., 20% of the storms have duration 25 to 45 hrs. and 15% of the storms lasted 45 to 65 hrs. Thus it can be seen that a majority are of duration 5 to 25 hrs.

An attempt has also been made to correlate the magnetic storms with Solar flares. About 90% of the storms are found to be preceded by Solar flares.

It is interesting to note that there is an enhancement in magnitude during day time for most of the storms. The analysis regarding storm–time variations and related statistical data is still under progress.

Conclusions

With data available for only one year and for only one component, the data has been presented here without going into many interpretations. But from figs. I & IV it can be generally concluded, subject to further verification later, that the storms of small range have been of lesser duration.

Acknowledgement

The authors wish to thank Dr. S. Balakrishna, Head of the Department of Geology for the help and guidance he gave them during this study.

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TABLE — I

Magnetic Storm Data at Hyderabad for 1962

Sl. No.	Greenwich date	Storm Time G. M. T. of begin Hr.	Min.	G. M. T. of ending Day	Hr.	Sudden Commencement Type	Amplitude	C. fig. Degree of activity	Range in H (gammas)
1	2	3		4		5	6	7	8
1.	Jan. 10 1962	02	15	10	21	S.C.	+ 20	s	240
2.	Jan. 19 1962	01	15	19	20	S.C.	+ 10	m	135
3.	Feb. 4 1962	09	30	05	04	S.C.	+ 5	m.s	156
4.	Feb. 11 1962	10	00	12	07	S.C.	+ 15	m.s	135
5.	Feb. 14 1962	17	15	16	22	S.C.*	+ 10	s	278
6.	Feb. 22 1962	02	45	22	17	S.C.	+ 40	m.s	133
7.	Feb. 26 1962	08	30	27	22	S.C.*	+ 35	m.s	165
8.	Mar. 5 1962	02	20	05	19	S.C.*	+ 23	m.s	130
9.	Mar. 6 1962	01	55	06	20	S.C.*	+ 23	m.s	128
10.	Apr. 10 1962	05	00	10	20	S.C.*	—	m	95

11.	May	30	1962	23	00	01	12	S.C.*	—		280 (more than)
12.	Jun.	3	1962	04	00	04	12	S.C.*	—	—	—
13.	Jun.	26	1962	07	15	(Sudden Impulse)			+ 55	—	—
14.	Jun.	26	1962	08	30	28	15	S.C.*	—	m.s	105
15.	July	3	1962	01	30	04	20	S.C.*	+ 15	m.s	105
16.	July	13	1962	—		—		—	—	—	62 (more than)
17.	July	26	1962	—		—		—	—	—	125 (more than)
18.	July	27	1962	18	30	(Sudden impulse)			— 28	—	—
19.	Aug.	6	1962	04	30	—		S.C.*	+ 10	m	90
20.	Aug.	19	1962	20	30	22	12	S.C.	—	m	90
21.	Aug.	30	1962	—		(4th Sept. 19 hrs.)			—	m	98
22.	Sep.	12	1962	06	00	—		—	—	—	—
23.	Oct.	1	1262	—		02	18	—	—	m.s	100
24.	Oct.	6	1962	06	35	(Sudden impulse)			—	—	—
25.	Oct.	7	1962	20	26	11	20	S.C.*	—	m.s	100

TABLE — I (*Contd.*)

Magnetic Storm Date at Hyderabad for 1962

Sl. No.	Greenwich date	Storm Time G. M. T. of begin Hr.	Min.	G. M. T. of ending Day	Hr.	Sudden Commencement Type	Amplitude	C. fig. Degree of activity	Range in H (gammas)
1	2	3		4		5	6	7	8
26.	Oct. 16 1962	—		17	12	S.C.*	—	m	80
27.	Oct. 19 1962	08	00	21	00	S.C.*	—	m	85
28.	Oct. 22 1962	02	30	23	00	S.C.*	—	m	60
29.	Oct. 24 1962	15	15	(Sudden	impulse)		—	—	—
30.	Oct. 25 1962	02	31	29	02	S.C.*	—	m	87
31.	Nov. 4 1962	16	30	(Sudden	impulse)		+ 60	—	—
32.	Dec. 4 1962	03	33	05	15	S.C.	—	m.s	105
33.	Dec. 12 1962	19	30	—		—	—	s	275 (more than)
34.	Dec. 17 1962	03	40	21	20	S.C.	—	m	95
35.	Dec. 19 1962	04	25	(Sudden	impulse)		—	—	—

TABLE — II

Comparison of Starting Times

Sl. No.	Greenwich Date	Alibag		Annamalainagar		Trivandrum		Kodaikanal		Hyderabad	
		Hr.	Min.	Hr.	Min.	Hr.	Min.	Hr.	Min.	Hr.	Min.
1	2	3		4		5		6		7	
1.	Jan. 10 1962	02	12	02	12	02	12	02	13	02	15
2.	Jan. 19 1962	01	14	01	14	01	14	Not recorded		01	15
3.	Feb. 4 1962	09	29	09	29	Record lost		09	27	09	30
4.	Feb. 14 1962	17	—	17	—	17	—	Not recorded		17	15
5.	Feb. 26 1962	08	30	08	30	08	30	12	31	08	30
6.	Apr. 20 1962	23	56	23	56	23	56	23	53	Record lost	
7.	May. 30 1962	22	—	22	—	22	—	Not recorded		23	00
8.	Jul. 25 1962	19	—	19	—	19	—	Not recorded		Record lost	
9.	Sep. 11 1962	19	—	19	—	19	—	19	31	Not recorded	
10.	Oct. 7 1962	20	26	20	26	20	26	20	24	20	26

INSTRUMENTATION FOR ULTRASONIC INVESTIGATIONS ON ROCKS

BY

S. BALAKRISHNA AND Y. V. RAMANA,
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Abstract

The determination of sound velocity, attenuation and dispersion in rocks is of interest to those studying the physical properties of rocks and these are perhaps, of even greater interest to students of seismology for correlating field and laboratory data and for carrying out investigations on model studies. Here the methods and techniques involving the use of ultrasonic energies that have been successfully set-up for the study of rocks are described. The details about the instrumentation involved in these experimental applications are presented along with the circuitry, methods of measurement, standardization, calibration etc. In fact, details of a resonance technique and two pulse techniques (pulse reflection and pulse direct transmission techniques) are presented and the methods of measuring velocities and attenuation are discussed. A few of the results obtained in Peninsular shield rocks by the different techniques are presented.

Introduction

THE authors have successfully set up a base electronics laboratory that is necessary for the ultrasonic investigations and in all three methods for carrying out studies on rocks have been established. These comprise of a resonance technique and two pulse techniques namely the pulse reflection and pulse direct transmission techniques. Emphasis has been laid on the instrumentation aspects and the techniques described here offer a good means of carrying out detailed investigations on rocks. Details of the three ultrasonic techniques are presented along with a few of the results obtained on Peninsular shield rocks. Each one of the techniques described here is good in its own way and each has certain special applications. All the three techniques are dynamic techniques and all of them are based upon the usage of piezoelectric elements as the transducers.

Experimental Techniques.

Resonance Technique:

This is by far the simplest dynamic technique and this has been set up for the determination of ultrasonic velocities in rocks. This method is similar to the one used by Dr. S. Bhagavantam and his collaborators[1]. The introduction of the wedge for resonance tests by Dr. Bhagavantam has enabled the application of the method for the study of rocks.

The test equipment for the resonance technique can be classified into three major parts namely the electronic part, the transducer part and the detection part. The electronic part consists of a power supply and an R. F. Oscillator, to convert A. C. voltages into D. C. voltages for plate and screen supplies and for the production of continuous high frequency electrical energy respectively. It may be noted that an oscillator of the Hartley type as shown in figure two was constructed and used by providing the screen voltage for sustaining oscillations. The transducer serves to convert the high-frequency electrical energy into high frequency mechnical energy. The transducer here used is a quartz wedge and this helps in the production of a number of frequencies, since the frequency is a parameter dependent upon the thickness.

The detection, amplification and indicating circuits come next. Detection could be had either by optical methods or electronic methods. Optical methods involve the use of a source, collimator, telescope and liquid cell arrangement, so as to have diffraction patterns etc. The electrical or electronic methods involve the use of either a grid dip meter or a plate milliammeter. In either case the determination of the fundamental mode of vibration is by using an accurately reading wave meter or frequency meter, and when once the fundamental frequency is known the velocity could be calculated, provided the thickness of the rock sample is known.

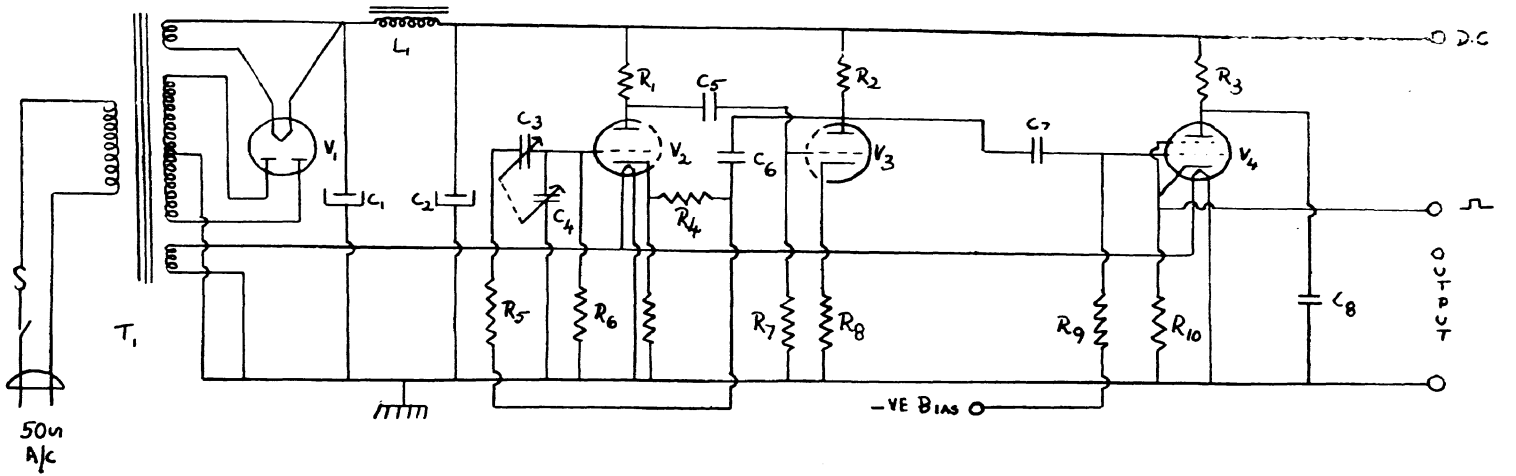
Pulse Techniques:

Coming to the pulse techniques, generally speaking the equipment for ultrasonic inspection of solid materials is based on either a knowledge of the amplitude of transmitted energy only or on a knowledge of the amplitude and transit time of transmitted or reflected energy and it may be pointed out that both the types are in usage in this laboratory.

Pulse Reflection Technique: This is the second dynamic method set up for rock studies and this is similar to the one used by Krishnamurthy and Balakrishna[9]. This technique is based on the following principle: Short duration electrical pulses set up by a pulse generator are fed to an oscillator and the pulsed oscillatory energy is fed to a transmitting transducer which converts them into short acoustic vibrations, which are propagated through the liquid column (water) and through the rock or material under study and the outcoming energy is picked up by a similar transducer which converts back the acoustic energy into feeble electrical energy that could be amplified and displayed. When the rock specimen that is mounted between the two transducers is rotated the intensity of the pulse pattern as observed on the oscilloscope changes. This change in intensity is due to the acoustical energy being refracted away from the normal when emerging from the rock specimen due to the traverse from rarer to denser medium. In practice, corresponding to the longitudinal and torsional modes of propagation in the solid medium two sharp and well defined dips in intensity, could be observed, from a knowledge of which, the critical angles i_l and i_t could be measured, and the respective velocities could be thereafter evaluated.

The pulse reflection technique involves the use of a pulse generator, pulsed r. f. oscillator and transmitting transducer on the transmitting side and receiving transducer and broadband amplifier, rectifier and oscilloscope on the receiving side. Thus the equipment essentially consists of electronic equipment, other than the piezo-electric transducers. The necessary equipment has been completely designed and fabricated to meet the needs of this set up and the salient features of the individual units are briefly described.

Figure one shows the circuit diagram of the pulse generator and this comprises of a power supply, an RC. generator and synchronizing generator and a triggering generator. The use of the thyratron valve in the triggering stage helps in obtaining impulsive signals of constant periodicity as it gives good response to even small irregular inputs. The output of this generator is fed to an r. f. oscillator that is shown in figure two. This is of the Hartley type and pulsing is done by feeding the output from the pulse generator to the screen of the oscillator tube. It is the pulsed R F output that is fed



PULSE GENERATOR.

fig. 1.

VALVES

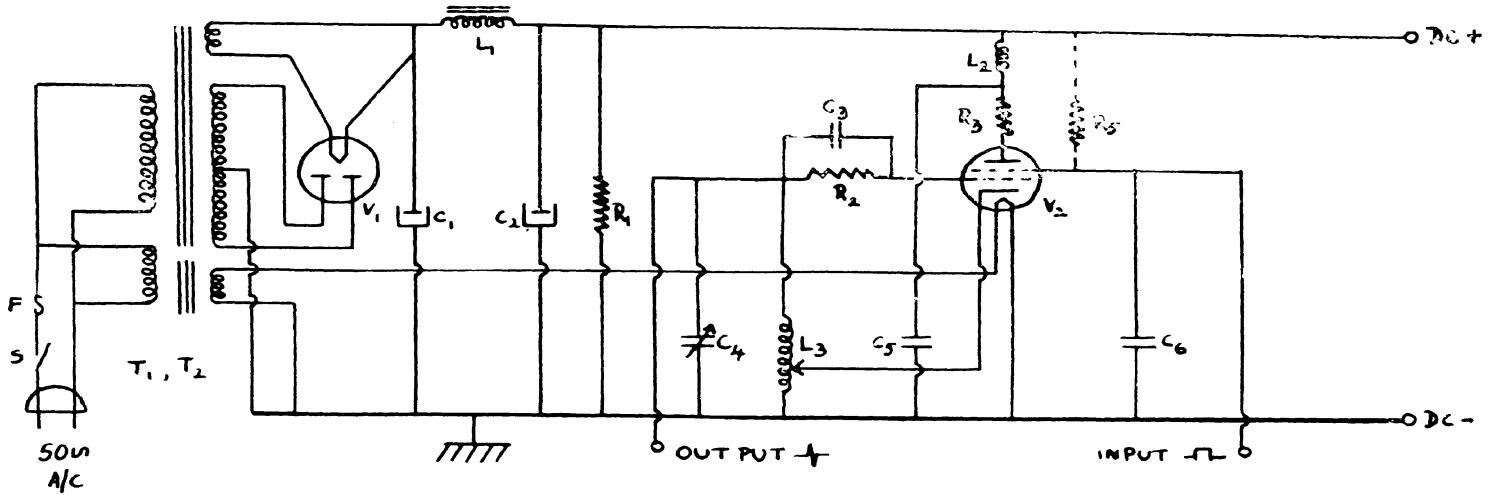
V_1 5U4G
V_2 ½6SN7
V_3 ½6SN7
V_4 2050

RESISTORS

R_1 4K
R_2 4K
R_3 500K
R_4 15K
R_5 1M
R_6 1M
R_7 100K
R_8 15ohms
R_9 100K
R_{10} 1K
R_{11} 2K

CONDENSERS

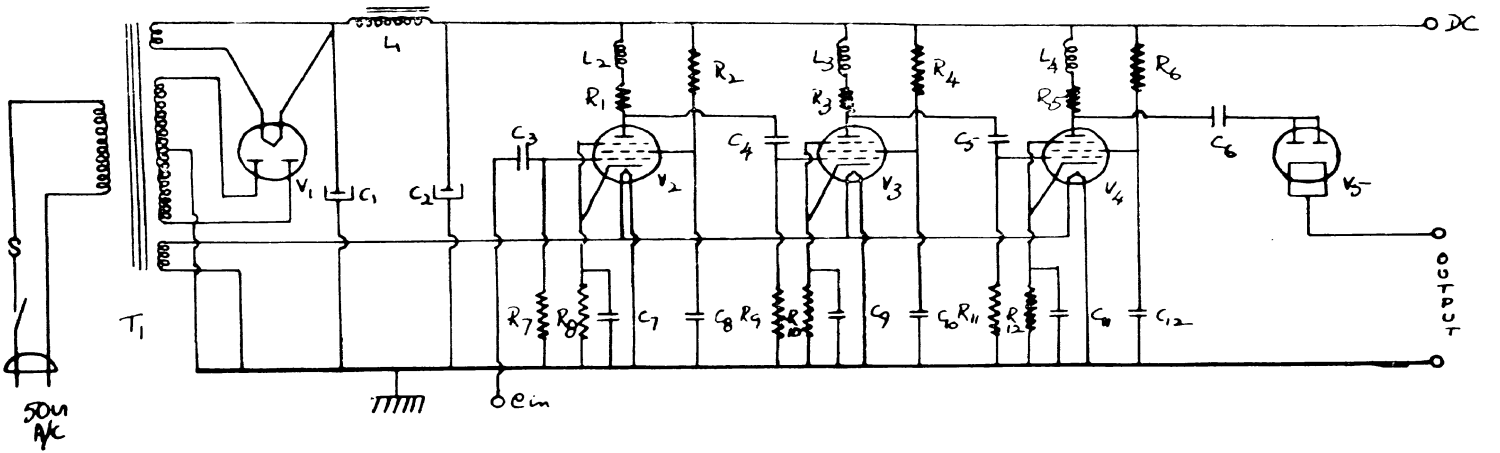
C_1 32 Mfd.
C_2 32 Mfd.
C_3 500 Pfd.
C_4 500 Pfd.
C_5 0.1 Mfd.
C_6 0.1 Mfd.
C_7 100 Pfd.



PULSED OSCILLATOR

fig 2.

V_1 5R4GT	R_1 Voltage dropper.	C_1 4 Mfd. 1000V.
V_2 807	R_2 12K.	C_2 4 Mfd. 1000V.
	R_3 3K.	C_3 400 Pfd.
	R_4 Dropping resistor for screen supplies.	C_4 500 Pfd.
		C_5 0.1 Mfd : C_6 300 Pfd.
	R_5 Bleeder	
INDUCTANCES :	L_1 Power choke. : L_2 R. F. choke.	



WIDE-BAND AMPLIFIER & RECTIFIER

VALVES		RESISTORS	CONDENSERS (MFD)	
V_1 5U4G	R_1 3.3K	R_7 56K	C_1 32	C_7 25
V_2 6AC7	R_2 47K	R_8 150ohms	C_2 32	C_8 0.1
V_3 6AC7	R_3 3K	R_9 56K	C_3 0.01	C_9 25
V_4 6AC7	R_4 47K	R_{10} 400ohms	C_4 0.01	C_{10} 0.1
V_5 6H6	R_5 3.3K	R_{11} 56K	C_5 0.01	C_{11} 25
	R_6 47K	R_{12} 1K	C_6 0.01	C_{12} 0.1

INDUCTANCES: L_1 8Henrys – 80 milliamps : L_2 L_3 L_4 Between 5 and 10 Microhenrys.
T_1 Power Transformer – 150 Milliamps.

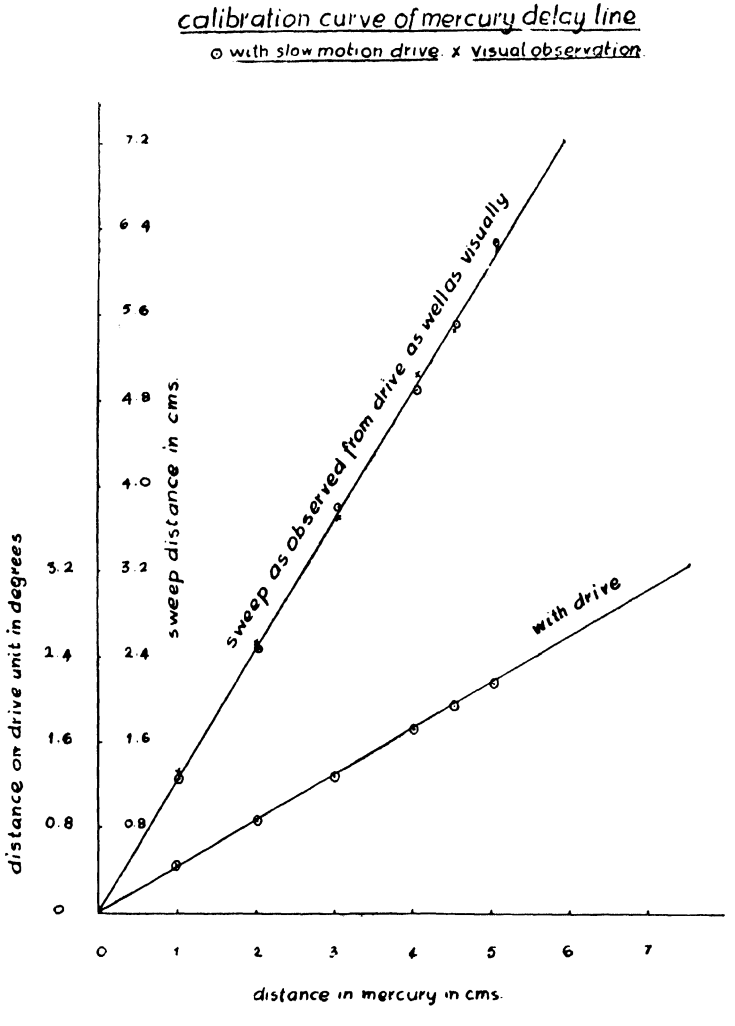


fig 4

Figure (4)

to the transmitting crystal. The r. f. oscillator helps in tuning the required frequency and also enables the use of higher power. Figure three shows the circuitry of the amplifier. The received pulse being feeble is amplified by a three stage R. C. coupled wide band amplifier. The amplified output is rectified so as to have only the positive or negative spikes and this is what is observed on the oscilloscope. Throughout crystals of one megacycle fundamental frequency were used and alignment was made possible by using a mechanical unit which enables the crystal to be moved in the three planes and suitable provision has been made to hold the rock sample and for its rotation.

Plate one shows the complete set up of the pulse reflection technique and plate two shows the pulse pattern obtained, clearly indicating the positive spike alone.

Pulse Direct Transmission Techinique: This is called the direct transmission technique as the transducers are in direct contact with the rock specimen and this experiment does not involve the use of any liquid as is necessary in the pulse reflection technique. But suitable couplents such as oil, grease, have to be used between the transducers and the elastic medium, as otherwise the vibrations will not pass through. The coupling medium is important and may be almost any liquid which will wet the surfaces and stay between the crystals and the test material.

The principle of the direct transmission technique is based on the computation of velocity, from a knowledge of sample size and travel time. This method is similar to the one used by Hughes[8] and subsequently several others and this has been set up to carry out systematic investigations on Indian rocks. Here the rock sample is driven by a barium titanate ceramic transducer and an identical transducer at the other end detects the vibration and converts it into feeble electrical pulses that are amplified and visualized on the screen of a CRO. The barium titanate transducers used here are in the form of circular plates of about 1" diameter and have a fundamental frequency of 1 Mcs. for free longitudinal vibration in the direction of thickness. The rock samples studied are of cubical or rectangular bar shape and therefore, the measurement of velocities in the three mutually perpendicular directions is feasible.

Here a Hewlett Packard pulse generator has been used as the pulsing unit. The pulse generator is capable of giving 50 watts peak output. Throughout a pulse length of 6 microseconds with a repetition rate of 3 Kcs. has been used. This unit has a pulse rise and decay time of 0.02 microseconds and a synchronizing voltage of 15 volts is also available. The DC pulse from this generator is fed to an r. f. oscillator that was locally fabricated and is similar to the one shown in figure two. An 807 tube is used as the oscillator tube and the oscillator is so designed that the pulse gives the necessary triggering voltage to the screen. The pulsed r. f. output is the signal source for energizing the transmitting transducer. The advantage of using the r. f. oscillator stage here is its application in dispersion or attenuation studies, as the frequencies could be changed with ease and as one could work at the harmonics too. At the receiving end the energy is amplified by using a Tektronix wide band amplifier that has a maximum gain of 100 and that has a band-pass of 5 Cps to 12 Mcs. This amplified output is fed to the vertical deflection plates of the oscilloscope. The synchronizing output of the pulse generator is also fed to the scope so as to get a stable pattern in phase. The oscilloscope used for these studies is a Philips general purpose instrument, that has provision for both internal and external synchronization. There is a good choice of sweep speeds and the vertical amplifier has a band-pass of 3 Cps to 14 Mcs and has better than $50V_{p-p}$/Cm. sensitivity. The vertical amplifier of the scope has a rise time of 0.025 microseconds and so has very good response for square-waves which are produced without over-shoot. Further, the built-in calibrating voltages and frequencies that are available from the CRO help in checking the amplitude and delay measurements.

The travel time measurements have been made taking time of travel through mercury as standard using the time base of scope indirectly. A slow motion drive mechanism (least count 0.072^{0}) was fixed to the x-movement potentiometer of CRO to enable the measurement of sweep distance, accurately. In the absence of a suitable double beam oscilloscope or a time marker or movable marker generator, the type of work done by calibrating the sweep against the mercury delay has been found to be satisfactory and accurate measurements of the order of 0.2 microseconds or more have been possible. For calibration purposes the pulsed r. f. signal

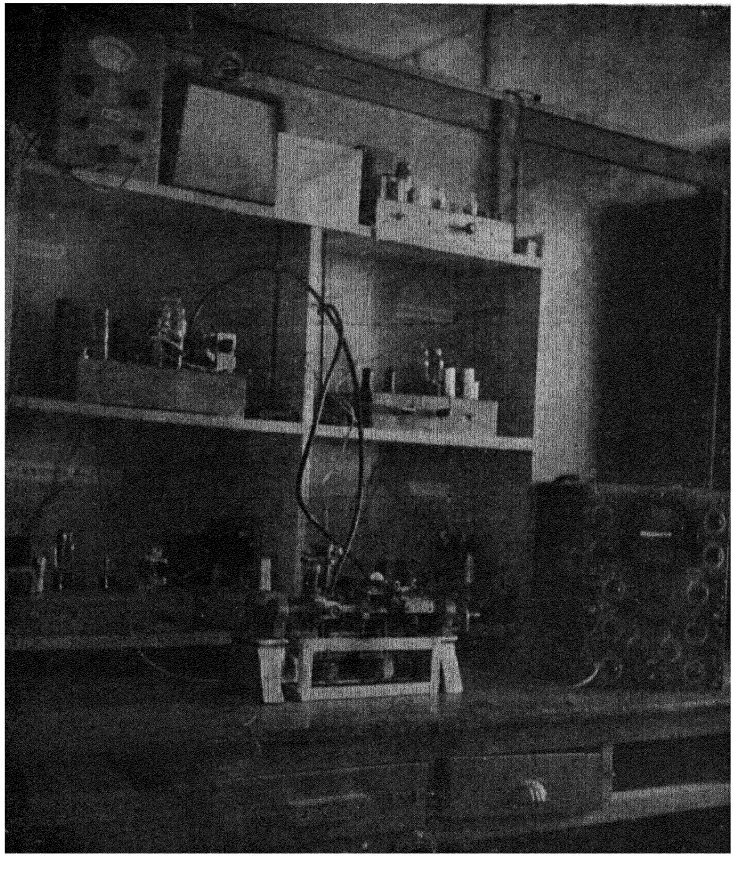


Plate (1)

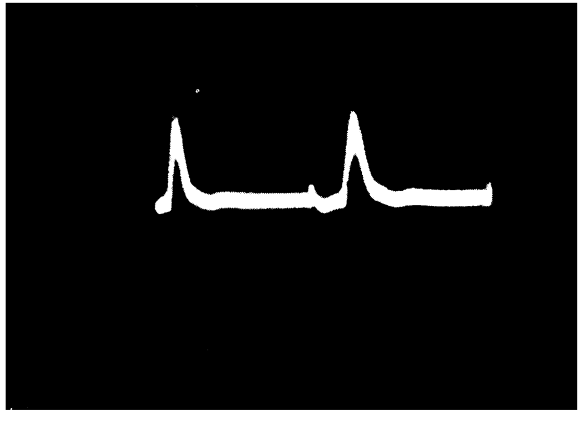


Plate (2)

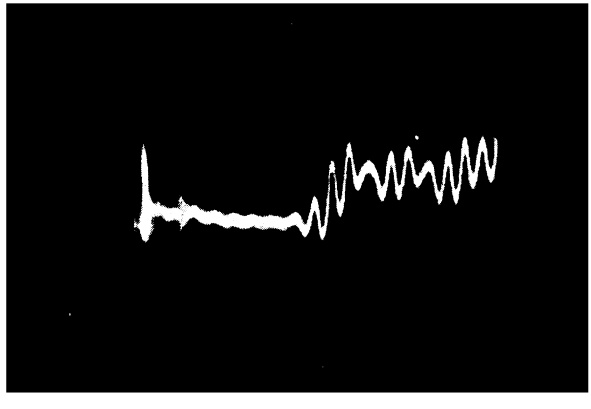


Plate (3)

is also passed through the mercury column (the delay introduced is a measure of the travel time) and at the receiving end, it is amplified and fed to the vertical deflection plates of the same scope. The mechanical device used to move the receiving crystal in mercury has a least count of 0.001 Cms. Figure four shows the plots of delay distance in mercury against sweep length and delay distance in mercury against slow motion drive distance. From the calibration graph the equivalent length of mercury column could be read, and this will in turn help in determining the delay due to the rock sample. It should be noted that throughout a sweep speed of 45 microseconds for 8 Cms of sweep length has been used and this has been verified using a standard AVO signal source as well as the internal source. The velocity values in mercury as obtained from the calibration curves are within 1% of the standard value and this is good proof of the working of the set-up.

Attenuation Measurements:

Attenuation measurements too are possible by all the three techniques described here. An assessment about the absorption is possible in the case of the resonance technique from a knowledge of the number of the fringe orders and from the intensity of the fringes. In the case of the pulse reflection technique the total over-all absorption could be evaluated by using a attenuator in series with the received output. In the pulse methods the attenuation measurements are based on a knowledge of the amplitude or peak height or on the knowledge of output power. But in actual usage, based upon the peak heights itself measurements can be made in more than one way and they may be classified as follows:

Peak Height Method: Here a number of samples from a single rock specimen are made of differing heights and otherwise identical shape and in each case the peak height and size is noted and the attenuation in db/cm calculated. Also a graph between peak height and sample size could be drawn and attenuation can be calculated from the graph.

Coincidence Method: Using an attenuator in series with the output, the loss in db/cm can be evaluated. Here also a number of samples of different heights are used. Using the longest sample the attenuator settings to give a particular amplitude

on scope are noted and later using smaller samples, the corresponding decibel values to give the same peak height are noted. The difference in sizes gives the actual size and from the corresponding decibel values the loss in db/cm can be calculated. Here also a graphical solution is possible by plotting the size against the attenuator values.

Pulse Decay Method : Here the peak heights and the corresponding delays are noted using a single sample and the db/cm calculated.

Results have been obtained using the first two methods and fuller details are beyond the scope of the present paper. Plate 3 is a photograph to show the pulse pattern obtained in the direct method and one can clearly see the delay as well as the peak height clearly.

TABLE - I

Longitudinal Elastic Wave Velocities by Different Methods in Granites

Sl. No.	Direct Method Km/Sec.	Critical Method Km/Sec.	Wedge Method Km/Sec.	Average Velocity Km/Sec.
1	7.12	7.15	6.86	7.04
2	6.57	6.54	6.32	6.48
3	6.59	6.52	6.74	6.62
4	6.74	6.88	6.78	6.80
5	7.21	7.18	6.70	7.03
6	6.57	6.61	6.65	6.61
7	6.00	6.11	6.56	6.22
8	6.50	6.82	6.60	6.66
9	6.61	6.82	6.81	6.75
10	6.66	6.30	6.49	6.48

Results and Discussion

Table one indicates the velocity values obtained in the case of a few granites of Hyderabad region by the direct pulse, pulse reflection and resonance methods respectively along with the average values. The results obtained by the three methods are in good agreement with each other and the deviation from the average value is less than 4% in most of the cases. Amongst the shield rocks, granites have been chosen for presentation here as they have been found to be isotropic, while traps showed anisotropy of upto 10 percent. Extensive studies on scatter in velocities, variation of velocities with composition and textural and physical properties and variation of attenuation, etc., have been carried out and fuller discussion of the results is beyond the scope of this paper. But mention may be made here that the attenuation in most rocks at the 1Mcs frequency have been found to hover between 2 and 3 db/cm and the attenuation has been found to increase with increasing frequency and practically very little dispersion has been noticed.

Acknowledgement

Thanks are due to Dr. G. Sivarama Sastry for helping in the design and testing of the electronic equipment and to the C. S. I. R. for the financial assistance.

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PART PLAYED BY APPLIED GEOPHYSICS IN THE DEVELOPMENT OF THEORETICAL GEOPHYSICS

BY

P. V. SANKER NARAYAN

WHEN it came to the question of choosing a title for this address the exact words that came to my mind were something like this :— When the dog wags its tail the tail also wags the dog a little. This is a simple fact of observation ; it is also in conformity with Newton's Third Law. Even so I felt I might be transgressing the limits of good taste by choosing such a title for presentation before a distinguished audience. So I preferred the more sober sounding prosaic title that you see printed in the Programme. Geophysics, Applied or Pure, has come to occupy such a status at the present time that there is hardly anything in the universe which does not come within its purview in a definitional sense ! A few decades ago the earth scientists around the world meant 'Physics of the Solid Earth' when they used the term 'Geophysics'. Soon after the First World War such vast strides of progress were made in our knowledge of the Upper atmosphere through studies of the inter-relationship between Geomagnetic, Ionospheric and Solar phenomena that the science of the Upper Atmosphere had to be given the status of a separate discipline; and what could be more logical than to consider this discipline as coming under Geophysics since the atmosphere belongs more to the earth than to anything else in the universe. With the advent of the space age we now think in terms of Space Geophysics even though we may be studying the physics of matter millions of miles away from the earth. Truly we can be happy at the ever-increasing array of disciplines which come under this wonderful noun, Geophysics. The more, the merrier after all !

The term 'Applied Geophysics' can mean many things to many people. To the mining Geologist or the Petroleum Geologist Applied Geophysics would just mean the science as applied to the exploration of minerals. For a Space Scientist Applied Geophysics is that which helps him in understanding the mysteries of space and in the design of space vehicles and planning of successful space travel by man. For a Civil Engi-

neer Applied Geophysics has its best sense when it helps him in deciding on the best location for a dam site or some large structure or helps him in solving some tricky erosion problem or the like. Whatever is the view point one takes, it appears the Applied Branch of Geophysics has always been the most appealing and the most appreciated. Every branch of modern science has seen growth under stimulus from the applied side. However it looks that no science has had this stimulus applied with such intensity as Geophysics had. This is probably because of its direct association with mineral exploration and hence the straight impact on the economic advancement and power potential of every nation. We shall briefly examine a few outstanding cases in Geophysics where this has happened in the last three or four decades.

Geophysical Exploration for minerals in a scientific sense started only around the turn of this century when large scale magnetic surveys were made with the ***Dip Needle*** for locating iron ore in Europe and in North America. It met with unprecedented success in the Kiruna area of Sweden and the Lake Superior Iron Ranges of North America. The next big sweep in exploration techniques came up in the 1920s with the evolution of the Torsion Balance by the famous Hungarian Physicist Baron Roland Von Eotvos. He perfected the theory, instrumentation and practice of gravity surveying so thoroughly that by the mid-twenties every oil field in the United States and Europe was made holy by a preliminary ***Torsion Balance*** Survey. In my travels with magnetometers in the western United States I had the pleasant experience of facing an old-timer who expressed sheer disappointment when he did not see a Torsion Balance with me. He certainly took me for a primitive man and said that in his days, even if you saw a gusher shooting black oil and flame, you still ***got to*** send a couple of Torsion Boys up there to discover the hole! He really meant giving the hole the proper official geophysical blessing! Such was the impact of the Torsion Balance on Oil Exploration. Simultaneously with these developments in gravimetric and magnetic methods of exploration came the seismic refraction techniques which gave the geologists an X-Ray as it were in determining the depth, thickness and attitude of sedimentary beds in their search for oil. In fact at the present time it can be safely said that no tool in the arsenal of Applied Geophysics has such high precision and

resolving power as the seismic method and it is the one most-sought-after despite its very high cost.

One of the finest examples where sheer pressure from the Applied branch of Geophysics made the most spectacular advance in instrumentation is the modern gravimeter. In the 1930s the tempo of gravity exploration for oil was so high in the United States that Torsion Balance and Pendulum Apparatus were considered far too time-consuming and expensive. The oil companies had this seemingly simple problem before them:— How to get a reading of gravity in five minutes with a precision of 0.1 milligal, that is to a precision of about One Part in Ten Million, using a gear weighing less than 100 lbs. The instrument designers and theoreticians said this was clearly impossible and was too much asking. But it worked and by the late 30s the first gravity meters came up which weighed certainly less than 100 lbs., gave a reading of gravity to about One Part in One Million or so in a matter of 5 to 10 minutes. There were still plenty of grumblers, for these gravity meters had very narrow measuring ranges and also needed very carefully controlled thermostating which all meant a lot of weight to carry in the form of battery packs when out in the field. The problem was attacked relentlessly again and by the late 1940s Sam Worden of the United States came up with a meter now known by his name. This gives a measuring range of more than 5,000 milligals, as against a hundred milligals or so of the older instruments, that is covering the entire range of gravity variations from the equator to poles. What is more, he dispensed with thermostating entirely by making the sensing element completely temperature-compensated. The present day Worden Gravity-meter weighs only about 5 lbs., gives a reading of gravity interval correct to One Part in a Hundred Million and does that in a matter of 3 to 4 minutes. In the process of this evolution of gravity meters such outstanding physical concepts like the Zero-Length Spring have been evolved and entire projects of research have been initiated on the elastic behaviour of Quarts, on its isotropism or the lack of it.

Simultaneously with these developments, pressure from another source—the geodesists—has been stimulating active research in high precision determination of gravity on an absolute basis. Already the ***Minimum Pendulum apparatus*** had been developed which gives the absolute value of gravity to

about One Part in One Million. However for establishing a World Gravity Network with a high standard of precision the geodesists wanted something much better than that offered by the pendulum. Two fundamental methods have been experimented upon in this direction. One is a highly sophisticated version of the simple Falling Plate experiment taught in elementary Physics classes. While this had some measure of success, its intrinsic accuracy has been challenged on the grounds that the bar under free fall undergoes a series of modes of body vibrations whose effect on the ultimate evaluation of the acceleration cannot be determined with sufficient accuracy. So this method has receded into the background. A group of gravity men from Wisconsin and Princeton are now engaged in perfecting a slightly different technique where a small polished steel ball of 2 to 3 mm. diameter is dropped in a vertical evacuated tower. A pulsed beam of light sent vertically up is reflected from the bottom of the falling ball and the continuous decrease in the total travel time of these light pulses is measured to a precision of One Part in a Hundred Million or so. While the method promises an intrinsic accuracy of a very high order, the electronics involved in the measurement are extremely complicated. Along these lines of research in gravity active investigations are under way at Princeton on a very fundamental issue of Physics, *i. e.* Is the Universal Gravitation Constant so constant with time after all ? Prof. Dicke of Princeton has done pioneering experiments along these lines. If a lack of constancy in the gravitation constant is proved beyond doubt, then Physics itself is going to get a bad jolt, for many of the vital constants of Physics are going to need revision. Physicists are of course quite used to such surprises. In fact they thrive best on them, for all the great discoveries of Physics came as startling surprises which almost threatened to shake down the whole edifice of theory every time !

Magnetometry as applied to Geophysical Exploration, has also faced the same situation during the last two decades. By 1950 Exploration Geophysicists were already getting tired of the conventional *Schmidt Magnetometer* which gave relative values of either the Vertical or the Horizontal Intensity of earth's magnetic field correct to about One Part in 20,000 or so in a matter of 5 to 10 minutes. These meters had to be levelled and oriented with respect to the magnetic meridian. All this took time and care. The Applied Boys wanted a

reading correct to One Part in 50,000 or better in a hurry without the worries of orientation, levelling etc. So back to the theorists the problem went. Happily for us great Physicists like Bloch had already laid the foundations for Nuclear Magnetic Induction methods as early as the late thirties. By 1957 we got the first models of the *Nuclear Precession Magnetometer* (more popularly known as the *Proton Magnetometer*) which gave absolute values of the Total Intensity of earth's field correct to One Part in 50,000 or better if you so wished, in a time as small as 5 to 10 seconds — and with no worry of levelling or orientation. We could say magnetometry witnessed a revolution in 1957. 1957 was a great year for magnetometry from another point of view for, in October that year man was able, for the first time to hurl an object into space and keep it there orbiting around us. Now the demands from a new clan of scientists—Space Geophysicists—threw a challenge at magnetic instrumentation. The Space Scientists wanted a unit as small as a match-box (from considerations of payload) which could measure extremely weak magnetic fields in space to One Part in 50,000 or better if desired. This was to be done in rapid succession—say one sampling every 5 seconds or less, as the orbital speed of the satellites are extremely high. And of course no orientation problems please! All this looks like a dinner order in a cafetaria, someone remarked at that time! From the arsenal of Modern Physics marched out a whole horde of magnetometers, each meeting the challenge and even outdoing it. The *Spectoscropic Magnetometers* (as they are collectively called) are the *Rubidium Vapour Magnetometer*, the *Helium Metastable Magnetometer* and the *Maser Magnetometer*. Possibly there may be some more that we do not know about as yet, due to the clamp of secrecy around these inventions at the present time. All these magnetometers share some common intrinsic advantage over the conventional type of instruments using a magneto-mechanical system for the sensing element. For one thing, they make use of the interaction of fundamental charged particles—proton or electron—and a magnetic field. As such, the determination of the field intensity is controlled only by one fundamental constant—the gyromagnetic ratio in this case, which is now known with extremely high precision. Secondly, the determination of the intensity centres around our ability to measure a frequency very accurately. This is something which can be done with extremely high precision these days. Thirdly,

temperature variations which used to be a major worry in both gravimetry and conventional magnetometry poses no problem for these magnetometers since the changes in temperature influence the behaviour of a whole multitude of particles in a statistical sense only and have no control whatever on the actual determination of the frequency and hence the field intensity.

Coming to the seismic methods of exploration the progress report is as encouraging, if not more, than in other fields. Since 1940 the interpretation of seismic data has been refined to an incredible degree largely from the mathematical side as evidenced by the large number of first rate contributions to the subject which have appeared in the last two decades or so. Theoretical contributions of Ewing, Jardetsky, Press, Slotnick (only to mention a few outstanding names) are most notable in this line. Explosion seismology has become such a powerful tool for examining the subtle undulations and structures in subsurface layering that Geophysicists have now begun to use it freely for solving problems of academic interest such as studies of deep crustal layering. Since the time of Mohorovicic, seismologists have had to depend entirely upon natural earthquake waves to study crustal structure under continents and ocean basins. Since the last decade and a half pioneers like Ewing, Press, Woolard and many other scientists from Europe have used large scale explosion spreads covering hundreds of miles for sampling the deep crust and with unprecedented success. Possibilities in this line were limited only by the amount of detonating charge that small groups like universities could handle. Happily, since 1950, atomic testing involving release of immense amounts of energy has been going on with great frequency in some countries. This has afforded excellent opportunities to the academic groups in studies of the deep crust and mantle.

With the highly refined instrumentation and techniques the quality of field data has reached a high standard, and their interpretation has also passed into a new era which has stimulated mathematicians to develop various high resolution techniques having firm foundations in the theory of Potential. Three decades ago the interpreting geophysicist was quite happy to have a simple contoured map of gravity and or magnetic data as he was then looking only for the very large anomalous structures which were quite apparent on these

simple types of maps. With the intense activity in oil exploration there is hardly any really large anomalous structure left undiscovered in the major oil provinces of the world. One has now to be looking for the inconspicuous, the least obvious ones. What was originally neglected as a mere nosing of the contours on an anomaly map is now sought after with great interest and it is here that modern high resolution techniques come in handy. In this direction considerable development has taken place with the happy fusion of high power mathematics and the potentialities of modern high speed computors which can rapidly handle extremely tedious computations demanded by theory. Here indeed was a challenging field for the pure mathematician. Many of the mathematical theorems which were studied by Newton, Lagrange, Euler, Laplace and other famous mathematicians in sheer appreciation of their beauty could never see the light of day because their application meant computations of staggering magnitude. It was like building a pyramid with just two hands! But now with the high speed electronic computors this is no problem at all and these valuable mathematical tools have become the Geophysicist's most trustworthy servants. In Alladin's story someone was hawking "*New Lamps for Old*". We would like to do the same.

On the electrical side developments in prospecting techniques have not been wanting at all. With the fundamental work on self-potential and resistivity methods initiated by the Schlumberger brothers on the continent in 1913–14 a prolific field of exploration techniques came up. The products were the *Self-Potential* and *Resistivity* methods, *Electromagnetic Induction* Methods, the *Eltran* methods (abbreviation for Electrical Transients), *Telluric Current* Methods, and the latest entrant the *AFMAG* method (meaning Audiofrequency magnetic). These techniques either singly or in combination with other exploration methods have already provided invaluable service in locating metalliferous ore deposits and in tackling difficult groundwater problems. Coming to borehole surveying, the early parameters which ruled the field were Self-Potential and Resistivity. Since the last decade or so *Gamma Ray logging* and *Neutron Logging* methods have stepped in to aid the petroleum geologist in stratigraphic correlation in difficult areas where paleontologic or micropaleontologic evidence is either too meagre or far too complex to be of any help. A famous stratigrapher of the U. S. said in one of his speeches in praise

of these methods that what used to be marked as diastems, that is, unaccounted for intervals in the stratigraphic column in many areas of the U. S. have now completely disappeared from the maps since the Gamma Ray and Neutron logs can define these missing horizons in delicate detail. In fact it is coming to mean that words like hiatus and diastem can be deleted from the glossary of geologic terms!

I would like to make a brief reference to another branch of Geophysics which for some reason or the other has come to be looked upon as having the least applied value. This is *Geodesy*, which to put in a nutshell, is the science that deals with the figure of earth. If we go into some of the practical implications of this professorial science we will be appalled at the mistake that one makes in ignoring its practical value. It is the basis for all accurate map-making and naturally every nation has to depend on its growth for (1) fixing its geographic boundaries with precision, and (2) for locating enemy positions accurately in times of hostilities. I have an interesting war story here. During the last war a small island in the Pacific was chosen for strategic reasons to furnish a link in the supply line for the Pacific theatre. The latitude and longitude of this island as known then were furnished to a supply squadron of the U. S. Air Force. It so happened that the Japanese had already occupied the island with very heavy concentration of arms. Due to a serious error in the latitude and longitude values furnished by the Army Map Service the squadron was misdirected to another island a few miles away and was thus spared from being taken unawares and blown to bits by the Japanese artillery! This error in locating the island came as a blessing to the U. S. at that time, but it could have been equally disastrous as well. Highly precise triangulation and levelling on the earth's surface can be made use of for fixing positions on the surface very accurately only if the overall mean shape of the earth's surface can be defined with a sufficient degree of accuracy and also if the lateral irregularities of mass distributions within the earth are taken into account. This explains why at the present time a group of top-ranking geodesits around the world are engaged in intense worrying as to how best to arrive at the best-fitting figure of earth using the principle of isostasy. It also explains why institutions like the Army Map Service of the U. S. are sinking their money by the millions into this project. In fact

Geodesy, we could say is more an applied science than any other discipline of Geophysics. It is, shall we say, *More Catholic than the Pope Himself?*

In its frantic growth Applied Geophysics has not spared even such cataclysmic events of world history like war. We all admit philosophically that in the wake of a war, admixed with the acute miseries and agonies, a small measure of good also results. This has only been too true with our science and I can give three convincing examples. During the First World War the Germans and the British used the rather limited knowledge on seismic wave propagation available then, for locating the positions of large enemy guns by placing geophones in strategic positions in their own territory. The results showed such spectacular success that even before the war was over (1916) the U. S. Bureau of Standards took up the problem for an extensive study. This resulted in the direct application of explosion seismology to oil prospecting. By 1925 to 1930 so much had been known in refraction theory and practice that conventional shooting was set aside in favour of the more sophisticated fan-shooting which resulted in the discovery of virtually hundreds of shallow salt domes in the Gulf Coast of the U. S.

The next example again comes from the First World War where the famous German Physicist Barkhausen was employed by his country to do the not-too-pleasant job of eavesdropping on the British field phone lines. Being a first rate physicist he not only did this unpleasant duty for his country but also observed and studied the peculiar fluctuations of earth currents about which absolutely nothing was known at that time. The knowledge contributed by him as a by-product has essentially laid the foundations for application of *Telluric Currents* to Geophysical Prospecting.

The third case is the evolution of the now well-known *Flux-Gate Magnetometer*. During the early 1940's when the U. S. plunged into the war, a group of American physicists and engineers were given this problem by the War Department:- to develop the necessary instrumentation and technique by which the lurking German U-boats in the Atlantic could be located from a safe distance, that is from air. What was needed was an idea, a good one. Their brain trust pointed out the simple

principle of asymmetric distorsion of the hysterisis loop of an easily saturable magnetic material. With the requisite amount of conventional electronics put into it the principle gave the first *Magnetic Airborne Detector usually abbreviated as the MAD.* Its performance in locating enemy submarines in the Atlantic was so spectacular that by the end of the war (1946) it became, with slight modifications, the first Airborne Magnetometer of the world. Magnetic exploration passed into a new phase one could say, for now one did not have to confine exploration to the ground entirely. In fact the most inaccessible regions of the earth like the Himalayas, the Amazon or Congo jungles or the Sahara desert could be explored magnetically with great ease and speed from an aircraft.

By now I hope I have in a rather cursory fashion pointed out how and in what measure the applied part of Geophysics has influenced the growth of the pure science, and even other allied fields. In fact one gets the impression after hearing so much said that it is almost futile to draw that thin line of demarcation between the applied and the pure. To get back to the title that I started with we now begin to wonder whether the dog wagged its tail at all. Instead, it looks the tail wagged the dog all the while!

X-RAY STUDIES ON LIMESTONES

BY

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Abstract

The composition and the grain sizes of the constituents of sedimentary rocks are two basic properties that can be used in their classification. As the usual optical methods of determining the grain sizes are not suitable in the case of fine grained rocks, the authors have recently developed X-ray methods to determine the grain sizes and the composition of several rock types. These methods have been employed to study limestones belonging to three regions of South India — Huzurnagar (Palnad basin), Paniam (Kurnool basin) and Chincholi (Bhima basin). It has been found that such studies throw light on the petrogenetic history of these limestones. The present paper describes the experimental technique and the results obtained for the limestones of the three regions.

Introduction

IN recent years, the determination of grain size in rocks has assumed importance, as it has been found[1](Balakrishna, 1959) that many physical properties of rocks are influenced by the grain size. The usual method of determining the grain size is to prepare a thin section of the rock and measure the average diameter of about 200 grains, using a polarising microscope provided with a mechanical stage. The method besides being tedious has several defects. Such a measurement represents the size of only a section of the grains and not the over-all grain size. As the number of grains on which measurements are made cannot be very large, the average value obtained may not be a good approximation to the over-all grain size. Hence the authors have examined[2] (Krishna Rao et al 1960) if an X-ray method could be used to determine the grain size in rocks. First the grain size of quartzite a monomineralic rock was determined using the method[3](Taylor, 1952) of counting spots on the Debye-Scherrer diffraction ring and the values obtained were compared with the grain size determined by the

optical method. As there was good agreement between the values of the grain sizes obtained by the two methods, the X-ray method has been extended to limestones[4](Krishna Rao et al 1963) containing only calcite and quartz. As a knowledge of the percentage composition of the constituents is necessary to determine the grain sizes in a multi-mineral rock, an X-ray method has been devised to determine also the composition of the rock. It is evident by these studies that the X-ray method is well suited to the study of the grain sizes of sedimentary rocks like fine-grained limestones which are not amenable to the usual optical examination. Hence it was thought worth while to study limestones collected from three regions of South India. The trend of the results obtained has been recently published in the form of a note[5] (Krishna Rao et al 1963). A detailed account of the experimental technique and the results obtained is presented in this paper.

Experimental

Transmission powder photographs of thin sections of the specimens (thickness about 0.3 mm.) are taken on a flat film using Cu K_d radiation from a Philips X-ray unit working at 30 K. V. and 15 M. A. with a specimen to film distance of about 7 cm. The diameter of the collimator is selected to suit the specimen. In the case of a coarse-grained rock a 2 mm. collimator has been used to get enough number of spots on the Debye-Scherrer ring. For a fine-grained specimen a pin-hole collimator is used to avoid overcrowding and overlapping of the diffraction spots. From the number of spots obtained on the Debye-Scherrer rings corresponding to 104 reflection of calcite and 101 of quartz, the grain size G in each case is evaluated by Eq. (1).

$$G = \sqrt[3]{\frac{Vp \cos\theta \, d\varphi}{2Y}} \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

In Eq. (1) Y is the number of spots on the Debye-Scherrer ring, V the effective volume of the mineral irradiated, p the multiplicity factor of the X-ray reflection, θ the Bragg angle and $d\varphi$ the divergence of the X-ray beam. V in each case is evaluated from the total volume of the specimen irradiated and the percentage composition of each mineral present in the specimen. The divergence of the X-ray beam is determined experimentally by finding photographically the width of the beam at two distances from the collimator.

The percentage composition of the specimen is determined by measuring the relative intensities of 104 ring of calcite and 101 ring of quartz. First, powder photographs of mixtures of calcite and quartz of known composition ranging from 50 to 100% of calcite have been obtained. Then, taking the microphotograph records of the powder lines, the ratio of the peak heights of 104 reflection of calcite and 101 of quartz is determined for each composition and a calibration curve is drawn between the percentage weight of calcite and the ratio of the peak heights.

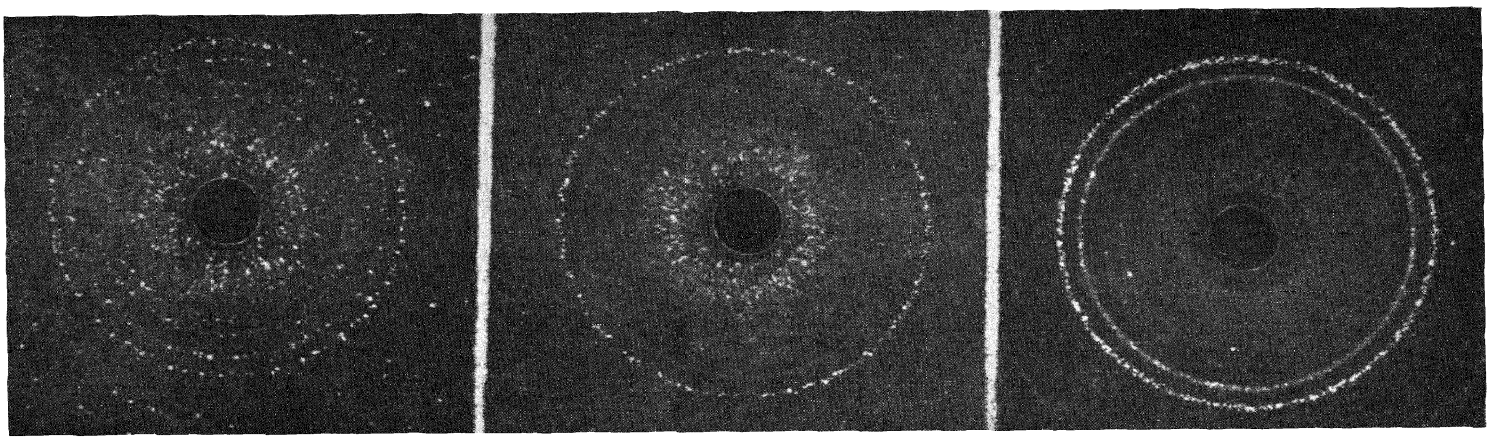
A second set of powder photographs of the experimental samples is taken in the same way as before excepting that the specimen is rotated during the exposure to get smooth diffraction rings. From the microphotograph records of the powder lines, the ratio of the peak heights of 104 reflection of calcite and 101 reflection of quartz is evaluated and the percentage weight of calcite in the specimen is read off from the calibration curve.

Results and Discussion

For all the specimens investigated, the X-ray photographs showed only diffraction rings of calcite and quartz. Chemical analysis revealed only traces of $MgCO_3$. Fig. 1 shows the characteristic X-ray patterns of limestones belonging to the three regions. The calibration curve is shown in Fig. 2. Tables 1 to 3 show the composition of the limestones of the three regions as determined by the X-ray method. Tables 4 to 6 give the grain sizes of calcite and quartz in different samples of the three regions.

In the case of Huzurnagar samples, the diffraction rings of calcite and quartz are both spotty. The grain sizes of calcite and quartz are nearly the same, thereby indicating a good sorting of grains by a mechanical process. If both calcite and quartz were chemically precipitated at the site of deposition, one would expect a smaller amount of quartz in the samples. Hence the Huzurnagar samples appear to be predominantly clastic in their origin.

In the photographs of the Chincholi samples, the diffraction ring due to quartz is continuous showing that the size of the quartz particles is of the order of 10^{-4} cm. One would



(a) (b) (c)

Figure 1. (a–c). X-ray diffraction patterns of limestones.

(a) Sample from Huzurnagar.
(b) Sample from Chincholi.
(c) Sample from Kurnool.

The inner intense ring corresponds to 101 reflection of quartz and the outer one is due to 104 reflection of calcite.

not expect that quartz of such fine grain size is brought to the site of deposition by a mechanical process. The percentage of quartz present in these samples is also small. These features indicate that the Chincholi deposits are chemical in their origin.

The photographs of samples from Kurnool show a continuous quartz ring with a superposition of discrete spots. This shows that in these samples, detrital quartz grains are also present along with very fine quartz particles. Hence it may be concluded that the origin of these limestones is of a hybrid nature both the chemical and mechanical processes contributing to their formation.

It may be mentioned here that there is no resemblance between the X-ray diffraction photographs of limestones from Palnad and Kurnool basins, whereas according to the stratigraphic studies made by the Geological Survey of India, the two basins have many similarities.

In conclusion, the authors wish to thank Dr. S. Balakrishna, Head of the Geology Department for the keen interest he has shown during the progress of this investigation.

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TABLE — I

Composition of Limestones from Huzurnagar (Palnad Basin)

Sample No.	Intensity of 104 reflection of Calcite (I_c)	Intensity of 101 reflection of Quartz (I_q)	I_c / I_q	% of Calcite	% of Quartz
H_5	2.05	1.65	1.24	64.5	35.5
H_6	1.20	0.90	1.33	66.0	34.0
H_{12}	1.40	1.30	1.07	61.0	39.0
H_8	1.30	0.80	1.62	70.0	30.0
M/4	3.85	2.60	1.48	69.0	31.0
H_{80}	6.30	3.70	1.70	71.0	29.0
H_{60}	5.50	2.20	2.50	79.0	21.0
M/61	2.05	3.60	0.57	50.0	50.0
M/26	2.80	2.05	1.36	66.0	34.0
M/64	2.00	0.90	2.22	76.5	23.5
M/62	2.20	1.40	1.57	69.0	31.0
M/28	3.60	1.80	2.00	74.0	26.0

TABLE — II

Composition of Limestones from Paniam (Kurnool Basin)

Sample No.	Intensity of 104 reflection of Calcite (I_c)	Intensity of 101 reflection of Quartz (I_q)	(I_c /I_q)	% of Calcite	% of Quartz
G1	2.60	1.20	2.16	76.0	24.0
G2	5.20	1.10	4.72	92.5	7.5
G3	3.90	1.20	3.25	84.5	15.5
G4	4.80	2.50	1.92	73.0	27.0
G5	2.40	0.65	3.69	76.5	13.5
G6	3.90	1.20	3.25	84.5	15.5
G7	4.10	1.05	3.90	88.0	12.0
G8	3.70	1.05	3.52	86.0	14.0
G9	3.40	0.80	4.25	90.0	10.0
G10	2.80	1.80	1.55	69.0	31.0
G11	1.70	0.60	2.83	81.0	19.0
G12	4.65	1.11	4.22	90.0	10.0

TABLE — III

Composition of Limestones from Chincholi (Bhima Basin)

Sample No.	Intensity of 104 reflection of Calcite (I_c)	Intensity of 101 reflection of Quartz (I_q)	I_c / I_q	% of Calcite	% of Quartz
C_1	3.80	1.30	2.92	82.5	17.5
C_4	1.80	0.80	2.25	76.0	24.0
C_9	1.60	0.30	5.33	95.0	5.0
C_{14}	1.65	0.80	2.06	75.0	25.0
C_{13}	2.20	0.60	3.66	86.0	14.0
C_{17}	4.60	1.00	4.60	91.5	8.5
C_{23}	1.15	0.40	2.87	82.0	18.0
M_3	6.60	2.00	3.30	84.5	15.5
M_4	6.80	1.30	5.23	94.5	5.5
M_5	7.30	1.50	4.86	93.0	7.0
M_2	6.60	1.30	5.07	94.0	6.0
C_{91}	6.90	1.70	4.05	89.0	11.0

TABLE — IV

Grain-Sizes of Calcite and Quartz in Huzurnagar Samples

Sample No.	Thickness of the sample in cm.	Total Vol. irradiated x 10^{-3} cc.	Volume of the Mineral x 10^{-3}cc.		Total number of spots		Grain-size of the mineral x 10^{-3}cm.	
			Calcite	Quartz	104 of Calcite	101 of Quartz	Calcite	Quartz
H_5	0.021	0.6798	0.4061	0.2737	867	703	3.9	3.6
H_6	0.020	0.6474	0.4244	0.2230	835	684	4.0	3.5
H_{12}	0.029	0.9389	0.5683	0.3706	817	1095	4.5	3.5
H_8	0.017	0.5503	0.3830	0.1673	1221	392	3.4	3.8
M/4	0.017	0.5503	0.3771	0.1732	1281	219	3.3	4.7
H_{80}	0.017	0.5503	0.3886	0.1617	1200	424	3.5	3.1
H_{60}	0.020	0.6474	0.5094	0.1380	840	698	4.2	2.9
M/61	0.018	0.5828	0.2882	0.2946	763	1140	3.6	3.2
M/26	0.013	0.4208	0.2758	0.1450	629	265	3.8	4.1
M/62	0.018	0.5828	0.3993	0.1835	835	672	3.9	3.3
M/64	0.017	0.5503	0.4190	0.1313	634	504	4.4	3.2
M/28	0.017	0.5503	0.4049	0.1454	1126	281	3.6	4.1

TABLE — V

Grain-Sizes of Calcite and Quartz in Kurnool Samples

Sample No.	Thickness of the sample in cm.	Total Vol. irradiated x 10^{-4} cc.	Volume of the Mineral x 10^{-4}cc.		Total number of spots		Grain-size of the mineral x 10^{-3}cm.	
			Calcite	Quartz	104 of Calcite	101 of Quartz	Calcite	Quartz
G_1	0.012	0.3983	0.3113	0.0870	515	Continuous ring	1.6	Order of 10^{-4} cm· (diffraction rings are continuous)
G_3	0.015	0.4978	0.4196	0.0782	417	,,	1.9	
G_4	0.014	0.4646	0.3372	0.1274	695	Spotty and continuous	1.5	
G_5	0.014	0.4646	0.4007	0.0639	576	,,	1.7	
G_6	0.015	0.4978	0.4196	0.0782	491	,,	1.8	
G_7	0.016	0.5310	0.4665	0.0645	626	,,	1.7	
G_8	0.015	0.4978	0.4270	0.0708	717	,,	1.6	
G_9	0.015	0.4978	0.4472	0.0506	555	,,	1.9	
G_{10}	0 015	0.4978	0.3210	0.1768	1020	,,	1.3	
G_{11}	0.014	0.4646	0.3749	0.0897	575	,,	1.5	
G_2	0.016	0.5310	0.4903	0.0407	733	594	1.7	

TABLE — VI

Grain-Sizes of Calcite and Quartz in Chincholi Samples

Sample No.	Thickness of the sample in cm.	Total Vol. irradiated x 10^{-4}cc.	Vol. irradiated due to Calcite x 10^{-4}cc.	No. of Spots on 104 reflection of Calcite	Grain-size of Calcite x 10^{-3}cm.	Grain-size of Quartz
C_1	0.016	0.5310	0.4369	429	1.9	Order of 10^{-4}cm.
C_4	0.010	0.3319	0.2510	675	1.4	(diffraction rings
C_9	0.011	0.3656	0.3469	508	1.8	are continuous)
C_{14}	0.016	0.5310	0.3768	604	1.6	
C_{13}	0.018	0.5974	0.5121	650	1.8	
C_{17}	0.018	0.5974	0.5455	815	1.7	
C_{23}	0.016	0.5310	0.4336	237	2.4	
M_3	0.015	0.4978	0.4191	668	1.6	
M_4	0 017	0.5641	0.5324	923	1.6	
M_5	0.016	0.5310	0.4930	763	1.7	
M_2	0.014	0.4646	0.4361	903	1.5	
C_{91}	0 011	0.3656	0.3245	510	1.7	

PHYSICAL PROPERTIES OF LIMESTONES

BY

DR. G. SHANKAR NARAYANA

PHYSICAL properties of rocks and their influence on geological features have been studied by many eminent workers throughout the world. Such studies in various rock types are very useful for the workers engaged in the different branches of Geology and Geophysics, because the interpretation of the Geophysical field data will become fruitful, only when they are correlated with the physical properties and behaviour of rocks at various stages. Such integrated study is bound to open out new fields and reveal some interesting results.

To establish the relation between different parameters and also to study the variations within the different formations of the same rock type, limestones have been chosen as ideal because of their uniformity in composition and their meagre mineral constituents. Limestones are present in most of the Geological formations of India. They range in age from the Pre-cambrian crystalline limestones to the Kankars and coral reefs under active formation today. But the largest deposits are to be found in Purana and Vindhyan formations. In the present investigation the physical properties of 250 limestone samples collected from the following regions of Purana group, which were deposited on the peninsular shield were studied.

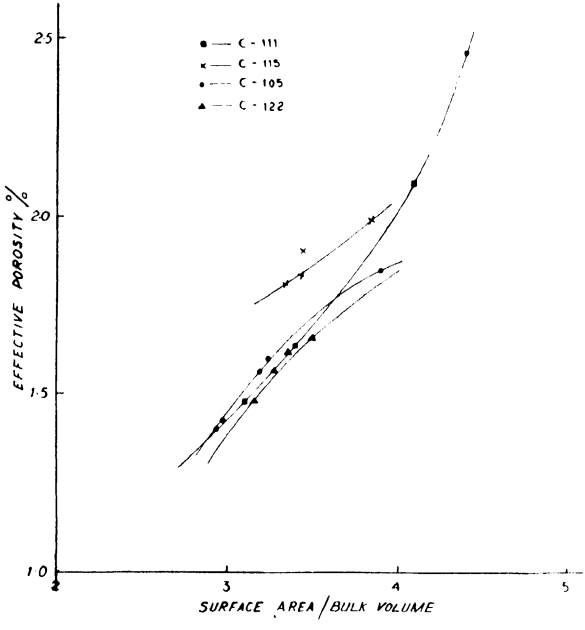
i. The North-Eastern part of the Palnad Basin (Huzurnagar area)

ii. The Middle Bhima series. (Chincholi area)

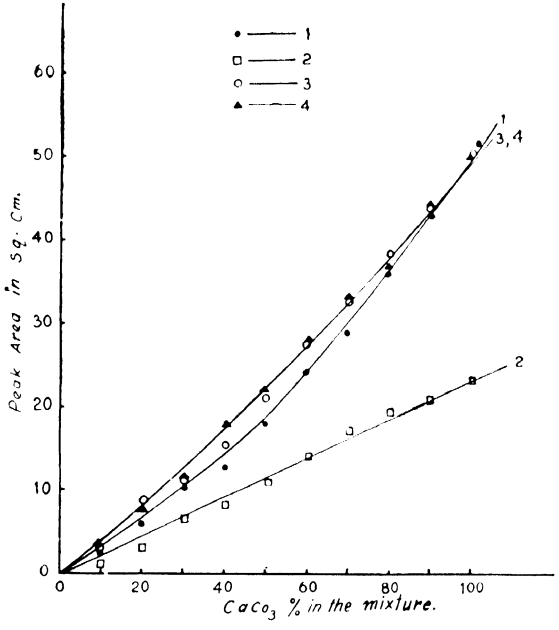
iii. Pakhal formations. (Near Khammammeth)

iv. Upper Cuddapahs. (Anantpur District)

Porosity, which is a function of granular structure, is one of the most basic properties of practical interest in sedimentary


C - 111
C - 115
C - 105
C - 122
EFFECTIVE POROSITY %
25
20
1.5
1.0
3
4
5
SURFACE AREA / BULK VOLUME

Graph (1)



Calibration Curves

Graph (2)

rock and influence the other properties like density, elastic constants, grain size. The mineralogical composition or chemical composition of the rock also has great importance in comparing the results obtained in the same rock type of different regions.

A modified form of Tickell's mercury porosimeter has been specially devised to measure effective porosity in rocks. This method, described by author in an earlier paper (1960), requires the specimens of definite geometric dimensions and the results are repeatable. The gas expansion technique to evolve the effective grain volume and the pore volume from it is the main principle of this method. This method is more advantageous for sedimentary rocks and vesicular traps, as this overcomes the disadvantage of the saturation method where in loosely held grains may be washed off due to boiling in water. In the sedimentary rocks two distinct general types of pore space (original and induced) are recognised, but limestones are characterised by the secondary or induced porosity. The effective porosity is of great practical interest because the significant difference in the values are noticed in the samples of the same rock formation.

In order to study the variation of effective porosity with the shape, size and surface area, cubical and rectangular parallelopipeds of number of limestones were prepared. The results in the table (I) show that the effective porosity decreases with the corresponding increase in the surface area and bulk volume.

The effective porosity values obtained by this method are in close agreement with the values obtained by other experimental and theoretical methods. Slitcher (1899), and Fraser and Graton (1935) have computed the various packing arrangements and they have shown that porosity of cubical packing is more than that of rhombohedral packing. From the above results also it can be seen that the maximum porosity values are obtained for the specimens having cubic dimensions.

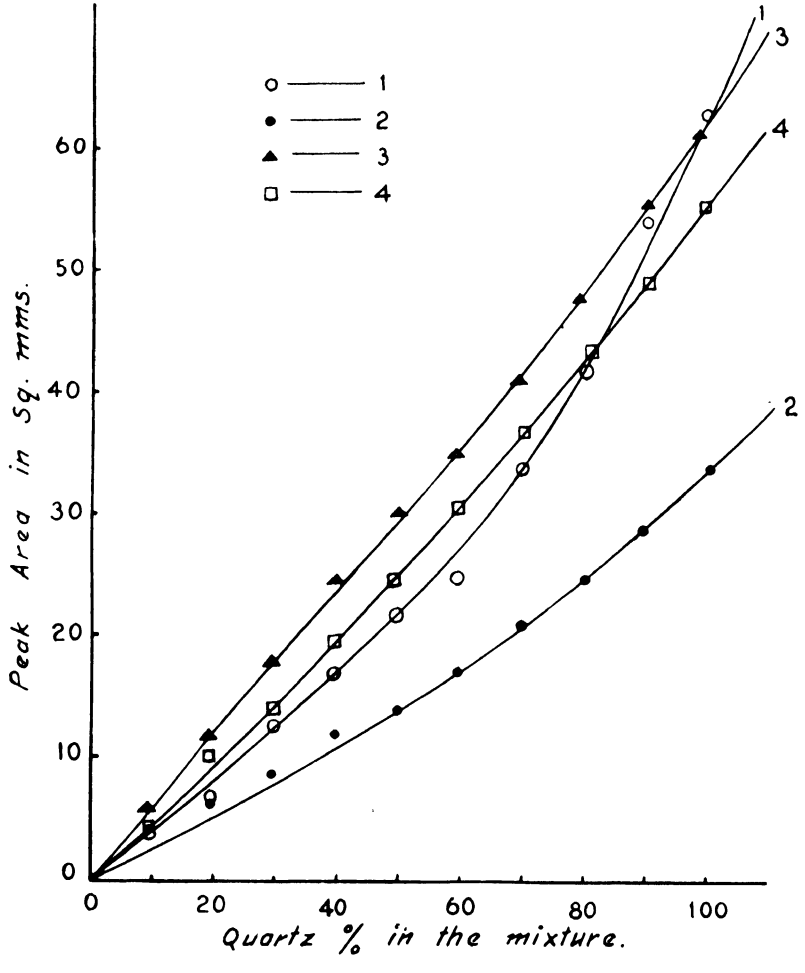
The ratio of surface area to Bulk volume versus the effective porosity are plotted in graph (I), the curve shows that the

effective porosity increases with the increase in the ratio of S. A./B. V. It can be concluded that surface area and Bulk volume are the important factors which influence the effective porosity.

Geologist is interested in knowing the structure of the Earth and a knowledge of elastic constants aid the Geologist in correlation and interpretation of the seismic field data. In order to evaluate the elastic constants, ultrasonic velocities in limestones are determined by using the wedge method developed by Bhagavantam and Bhimsenachar (1944) and also by the pulse rotation reflection technique devised by Ramana in this department. Elastic constants are calculated with a view to probe into their elastic properties with special reference to their scatter and an attempt is made to correlate the elastic constants with other physical properties. Some of these results are published in an earlier paper (1961). The ultrasonic velocities increase with the increase of density and decrease with the increase of porosity. Longitudinal velocity in all these limestones ranges from 5.2—7.2 Km./sec. torsional velocity ranges from 2.1—3.2 Km./sec. as shown in the table (II). As the same range is observed in other rock types it is not possible to decide the rock type by knowing the velocity.

The estimation of $CaCO_3$ content is another important field in which limestones are investigated. This is found to be an important factor which affects the physical properties. An estimation of this important constituent involves tedious processes. Differential thermal analysis apparatus (Delta therm) has been used to estimate the $CaCO_3$, $MgCO_3$ and quartz, the major constituents of limestones. This method is suitable for both qualitative and semiquantitative studies of the clay minerals. These studies are based on the measurement of heat evolved or absorbed when a material undergoes physical or chemical changes on being heated or cooled. Differential thermal results are plotted in the form of a continuous curve in which the thermal reactions are plotted against furnace temperatures, with endothermic reactions conventionally shown as downward deflections and exothermic reactions as upward deflections from a horizontal base line.

The D. T. A. apparatus made in Colorado, U. S. A., was used which has been designed to record four differential thermal curves of four unknown samples simultaneously with auto-



Calibration Curves

Graph (3)

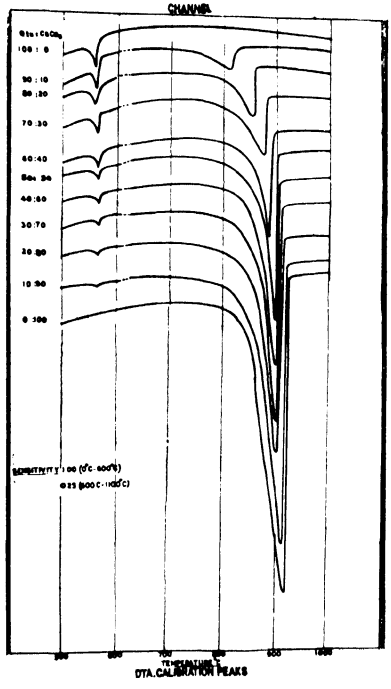


Figure (1)

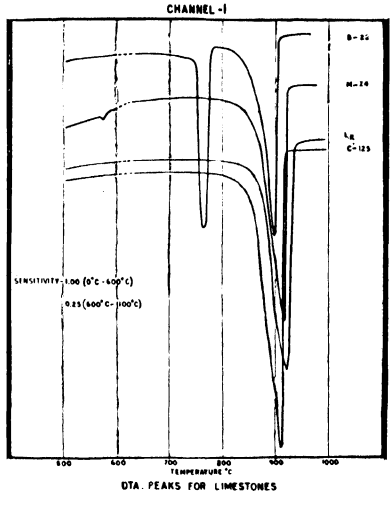


Figure (2)

matic programming of the run. The thermocouples used are chromel-Alumel type and inert material is calcined alumina, the rate of heating 10°C per minute is maintained throughout these investigations. Thermocouples are calibrated as advocated by Faust, utilising the property of the reversible α–β inversion of quartz at 573°C and also the endothermic peak at 580°C due to dehydration of kaolinite of Dry branch, Georgia. Thermograms of standard samples of calcite, dolomite, quartz and kaolinite are shown in fig. I. Calcite is characterised by the endothermic peak at (790°C—925°C), corresponding to the decomposition of carbonate ions associated with calcium.

To determine the $CaCO_3$ percentage in limestones, the instrument is calibrated by taking mixtures of $CaCO_3$ and quartz of known proportions. Each time the total quantity taken is maintained as 0.45 gms. and proportions varied from 0 to 100% of $CaCO_3$. The area inscribed by the peak and the tangents drawn at the end point and the starting point of the peak are measured accurately by using planimeter. In this investigation, the area of the peak in preference to its height is considered more desirable in the calculation of percentage of the particular component. The peaks obtained in all the runs by channel–I made with various proportions of $CaCO_3$ and quartz are shown in Fig. II and the peak areas with the proportions of the mixtures are given in table III.

Four linear curves are obtained (graph II) by taking percentage of $CaCO_3$ on the abscissa and the corresponding peak area of $CaCO_3$ in sq. cms. on ordinate. It is very interesting to note that all these curves are showing the same trend. Similarly the calibration is drawn for quartz which are shown in graph III.

Number of limestones, dolomites and shales have been subjected to differential thermal analysis and by measuring the peak areas, $CaCO_3$ and quartz percentages are computed from calibration curves, some of these thermograms are shown in the Fig. (III) and percentages are shown in Table IV. To test the accuracy of this method the same samples are analysed by Collin's calcimeter and X-ray methods.

$CaCO_3$ percentage in all these limestones ranges from 55%– 95%; in Chincholi limestones the Calcium content is

high. Dolomites have maximum of 35% $CaCO_3$. In all the limestones the Poisson's ratio is found to be 0.39–0.41. It is found that ultrasonic velocities are high in the limestones having high calcium content.

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TABLE — I

Effective Porosity of Chincholi Limestones

S. No.	Specimen Number	Bulk Volume c.cm. V_B	Surface Area sq. cm. S. A.	Surface Area / Bulk Volume S. A./V_B	Porosity % f
1.	C-101				
	i	7.20	28.40	3.95	1.70
	ii	4.84	19.25	3.98	1.83
	iii	3.50	15.40	4.40	2.10
2.	C-103				
	i	7.43	31.82	4.28	2.26
	ii	4.43	18.71	4.25	2.23
	iii	3.54	16.20	4.58	2.62
3.	C-105				
	i	15.76	50.40	3.20	1.56
	ii	11.95	38.65	3.23	1.62
	iii	11.18	32 85	2.94	1.40
	iv	9.92	29.59	2.98	1.42
4.	C-106				
	i	5.21	18.52	3.56	1.67
	ii	10.50	32.82	3.13	1.61
	iii	7.95	38.10	4.79	2.50
	iv	3.59	14.60	4.07	2.04
5.	C-108				
	i	5.62	25.52	4.54	2.57
	ii	4.66	21.27	4.56	2.68
	iii	2.57	13.12	5.10	2.97
6.	C-111				
	i	10.30	31.60	3.10	1.48
	ii	9.49	32.26	3.40	1.63
	iii	4.36	17.83	4.10	2.09
	iv	3.62	15.77	4.40	2.47
7.	C-113				
	i	10.47	36.10	3.43	1.86
	ii	9.40	31.40	3.34	1.82
	iii	6.96	23.85	3.43	1.92
	iv	4.70	18.00	3.84	1.99

TABLE — II

Elastic Constants of Chincholi Limestones

S. No.	Specimen Number	Density g./cm^3	I_t in degrees	I_l	V_t km./sec.	V_l km./sec.	Y*	n*	K*	σ
1.	C-103	2.71	43-3	12-39	2.198	6.850	3.92	1.36	10.91	0.441
2.	C-108	2.68	41-45	13-41	2.253	6.342	3.89	1.36	8.96	0.428
3.	C-110	2.71	40-38	13-20	2.303	6.651	4.16	1.44	10.07	0.451
4.	C-111	2.70	39-45	13-10	2.346	6.586	4.25	1.49	9.74	0.427
5.	C-114	2.71	41-1	12-42	2.287	6.823	4.07	1.42	10.71	0.436
6.	C-115	2.73	41-31	13-4	2.263	6.636	5.01	1.40	10.14	0.434
7.	C-124	2.70	41-45	13-18	2.253	6.521	3.83	1.37	9.65	0.397
8.	C-125	2.70	41-36	12-9	2.259	7.129	3.98	1.38	11.89	0.445
9.	C-126	2.61	40-54	13-36	2.291	6.380	3.91	1.37	8.81	0.427
10.	C-127	2.70	40-40	12-59	2.302	6.676	4.09	1.43	10.13	0.431
11.	C-118	2.72	40-30	13-2	2.310	6.651	4.15	1.45	10.07	0.431
12.	C-123	2.72	40-30	13-3	2.310	6.653	4.15	1.46	10.08	0.431
13.	C-113	2.69	40-42	13-5	2.300	6.628	4.06	1.42	9.92	0.430

TABLE — III

Peak Areas of $CaCO_3$ and Quartz

S. No.	$CaCO_3$ Qtz in the Mixture	Total Weight in grams	Peak Area 1st Channel		Peak Area 2nd Channel		Peak Area 3rd Channel		Peak Area 4th Channel	
			$CaCO_3$ in sq. cms.	Quartz in sq. mm.	$CaCO_3$ in sq. cms.	Quartz in sq. mm.	$CaCO_3$ in sq. cms.	Quartz in sq. mm.	$CaCO_3$ in sq. cms.	Quartz in sq. mm.
1.	100. 0	0.45	50.60	—	23.50	—	50.00	—	50.00	—
2.	90. 10	0.45	43.00	6	21.00	4	44.00	6	44.00	5
3.	80. 20	0.45	35.50	10	19.50	7	38.50	12	37.00	9
4.	70. 30	0.45	27.80	13	17.50	9	33.00	19	33.00	14
5.	60. 40	0.45	24.00	17	14.00	12	27.50	25	26.50	20
6.	50. 50	0.45	18.00	21	11.50	14	21.00	31	22.00	25
7.	40. 60	0.45	12.50	25	8.00	17	15.50	35	18.00	31
8.	30. 70	0.45	10.00	33	6.50	21	11.50	41	11.50	37
9.	20. 80	0.45	6.00	42	3.20	25	9.00	48	8.00	44
10.	10. 90	0.45	2.80	54	1.10	29	3.50	56	4.50	50
11.	0.100	0.45	—	63	—	34	—	63	—	56

TABLE — IV

Differential Thermal Analysis Results of Limestones

Channel 1.

S. No.	Specimen Number	Peak Area			Calcite Peak Temp. °C.			Qtz. Peak Temp. °C.	Dolomite Peak Temp. °C.			Percentage		
		$CaCO_3$ Sq. cm.	Quartz Sq.mm.	$MgCO_3$ Sq. cm.	Start	Maximum	End		Start	Maximum	End	Calcite.	Qtz.	$MgCO_3$
1.	B–22	23.00	—	16.0	805	898	904	—	743	762	778	57.5	—	32.0
2.	M–24	37.00	6	—	798	917	920	572	—	—	—	81.0	15.0	—
3.	K	41.50	—	—	825	919	944	—	—	—	—	87.0	—	—
4.	C–125	45.00	—	—	800	910	918	—	—	—	—	93.0	—	—

N. B. Sample Weight is 0.45 gm.
Sensitivity 1.0 —(0 °C to 600 °C)
0.25—(600 °C to 1100 °C)

LABORATORY RESISTIVITY DETERMINATIONS OF SOME OF THE ROCK FORMATIONS OF VISAKHAPATNAM & WEST GODAVARY DISTRICTS OF ANDHRA PRADESH

BY

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(Department of Geophysics, Andhra University, Waltair).

Abstract

A method of determining electrical resistivities of thin slices of rock samples in the laboratory is described. Electrical resistivity values so obtained in the laboratory for some of the rock formations like Khondalites and charnockites, constituting the Eastern Ghat ranges in and around Visakhapatnam are reported for the first time.

Also laboratory electrical resistivity values of core samples of some of the sedimentary formations, like Tirupati sandstones, Gollapalli sandstones, Ferruginous shales etc., of West Godavary District are also reported. The method of measurement for these core samples is essentially similar to that adopted by Keller (1959).

Introduction

THE existence of subterranean contrasts in electrical conductivity is an essential prerequisite for a possible application of electrical methods of prospecting. It is the aim of the studies in electrical properties of the geological formations to obtain clear ideas of such electrical conductivity contrasts and determine the usefulness of electrical resistivity data obtained in the field.

The parameters that are obtained from an electrical probing in an area are the depths to various geological horizons and their corresponding resistivity values. To interpret these values intelligently in terms of the economic importance of the formations, a prior study of these formations regarding their electrical properties is essential.

It was, of course, well recognised that the resistivity of a geological formation in the field and that of a sample removed from the formation are not exactly the same. The reasons for such a discrepancy are several. It is rarely that we encounter a homogeneous formation. Further, no geological formation is an isolated entity as is the sample thereof. The samples undergo certain changes when they are taken out of the formation, the most important being the change in the moisture content. Though burdened with such limitations, laboratory determinations of resistivities of formation samples prove very valuable in a better interpretation of field resistivity data.

Laboratory Determination of Resistivities

Determination of resistivities of materials can be made quite accurately by some of the conventional methods. If the dimensions of a material cut into a regular geometrical shape and the resistance between two of its opposite faces are known, it is possible to derive the specific resistance or the resistivity of the material by making use of the formula,

$$\rho = R \times K \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where ρ is the specific resistance or the resistivity,

R is the resistance between the two opposite faces, and

K is a factor depending on the shape and dimensions of the material.

If the material is of a regular rectangular shape of length l, breadth b and thickness d and R the resistance between the two opposite faces, A and B in Fig. 1., then the resistivity of the material can be expressed by

$$\rho = R. \frac{b \cdot d}{l} = R. \frac{s}{l} \quad \ldots\ldots\ldots(2)$$

where, s is the area of cross section oft he face A or B. If R is expressed in ohms, b, d, and l in centimeters, then the resistivity is expressed in ohm centimeters.

Resistance Measurement :

It can be seen that the accuracy in determining the resistivity of any material depends on the accuracy of measurement of resistance and the various dimensions. Since measurements of dimensions can be made with sufficient accuracy, it follows that the accuracy of measuring the resistance controls the accuracy of a resistivity determination.

The measurement of resistance is most frequently carried out by employing some form of Wheatstone bridge circuit, wherein two branches, the ratio arms, of the bridge are formed by two fixed resistances, the other two arms being formed by the unknown resistance and a standard resistance box permitting variation of known resistances.

Depending on the technique of measurement, resistivity determinations of earth formations can be broadly divided into two categories ; one applicable for the unconsolidated formations like gravels, sands, clays and soils and the other for the consolidated formations, or rocks. The present paper concerns the measurement of resistivities of consolidated formations.

Limitations in the Determination of Resistivities of Consolidated Formations

Several practical difficulties confront us in making resistivity measurements on consolidated formations. The purpose of such determinations is to obtain representative values of resistivities of formations as exist in the field as also to obtain clear ideas concerning electrical conductivity contrasts in the field. It is thus clear that laboratory determinations should be carried out under conditions as similar as possible to the field conditions even though complete simulation is difficult to attain. An account of the difficulties encountered and the attempts to overcome them are described below:

Irregular nature of the field specimens:

It was shown that resistivity determinations can be made easily on regular geometric shaped bodies. Hence, the field sample is cut into a regular geometric shape on which measurements can be made conveniently and the resistivity determined from its dimensions.

During the process of cutting and grinding it was observed that the natural waters present are either replaced or changed by addition of some salts or fluids. It is also likely that some of the pore spaces are filled by the rock particles. To bring the cut specimen to its field conditions, it is necessary that the specimen be kept for sometime in waters, if available, obtained from the same locality as the specimen.

High contact resistance :

Another serious difficulty in making resistivity measurements on rock specimens is the very high contact resistance experienced at the electrodes. For elimination of contact resistances different types of electrodes are employed. Of particular interest are the wetted electrodes and foil electrodes.

A wetted electrode is obtained by the use of a blotting paper moistened with brine solution between the electrode and the surface of the rock specimen to obtain a better contact. A drawback in employing this technique is that, unless the two surfaces of contact are far removed from each other compared to the other dimensions, the brine in the blotter affects the original property of the rock with time.

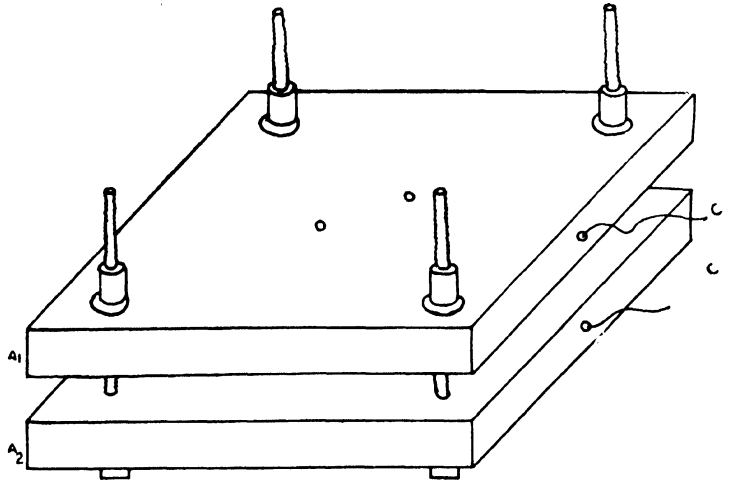
Foil electrodes are made by tightly pressing tin, silver, or gold foil on the surface of contact, so that it sticks closely to the grain structure of the specimen surface. Though the method is found fairly satisfactory, it is difficult to assess the closeness to the grain structure.

Another method of eliminating the high contact resistances is to silver-paint the surface. The silver-painting is found to bring in electrochemical effects.

Present Experimental Studies on Rock Resistivities

The present method employed is to cut the rock specimen into a regular geometric shape keeping the thickness small and uniform compared to the other dimensions to make the surface area large in order to obtain greater current penetration.

A thin, but thorough coating of pencil graphite, is given on to the two surfaces to provide a good contact. To improve



A_1 UPPER ELECTRODE.

A_2 LOWER ELECTRODE.

B BRASS PROJECTION FIXED TO EBONITE BLOCK.

C ELECTRIC LEADS CONNECTING TO BRASS PLATES.

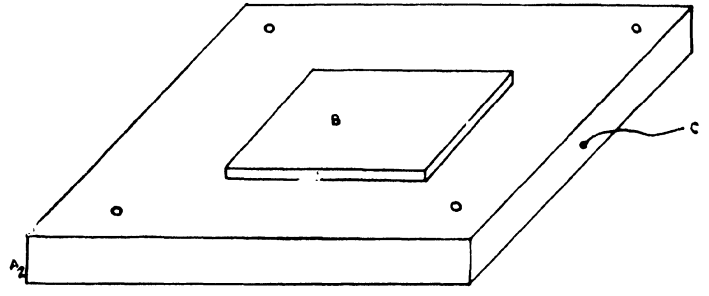


FIG. 1. ROCK SPECIMEN HOLDER

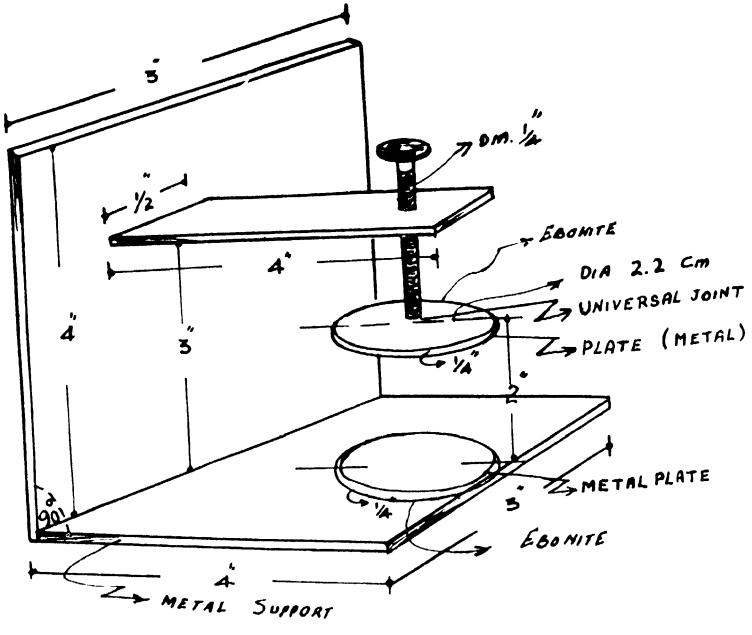


FIG 2. ROCK CORE SAMPLE HOLDER

the contact, tin foil is pressed over these surfaces. Comparable resistivity values are obtained for specimens of different dimensions obtained from a single field sample.

Rock specimen holder :

A rock specimen holder (fig. 1) has been designed for making measurements of resistance of rock sample slices. The electrodes of the specimen holder are made of brass. These two brass electrodes are fixed into the ebonite blocks, which are in their turn connected by screws to vary the distance between the two electrodes to suit the thickness of the specimens. One of the brass electrodes is made small in size to eliminate any possible capacitance effects in between the two brass electrodes.

A Philips conductivity bridge (type GM 4249 01) has been used for measuring the resistance. The instrument, in principle, is a Wheatstone bridge fed by a 50 cycle or a 1000 cycle voltage supplied by a transformer or a built-in 1000 cycle oscillator respectively. So long as the bridge is unbalanced a voltage is applied to the grid of an amplifying valve followed by a cathode ray indicator.

After fixing the specimen in the holder the resistance R in ohms is measured. The thickness t of the specimen slice, the length l and breadth b are measured accurately. The resistivity of the specimen ρ is calculated by the equation.

$$\rho = R \frac{l \cdot b}{t} \quad \ldots\ldots\ldots(3)$$

A few samples, typical country rocks around Visakhapatnam constituting the Eastern Ghat ranges are studied and tested for their resistivity values.

Results and Discussion

Visakhapatnam area:

The Visakhapatnam area is traversed by the hill ranges of Eastern Ghats of India. The rocks constituting the region belong to the Archaen group consisting of highly metamorphosed sediments known as the Khondalite series into which

hypersthene bearing rocks of charnockite series intrude. Sometimes leptynites are found near the contact of the two types.

The results of laboratory resistivity determinations on some of these rock formations are summarised in Table I. The number suffixes indicate changes in areas from which the specimens are collected while A_1, A_2, etc., indicate the series of samples cut from the rock designated A from the particular area. If there are more than one rock from the same area they are designated as R_1 A, R_1 B etc.

It can be seen from the results that while the Khondalites are least resistive with a resistivity range of 4.4×10^5 to 8.2×10^5 ohm-cms., the Charnockites and Quartzites are highly resistive with resistivity values ranging from 6.4×10^6 to 1.1×10^7 ohm-cms. The leptynites have intermediate resistivities with a range of 1.4×10^6 to 6.4×10^6 ohms-cms.

These ranges of resistivities are in conformity with the nature of types of rocks studied. While the Khondalities are meta-sedimentary rocks, the charnockites and Quartzites are intrusive and igneous in nature. The leptynites represent an intermediate series. The Khondalites are comparatively porous as they contain numerous foliation and joint planes. It may also be considered that in applying these relative values for prospecting for water in the area the Khondalitic areas have to be selected in preference to a charnockitic area or a leptynitic area. The results also show that electrical prospecting can be employed with success for demarcating the boundaries of these horizons, if covered.

West Godavari District:

About twenty core samples from the Gondwana formations in West Godavari District collected and kindly supplied by my colleague Mr. P. Sitapati Rao, were also tested for their resistivity values in the laboratory. These samples were mainly collected in connection with a magnetometric survey conducted by Mr. Rao in the area.

Sedimentary formations of Upper Gondwanas are found in East and West Godavari Districts (Krishnan, 1960). They mainly comprise three divisions, viz., the Gollapalli Sandstones,

Raghavapuram Shales and Tirupati Sandstones. Representative samples of these three formations from West Godavari District have been used in the present laboratory investigations.

The technique of measurement for core samples is slightly different from that employed for rock slices. A rock-core-sample holder (fig.2) has been designed, more or less similar to the one described by Keller (1959). The main alteration effected is that the two electrodes have been insulated from the rest of the core sample holder, thus eliminating any possible leakages or extraneous effects.

All the core samples were kept in flowing tap water for over a week under similar conditions before measurements were made. Resistance measurements were made with the Philips conductivity bridge. Table II shows the resistivity values for the samples.

Samples having the same number with a subscript denote that the core specimens are obtained from the same sample. The Raghavapuram shales register low resistivity values ranging from 1000 ohm-cms. to 2700 ohm-cms. The Raghavapuram shale samples are buff coloured with white patches.

The Gollapalli sandstones are dark brown in colour and are arenaceous. The samples are more less like grits with maximum amount of porosity. The electrical measurements had to be made rather quickly on these samples since water was flowing out of the sample due to the presence of large pores. That is perhaps the reason for the discrepancy observed in values for specimens obtained from a single sample. The resistivity ranges from about 3000 ohm-cms. to 7000 ohm-cms.

The Tirupati sandstones are hard and fine grained. They are red in colour. The resistivity values are rather high ranging from 7000 ohm-cms. to 14,000 ohm-cms. While the ranges obtained for the formations are wide, it may be observed that the formations could be discriminated. Since the measurements were made under uniform conditions for the limited samples it appears that resistivity contrasts may exist between the different formations.

Conclusions

Laboratory resistivity determination of samples would be useful in determining electrical resistivity contrasts, though they do not represent the field values. Resistivity determinations on a limited number of rock samples belonging to the archaen in Visakhapatnam region and Upper Gondwanas in West Godavary District are reported for the first time. Broadly the results indicate resistivity contrasts between Khondalites and Charnockites in Visakapatnam area and between the Raghavapuram shales, Gollapalli sandstones and Tirupati sandstones.

Acknowledgements

The author is grateful to Prof. M. S. Krishnan and late Prof. C. Mahadevan for their keen interest; to Dr. V. Bhaskara Rao for his assistance and discussion and to Mr. P. Sitapathi Rao for lending the core samples collected from West Godavary District for resistivity determinations.

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TABLE - 1

Resistivities of rock specimens around Visakhapatnam.

Sl. No.	Name of the rock type.	Sample No.	Resistivity in ohm/cms.
I.	Kondalites.	R_1	5.6×10^5
		R_2	4.4×10^5
		R_3	8.2×10^5
		$R_4 A_1$	6.2×10^5
		$R_4 A_2$	6.4×10^5
II.	Leptynites	$R_5 A_1$	3.8×10^6
		$R_5 A_2$	3.5×10^6
		$R_5 A_3$	4.2×10^6
		$R_5 B$	2.2×10^6
		$R_6 A_1$	1.4×10^6
		$R_6 A_2$	1.4×10^6
		$R_6 B$	6.4×10^6
III.	Charnockites	$R_7 A_1$	8.1×10^6
		$R_7 A_2$	6.4×10^6
IV.	Quartzite	R_8	1.1×10^7

TABLE - II

Sl. No.	Name of the rock type	Sample No.	Resistivity in ohm/cms.
I	Raghavapuram Shales.	1A	1960
		1B	1923
		2A	1822
		2B	1870
		3	1892
		4	1035
		5	2698
II	Gollapalli Sandstones.	6A	3213
		6B	3188
		7	4057
		8A	4698
		8B	4807
		9	3596
		10A	5189
		10B	5322
		11	5788
		12	6782
III	Tirupati Sandstones.	13	11180
		14A	13970
		14B	13240
		15A	7626
		15B	7679

NOTES ON THE TECTONICS OF SOUTHERN ASIA

BY

DR. M. S. KRISHNAN

THE region between the Siberian Platform (Angara Shield) in the north and the Indian Shield in the south is streaked with several major mountain chains of various ages, from Pre-Cambrian to the Kainozoic. The Angara geosyncline to the south of Angara Shield extends from the southern end of the Urals through East Kazakhstan, Altai, Western Sayan to Transbaikal and Yablonovy ranges. The effects of the caledonian orogeny is fairly well seen in several places e. g., in E. Kazakhstan, Karatau, Kuznetsk Alatau, Gorny Altai etc., but the whole of the geosyncline exhibits the effects of strong Hercynian orogeny which raised it up into mountain ranges. Though the Ural and Angara geosynclines have much in common and were folded up at about the same time, they are different in stratigraphy. The Mid-Carboniferous to lower Triassic orogeny (Hercynian) is well seen in Eastern Kazakhstan, the Altai, Kuznetsk basin etc. and is accompanied by granitic intrusions and some effusives. Several of these ranges were also affected in the Caledonian but the Hercynian phases were far more intense. In this zone, major block movements occurred in the late Kainozoic in the Altai and Sayan ranges on either side of Lake Baikal, so that it is now characterised by high seismicity (Nalivkin, 1960).

In Western China and Tibet there are numerous ranges, several of which appear to be gathered up in the Pamir Plateau. From north to south we have the Tarbagatai, Ala-Tau, Dzungaria, Tien shan, Kun Lun-Altyn Tagh-Nanshan, Arka Tagh, Karakorum-Thangla. The Tsai-dam depression lies between Nanshan and Thangla mountains. Between the last range and the Kailas Range (the northernmost of the Himalayan system) is the Trans-Himalaya in Tibet. To the west of the meridian of the Pamir Plateau in Soviet Central Asia are the Ala-Tau, Kyzyl-Kum, Alai, Ferghana ranges, Trans-Alai, Kara Tau and Elburz-Hindu Kush, the last being more or less continuous with the Karakorum. Nalivkin (1960) divides the Soviet Central Asian ranges into three groups: the northern ranges (Karatau, Talas-Alatau) separated from the

middle ranges by the valley of the Syr Darya; the middle ranges (Alai and Turkestan Mountains) separated by the Zaravshan and Alai valleys from the southern ranges which include Trans–Alai.

The *northern ranges* in Central Asia are mainly of Caledonian and earlier ages. Though affected by the Hercynian, the disturbances are only moderate, while those of the Cimmerian movements are quite feeble. In the *middle zone* the main folding is Hercynian, accompanied by granite intrusions, while the Cimmerian is also strong, as in the Ferghana Ranges; but the Himalayan movements are weak. In the *southern zone* the Cimmerian and Himalayan movements are strong and Cimmerian granites are found in several places including the Pamir ranges. It may be noted that the Himalayan disturbances commenced here in the Miocene and continued up to the recent.

In the Chinese and Tibetan Central Asia, the Tien Shan range experienced the most intense movements in the Hercynian but they exhibit also strong Caledonian elements. The later orogenies were not felt strongly in this region.

The next major range to the south is the Kun-Lun with its continuation in the Altyn–Tagh. It is of Hercynian and Cimmerian ages. The granites intrusive into the cores of the mountains are mainly of the Hercynian age. There are indications that earth's crust in this region is exceptionally thick, judging from the very large Bouguer gravity anomalies recorded, ranging between –350 to –500 mgal, the maximum being –560 mgals (Norin and Ambolt, 1950).

Between the Altyn Tagh – Nan Shan ranges on the north and the Thangla range on the south is the Tsaidam depression, which is said to represent a stable block entirely unaffected by compression since the Palaeozoic. The Thangla Range continues westwards into the Karakorum, Hindukush and Elburz mountains, a branch joining with the Karakum ranges east of the Caspian Sea. De Terra states that the Karakorum was folded during the Hercynian but there is reason to suppose that Cimmerian movements were equally powerful and Himalayan movements less intense. Knowledge of the Kun–Lun and Karakorum is still rather scanty. The Karakorum–Thangla range runs through Tibet and bends round to the

south beyond the north-east corner of Assam, being moulded round the Assam wedge which has affected the Himalayan and other ranges in the same way as the Kashmir wedge in the north-west area. In this region there are a series of parallel ridges which run north-west on the Tibetan side and south west on the China side and turn sharply round to the south and south-west along the Indo Burma border. The valleys between the ridges are occupied by the Yang-Tse and its tributaries, and the Mekong, Salween, Chindwin and Irrawaddy. These rivers flow for some 200 miles along narrow parallel defiles and then diverge over wide angles so that the Yang-Tse enters the Pacific south of Japan, the Mekong joins the South China Sea and the Salween and Irrawaddy go to the Bay of Bengal. The trends of the mountain chains here reflect the structure.

At the western extremity of the Himalayas also a similar phenomenon is seen in the effect of the Kashmir wedge. As a result the Hindukush-Karakorum mountains have been deflected northwards towards the Pamir while the Himalayan ranges and their western continuation exhibit V-shaped flexures pointing N. N. W. to N. W. The western limbs here comprise the Hazara mountains, Safed Koh, Kala Chitta and the ridges of the Baluchistan Arc.

The last range in Tibet next to the Himalayan system is the Trans-Himalaya which forms the real watershed separating the Central Asian drainage from that flowing south into the Indian Ocean. It appears to have been subjected mainly to the Cimmerian movements but may contain evidences of Hercynian and even Caledonian movements. Mesozoic granites have been intruded into them and they have provided the large quantities of pebbles and coarse clastics of which the thick Eocene conglomerates of Mt. Kailas are composed.

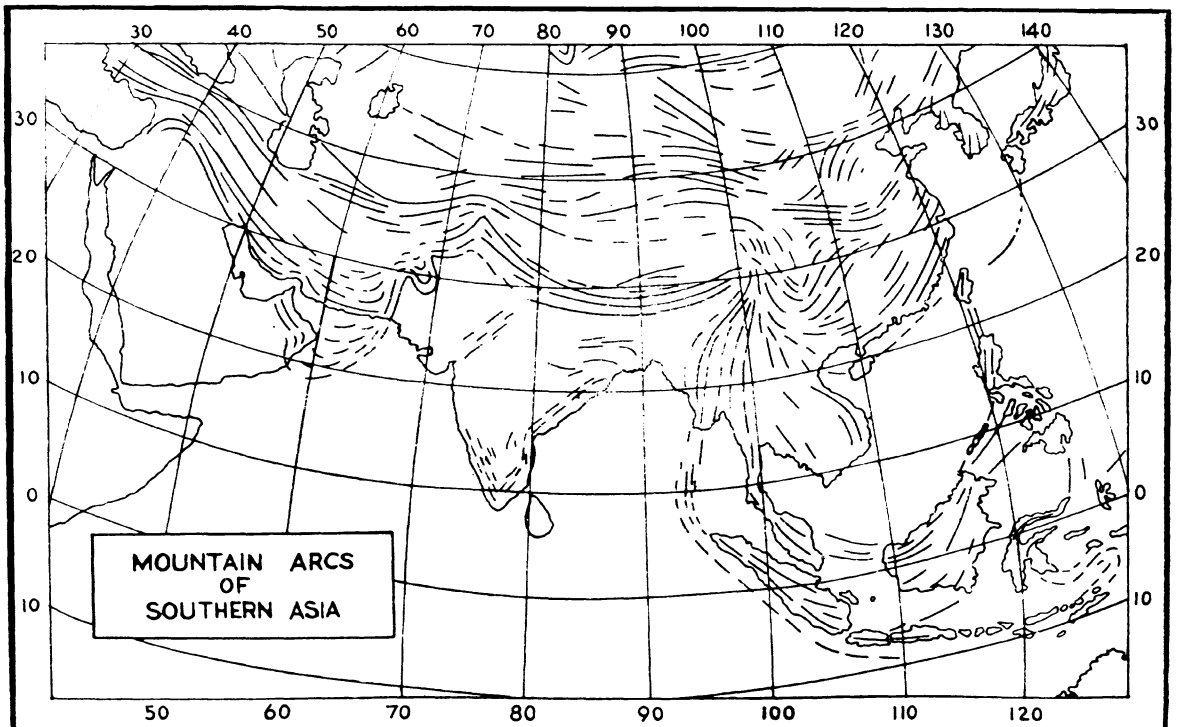
The Himalayan mountain system comprises (from north to south) the Ladakh, Zanskar, Main Himalaya, Lesser Himalaya and the foot-hills. These have all been formed during the Himalayan orogeny which began in the Upper Cretaceous and died down in Sub-Recent times. The activity is still felt as evidenced by the numerous earthquakes occurring in all parts of the Himalayan ranges. The thrusting in these mountains is practically all towards the south, as in the case of the other moutain arcs of Southern Asia. The enormous compression

to which the Tethyan basin was subjected in the area now occupied by the Himalayas, can be realised from the fact that the main range rises to a height of 7000 to 8700 metres with a number of peaks taller then 8000 metres. This would provide an indirect indication of the strength of the crust and the plasticity of the Upper Mantle.

The compression in the Himalayan area is so intense that the most of the folds are recumbent or broken up to form thrust-sheets, of which several are present. India has been pushed deep into the Asiatic continent so that Central Asia has been raised to an unprecedented altitude (average over 12,000 feet in Tibet) behind the numerous ridges of the Himalayas. The deposits of the original Tethys basin to the east and west of India extending far to the south to Mekran and Indonesia at either end, have been pushed back over many hundreds of miles and the strata raised to a maximum height of 29,000 ft. in the Central Himalayan range. There are also a series of parallel zones (parallel to the Himalayas) of negative and positive gravity anomalies, which have resulted from the compression of the crust in the Himalayan region.

The postulated Kashmir wedge of the Indian Peninsula presumably extends towards the Pamir region, as evidenced by the northward flexure of the mountain ranges. The zone of intermediate earthquake shocks in the Pamir region (about lat. 37° N: long. 70° E) should also be attributed to the direct or indirect effect of this wedge. A similar condition obtains near Quetta in Baluchistan where a wedge of smaller dimensions is inferred to be present from the gathering of strata at the surface into a festoon. Here, however, the earthquakes originate from the 'shallow' zone. Though data are not readily available about the areas in front of the Assam wedge, the Sikang-Szechuan region of South-West China is known to be highly seismic and may be similar to the Pamir region in structure.

The Asian continent's eastern margin is bordered by a series of Island Arcs from Kamchatka to the Philippines and Celebes. On its south-east are the Banda and Sunda Arcs (East Indian Archipelago), the former of which has been distorted by Australia and New Guinea. On the south, the Asian continent is opposed by two shield areas, the Indian and Arabian, and any Island Arc structure originally present,


30 40 50 60 70 80 90 100 110 120 130 140
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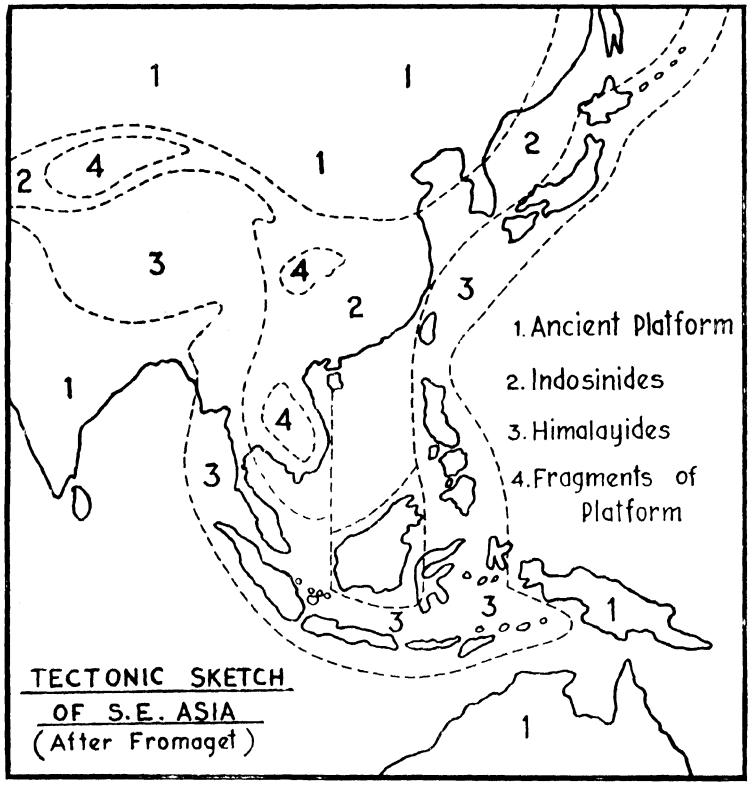
MOUNTAIN ARCS
OF
SOUTHERN ASIA
50 60 70 80 90 100 110 120

Figure (1)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1. Ancient Platform
2. Indosinides
3. Himalayides
4. Fragments of Platform
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TECTONIC SKETCH
OF S.E. ASIA
(After Fromaget)

Figure (2)

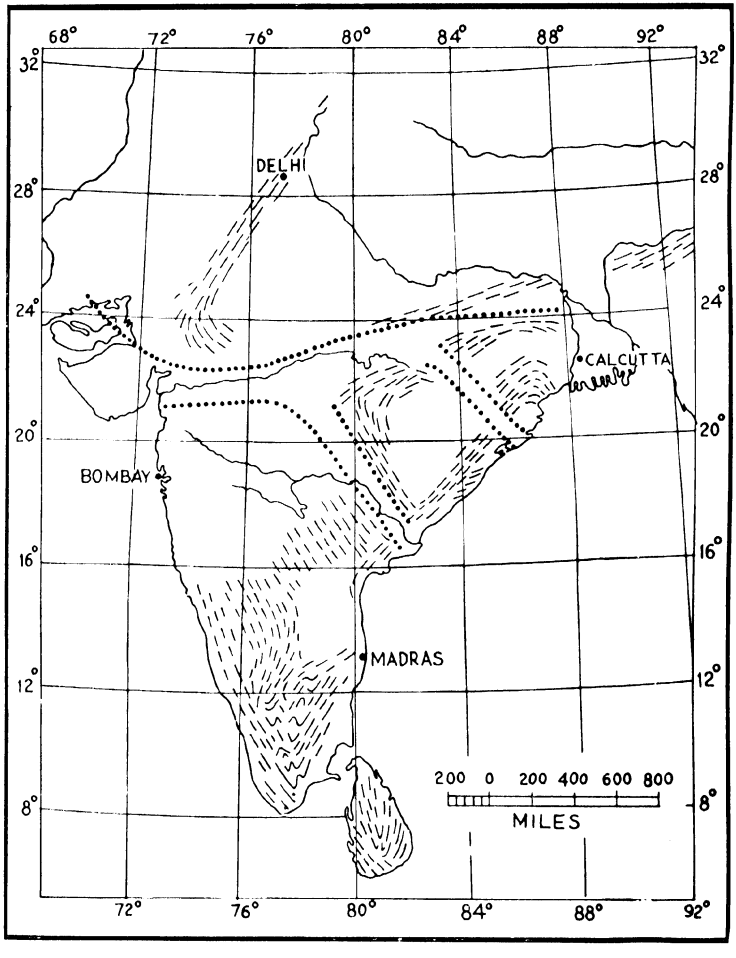
68°
72°
76°
80°
84°
88°
92°
32°
28°
24°
20°
16°
12°
8°
DELHI
CALCUTTA
BOMBAY
MADRAS
200 0 200 400 600 800
MILES

Figure (3)

before India and Arabia moved to their present positions, has been obliterated. Cretaceous and early Kainozoic lavas present in the Himalayan, Baluchistan, and Zagros Arcs may represent remnants of the volcanic materials. The front of the Mekran Arc has been faulted down into the Arabian Sea but its continuation is found in Oman and it joins the Zagros range through Oman across the Persian Gulf.

The Peninsula of India exposes Archaean rocks and Proterozoic basins, with a large tract of effusive lavas (Deccan Trap) in Western and Central India. The northern margin is bent down under the front of the Himalayas and is covered by the thick alluvium of the Indus, Ganges and Brahmaputra rivers. The thickness of the alluvium and sedimentary strata is known to be of the order of 25,000 ft. from aeromagnetic and gravity surveys for petroleum in Upper Assam, Bihar and U.P.

The Punjab Salt Range in N. W. Punjab and the southern border of the Lesser Himalayan zone all along the Himalayan front appear to mark the original northern limits of the Peninsular mass. They contain the equivalents of the Vindhyan System and also Lower Gondwana coal-bearing strata in several places from U. P. eastwards into Assam Himalayas. The unfossiliferous Sub-Himalayan formations (Blaini-Infra-Krol-Krol-Tal succession and their equivalents), whose age is surmised to extend from the Upper Palaeozoic to the end of the Mesozoic, are entirely different in facies and lithology from the Tethyan rocks which occur beyond and to the north of the Central Himalayan axis. Some of these strata are unmistakably deposits of semi-arid or arid environment as they contain dolomite-gypsum. They may have been formed in the sub-tropical desert belt along the northern border of Gondwaland when India was still a part of Gondwanaland and was located far to the south of the equator. The stupendous compression of the ocean basin (or basins) which lay between India and Central Asia has now thrown the strata one over the other in great disarray and brought the originally widely separated lands so close together that they are thrust over one another. The Zagros, Oman, Baluchistan, Himalayan and Burmese Arcs and the southern border of the Sunda Arc are all parts of the same marine Zone (Tethyan). The Indian Peninsular mass has been thrust into it together with the deposits of a southern marine basin in which the Sub-Himalayan formations were originally deposited. The distortion suffered by the Tethyan

belt, which can be clearly seen in a map, is due to the northward drift of India over many degrees of latitude.

The Peninsula of India took shape in the Upper Jurassic on the eastern side and in the Miocene on the western side. On the eastern coast there are several exposures of upper Gondwana formations which are associated in a few localities with Neocomian fossils (Spath 1933) which represent marine intercalations. The coast is parallel to the Eastern Ghats down to Madras and to the fold directions of the gneis ses further south. To the South of Madras, however, the coastal strip is covered by Cretaceous and Tertiary strata to a width of 20 to 40 miles from the coast. The Western coast shows Miocene rocks in the South (in Kerala) and Eocene and younger rocks in Gujarat. The presence of Eocene rocks has not been proved on the south-western coast, so that it is likely that it was encroached on by the sea in the Miocene.

The Peninsula shows three or four major graben structures along the Narmada-Son-Damodar, the Mahanadi and the Godavari valleys. They were probably formed during the Lower Gondwana times and may be as late as the Mahadeva or Rajmahal. The Narmada rift has been in existence at least since the Permo-Carboniferous, as witness the occurrences of marine strata of that age at Umaria and Manendragadh. This rift is connected through Gujarat and Kutch with the Salt Range. The folding of the Kutch region may have been due to the differential movements between the blocks on either side of the rift at some stage of the drift of India. It may be as early as late Eocene or as late as the Pliocene when the Himalayan area was still undergoing movement. The faulting of the Mekran and Bombay coasts took place in late Pliocene while the Kathiawar coast appears to have been uplifted in late Pleistocene. Drilling for oil in both Cambay and the Rajmahal areas have shown that the basaltic flows in them are step-faulted to considerable depths, about 6,000 to 7,000 ft. in Cambay and 10,000 ft. in the Ganges delta.

There are reasons to believe that some parts of the Indian shield have been uplifted during the Kainozoic era. This applies also to the Assam plateau whose southern flanks show Paleogene strata dipping steeply down into a monocline and disappearing under the plains of Sylhet. Pleistocene movements are known in the Pir Panjal, Potwar plateau to the

north-west of the Indian Peninsula and also in the Kainozoic orogenic zone of Soviet Central Asia and Hindukush.

On the convex side of the Zagros (and the Oman) mountains is the stable mass of Arabia with its comparatively gently folded foreland strata resting on an ancient platform. Arabia was part of Africa before the Red Sea rift separated it in late Eocene and Oligocene (Tromp, 1950) and it drifted into its present position. It then acted as the 'foreland' to the Tethyan basin of Iran. Its margin was faulted down in a late phase of the Himalayan movement (Upper Pliocene) and it will be filled up by sediments in due course. This faulting may be envisaged as due to the halting of the movement of the Arabian massif by the development of fractures along the Mekran and Persian Gulf which permitted India to move on.

To the east of India is the Burmese Arc. Beyond the median belt of Burma composed of Kainozoic strata, is the Shan–Malay belt of Pre-Cambrian, Palaeozoic and some Mesozoic strata whose lithological, faunal and structural affinities are with Cathaysia and Central China. That is, this region lay originally to the north of the Tethys, and the Shan belt is tectonically connected with the Thangla and Karakorum zone of Central Asia which were severely folded during the Cimmerian orogeny. This belt runs south into Malaya, turns round and continues through Borneo into the northern part of the Philippines. There was a Triassic geosyncline in Indo-China and Northern Thailand which according to Fromaget (1942) was raised into the 'Indosinides' during the Cimmerian orogeny, accompanied by ophiolites, radiolarites and granites of late Triassic to Jurassic age, the last with tin and tungsten mineralisation over a large part. There are also a few later elements of Upper Mesozoic and Lower Kainozoic age which cut across Tonkin and Northern Laos. The northern strip of the Sunda Arc also belongs to the same tectonic belt, which is older than the Kainozoic belt of Burmese–Andaman arc and its continuation into the chain of Nias Mentawei and other islands and the volcanic zone of Sumatra–Java. The Indonesian Archipelago, where these two tectonic zones have met as parallel strips, is now spreading or expanding towards the Indian Ocean and shows dextral wrench faults. This Arc, which is in every way similar to the Island Arcs of the Pacific, is now in the Indian Ocean area because of the movement of the Australia and New Guinea to their present positions by

which they have really annexed a part of the Pacific to the Indian Ocean. The latter movement has also produced the complicated structures in the Banda Arc where Eastern Celebes belonging to this Arc has been pressed against Western Celebes which may be part of the Sunda Arc. Australia and New Guinea appear to be pressing back the Banda Arc towards S. E. Asia as a result of which the Sunda Arc is moving out to the south and southwest without impediment.

Finally it may be mentioned that the Tibet–Sinkiang region is a high plateau with an excessive thickness of crust and high negative gravity anomalies along its mountain ranges. It would appear that the Tibetan plateau is not only subject to heavy erosion at the surface but also to sub–crustal spreading in the form of island arcs. Recent volcanism, transcurrent faulting and overthrusting towards the ocean are common in the arcs of SE Asia. Readjustment of equilibrium is thus actively taking place in the crust of South–east Asia through continental spreading. Such spreading to the south of Tibet is prevented by the Indian shield, which may indeed be still drifting northwards though at a very small velocity.

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SEISMOLOGICAL INSTRUMENTATION

BY

JAI KRISHNA*

Introduction

EARTHQUAKES have been occurring from the times immemorial bringing in their wake tremendous loss of life and property. This fact has been taken into account by the engineering practice which has developed with the growth of civilisation, specially in such regions where they were felt very frequently *e. g.*, Japan, U. S. A. etc. It was, however, felt that it was difficult to maintain continuity of thinking if, for scientific growth, the vague descriptions by the observers were the only data to draw upon. This feeling gave birth to the idea of measuring their intensity and effects through instruments so that the descriptions became more precise and better comparable with each other.

Simultaneous with the growth of this idea was the work of Poisson who published the fundamental theory of the transmission of elastic waves through solids. It was the consummation of this theory and the study of the earthquake records obtained on earlier instruments that made possible the study of the interior of the earth and the earth crust. It is proposed to discuss in this paper the instrumentation that has led to this study and explain modern developments.

Early Instruments and Growth of Thinking

The earliest instruments designed to measure an earthquake motion consisted of a pendulum (horizontal or vertical or torsional) in which the inertia of the suspended mass is relied upon to provide the base for measurement, and the relative movements of the pivot (horizontal, vertical and angular) are measured and recorded by suitable means. Through the period of about a century, the basic idea has not changed although the mechanism has undergone great refinements. The reason of this is not the failure of human ingenuity but the helplessness in view of the fact that for all relative measurements, one

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counts upon the availability of a stable point, but in this case, the earth which could provide such a point is itself in motion. The suspended mass is thus attached to the earth with the minimum of restraint so that the inertia acting on the mass is not interfered with excessively. This system has worked quite satisfactorily, and in the past 75 years or so, records of earthquake waves have been obtained at stations spread all over the globe to give information regarding the intensity and location of the disturbances that have occurred during this period. These records have also been utilised in estimating the constitution of the earth at various levels below surface, since the time of arrival of a wave at a particular station is a measure of the distance of the origin of the disturbance and material through which the wave has passed. For engineers, these records are of value as they help locating the possible areas of future disturbances and the characteristics of the foundation on which the engineering structures stand.

The earlier instruments, were comparatively long period instruments having high magnification and they recorded waves that came from long distances. If the origin of disturbance was not far from the instrument or the shock was big, these instruments were unable to record the microtremors, while for long distances even big shocks did not dislocate the recording device. For engineering purposes this information is not adequate. For the design of engineering structures one ought to know the reactions of the foundation material to strong motion which could damage the structures. Tremors which cause small stresses are of no significance in this respect, although their record yields useful information regarding the constitution of the earth's crust. In the last 30 years strong motion instruments have been designed and installed in California and a similar programme has been recently undertaken in Japan. Some of the instruments in California have very successfully recorded some strong motions in that region and have almost given birth to the modern thinking in the field of Earthquake Engineering. It is clearly established that if the future Earthquake Engineer has to design engineering structures to afford reasonable safety, all seismic regions should have a network of strong motion instruments to give the much needed information regarding the interaction of earthquake waves, geological and soil characteristics and the dynamic response of structures which stand on such soils.

The California records have enabled the establishment of magnitude-Distance-Acceleration curves (1) shown as Fig. 1, which help in estimating the ground motion expected at a certain site in a possible future shock. Such curves, however, will have reasonable validity only in California. But such data has to be collected over all the seismic regions so that similar curves may be made available for those regions. This will be a useful step in the design of earthquake-resistant structures.

The instrument used in California has been designed by the U.S.C.G.S. (2,3) to record accelerations of ground during strong motions. Towards the same purpose Japanese seismologists have designed SMAC (4) and DC Type accelerographs recently. They are three-component instruments with elaborate starting and recording equipment. In order to have a large number of instruments in a short time, a simplified oscilloscope has been designed at the California Institute of Technology (5) and has been redesigned at the Roorkee School of Research and Training in Earthquake Engineering (6). It consists of a simple pendulum held at a point capable of providing oscillation of a mass in all directions without restriction. The mass is held between two permanent magnets for damping the motion, and the mass, length and diameter of pivotal wire, position of pivot and the top mass are so adjusted that the instrument has the desired natural period and is robust.

Seismograph Characteristics

Type Description	Period SEC	Galv. Period SEC	Magnification	Record Speed mm/sec	Sensitivity mm/0.1g	Maximum Acceleration
Seismographs for Distant Earthquake Recording						
Wood-Anderson	0.8	—	2800	/-	—	—
Galitzin	12	12	1000	—	—	—
Sprengnether	2	2	3000	/-	—	—
Benioff	1.0	0.25	30000	/-	—	—
Milne-Shaw	12	—	250	—	—	—
Strong Motion Accelerometers for Earthquake Engineering						
U.S.C.&G.S.	0.035-0.10	—	—	10	0.26	0.5
S. M. A. C. Japan	0.10	—	—	10	4	1.0

Basic Principles

The recording instruments basically consist of a mass suspended from a spring and moving in a damped field. The frame holding the suspension wire is fixed to a point so that the mass vibrates like a pendulum and its motion is governed by the following equation of motion :

$$m\ddot{x} + cx + k\dot{x} = o \quad \ldots\ldots (1)$$

where 'x' is the relative displacement of the mass 'm' at any time 't' due to some initial disturbance 'c' the coefficient of viscous damping and 'k' is the spring constant. If the above equation describes the characteristics of an instrument meant to record ground motion given by $y = y_o \sin \omega t$, its solution will be

$$x = \frac{(\omega/p^2)}{\sqrt{[\,1-(\omega/p)^2]^2+[2(\eta/\eta_c)(\omega/p)]^2}}\; y_o \sin(\omega t - \phi) \ldots (2)$$

where $p^2 = k/m$; $\eta = c/2m$; $\eta_c = p$ and

$$\tan \phi = [2(\eta/\eta_c)(\omega/p)] \,/\, [1-(\omega/p)^2] \ldots\ldots (3)$$

or $x = A.\, y_o \sin(\omega t - \phi)$ say,

The coefficient 'A' can be represented by the curves shown in Fig. 2.

It will be seen from Eq. 3 and Fig. 2 that as (ω/p) increases, $Q \to 1$ and $\phi \to o$ Thus, if, ω/p is more than 2,

$$x \approx y_o \sin \omega t \approx y$$

An instrument having large 'p' (i.e. light spring support to the mass) will respond to this requirement and will record small motions directly.

If the spring is stiff so that (ω/p) is small, the denominator in Eq. 2 $\to$ 1 and $\phi \to o$ from Eq. 3. Eq. 2 can be rewritten as :

$$x \approx (w/p)^2 y_o \sin \omega t$$
$$\approx (1/p^2)\ddot{y}$$

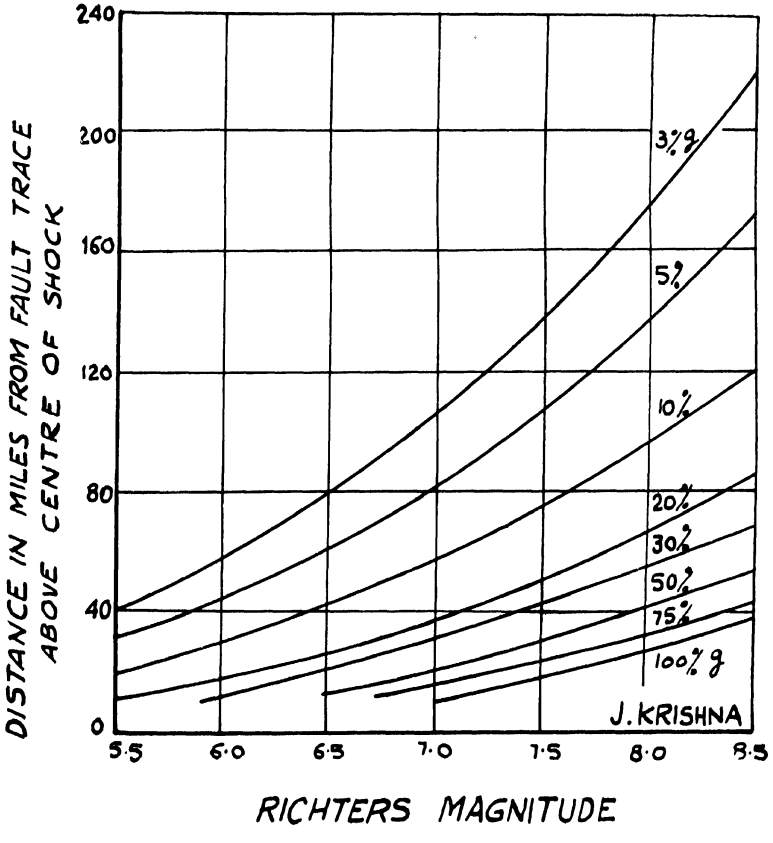

Figure (1)

Variation of Ground Acceleration with distance due to Earthquake Shocks of different magnitudes. (Depth of centre of shock assumed 15 miles below ground level).

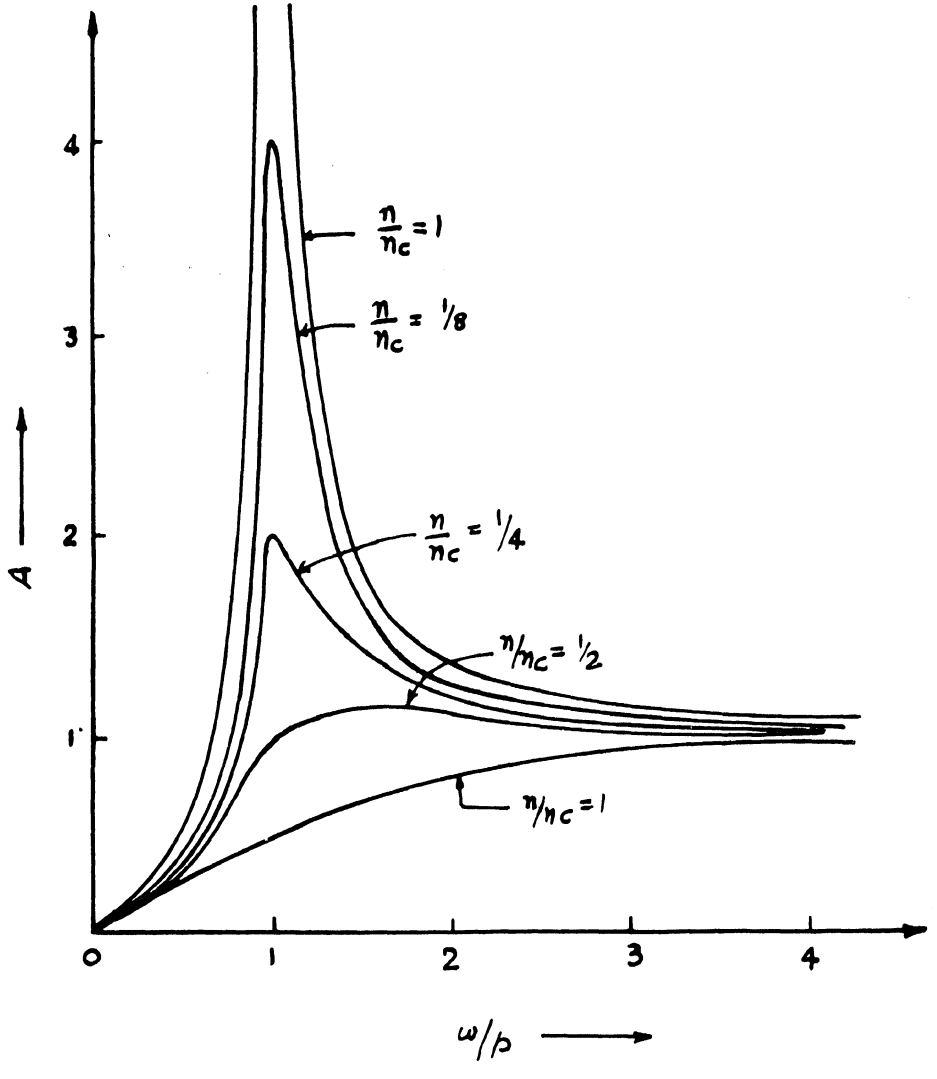
4
3
2
1
A
$\frac{n}{n_c} = 1$
$\frac{n}{n_c} = 1/8$
$\frac{n}{n_c} = 1/4$
$n/n_c = 1/2$
$n/n_c = 1$
0
1
2
3
4
ω/ν

FIG. 2.

FIG. 3_AVERAGE ACCELERATION SPECTRUM CURVES

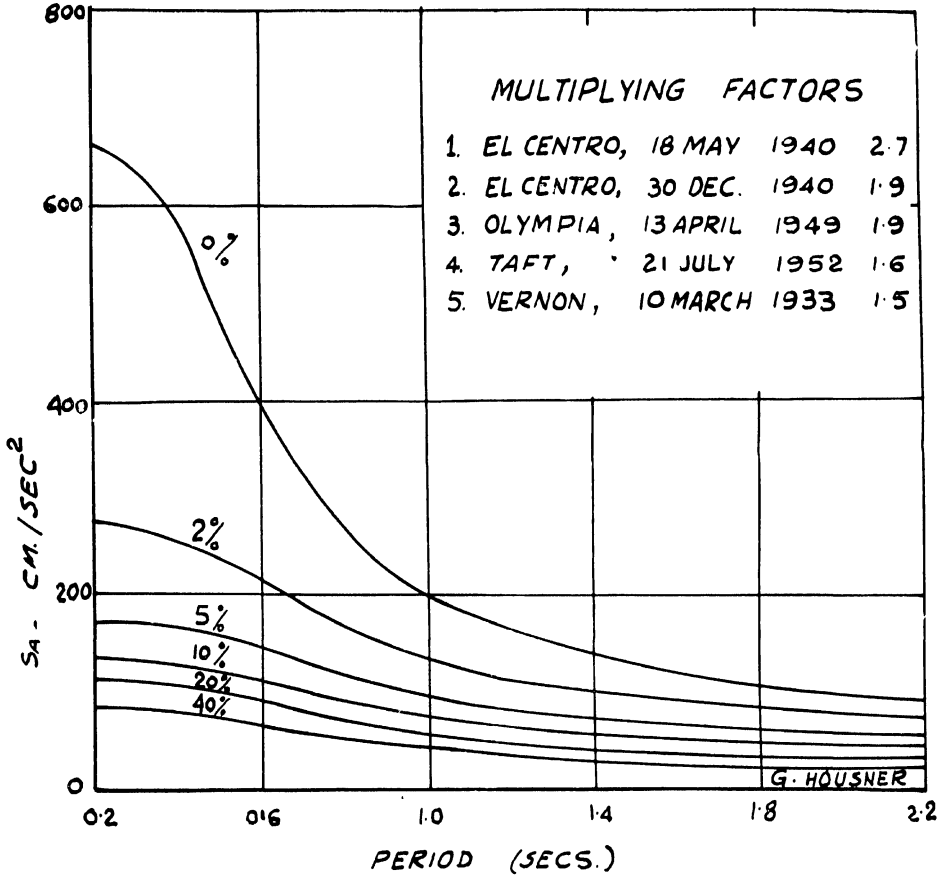

Figure (3)

The instrument will record ground acceleration and will thus give the important information regarding the forces applied to the structure. This will explain the utility of designing instruments with stiff springs for engineering purposes, and those with light springs for obtaining other seismological data regarding earthquakes.

Structural Response Recorders:

The Earthquakes School at Roorkee has designed the simple pendulum oscilloscope in such a way that it is stable and the natural period and damping are adjusted to suit the requirements for the study of the behaviour of different engineering structures during an earthquake. In a way, each instrument has been designed as an equivalent to an engineering structure so that it has predominantly the same dynamic properties. It is proposed to place several instruments (in other words, several idealised models of engineering structures) at one station so that it is possible to know the response of several structures at the same time when an earthquake occurs. If such stations are built all along the seismic regions a good deal of data can be obtained which will directly help the engineer in design work. The maximum value of the response as recorded by this instrument gives a point on the Response Spectrum Curves (7) shown as Fig. 3 and consequently relationships between the effects of the same size of earthquakes on a structure in one region and the other, and for different structures in the same region could be established. This data will be invaluable although it may take a long time to collect it.

Characteristics of the Instruments at one Station

Period	Damping — % of the critical
0.40	5% to 10%
0.75	-do-
1.25	-do-

Instrumentation for Prediction of Earthquakes

One of the most important directions that the light spring instruments should take is the study of the changes that occur

in the earth mass before an earthquake actually occurs. Some attempt has been made to design instruments to record the magnetic changes preceeding earthquakes, but since such changes occur much too often on account of reasons other than earthquakes also, these devices have failed to be useful so far.

It is surmised that the earth mass that ruptures and results in an earthquake is undergoing changes continuously. Strains are building up, density and other characteristics of the material constituting such mass are changing. Further, seismological studies are possible to find the limiting strains that will result in rupture. The point at issue is that the instrumentation required for prediction should be able to record the changes in the wave characteristics with the changes in the properties of the mass that is likely to rupture. This direction seems to offer one of the most useful fields for research.

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PALEOMAGNETISM OF DECCAN TRAPS OF VIKARABAD, CHINCHOLI AND GULBARGA AREAS

BY

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Abstract

Paleomagnetism of thirty three rock samples from Vikarabad, Chincholi and Gulbarga areas in south eastern margin of Deccan trap exposures has been studied. The results give a mean azimuth of 145° and a mean dip of 60° down, with radius of 50% circle of confidence of nearly 4_0. These results are very similar to those obtained by Deutsch et al (1958) for Deccan traps of Amba area and of Clegg et al (1956) for traps of Khandala area. From these data the ancient latitude of Nagpur (Central India) obtained is nearly 37_0 S, consistent with the position of India in the southern hemisphere during cretaceous times. Thermoremanent studies of these rocks indicate that their magnetisation is fairly stable.

WE carried out an investigation of Paleomagnetism of Deccan traps of three areas, Vikarabad, Chincholi and Gulbarga situated along the south eastern margin of the Deccan trap exposures. Between Hyderabad and Vikarabad the exposures of the traps seem to overlie the Hyderabad granites while near Chincholi, limestones of the Bhima series directly underlie the traps. Oriented specimens were collected from quarries near mile-stone 27 on Vikarabad-Hyderabad road at latitude 17° 20′ and longitude 78° 7′ and from about five miles SE of Vikarabad on Vikarabad-Hyderabad road (17° 20′ : 77° 56′ 22″).

The Chincholi specimens were collected from two sites about one mile apart near Bhoglingadhalli ; and the Gulbarga specimens from a large quarry near M. S. K. mills on the outskirts of that town.

The inclination and azimuth with respect to the present north were measured for each specimen using an astatic mag-

TABLE — I

Results of Paleomagnetic Studies from three localities

	Locality	Elevation (feet)	Latitude North	Longitude East	Samples collected	Cores studied	Mean Vector		J (Intensity) variation (emu/gm.)	Radius of 50% circle of confidence (Fisher)	Magnetisation sense
							Inclination	Declination			
1.	Vikarabad (2 sites)	2125	17°20′	78°	9 (3 rejected)	48	60°+	140° N	0.0034 to 0.012	4°38′	Reverse
2.	Chincholi (2 sites)	1600	17°28′53″	77°28′	11 (2 Rejected)	59	61°30′+	152°30′ N	0.002 to 0.014	3°30′	Reverse
3.	Gulbarga (2 sites)	1550	17°18′36″	76°56′34″	13	69	58°+	145° N	0.003 to 0.0067	3°7′	Reverse

TABLE — II

Calculated pole positions and other parameters for three localities

	Locality	Present Lat. of site	Present Long. of site	Ancient Lat. of site	North Pole Position		Nagpur		Ancient dip at Nagpur
					Latitude	Longitude	Present Latitude	Ancient Latitude	
1.	Vikarabad	17°20′	78°	40°45′ S	21° N	70°30′ W	22° N	37°48′ S	57° Down
2.	Chincholi	17°28′53″	77°28′	42°36′ S	24°48′ N	80°30′ W	22° N	39°17′ S	58°24′ Down
3.	Gulbarga	17°18′36″	76°56′34″	38°36′ S	25°15′ N	73° W	22° N	35°30′ S	55° Down

TABLE — III

Comparison of results of present Paleomagnetic studies with those of Amba and Khandala areas

	Locality	Mean Latitude (North)	Mean Longitude (East)	Elevation Above mean sea level (Ft.)	Mean declination East of true North	Mean dip position downwards	References
1.	Amba (Lower)	17°.00	73°.46′	500–1800	144°	+60°	E. R. Deutsch Radhakrishnamurthy P.W. Sahasrabudhe (1958)
2.	Khandala area	18°.45′	73°.22′	500–2525	139°	+62°	T. A. Clegg E. R. Deutsch D. H. Griffith (1956)
3.	Vikarabad Chincholi Gulbarga	17°.22′	77°.30′	1550–2125	145°	+60°	

netometer. The astatic pair for the magnetometer was constructed at the Tata Institute of Fundamental Research with the help of rock magnetism group of the institute. The apparatus is a simplified version of the instrument first designed and constructed by Prof. P. M. S. Blackett. The sensitivity of the magnetometer is 3×10^{-6} Oersted for one cm. deflection at an optical path of 2 meters length. This amplification is quite adequate for the study of granites, basalts, dolerites etc., but not enough for the study of sedimentary rocks. From each rock specimen five or six cores were prepared and studied, the total number studied being 176.

The resultant vector obtained for each rock specimen is plotted on stereographic projection in Fig. 1. Fig. 2 shows the histograms of declinations and dips plotted for all the specimens studied. In table I are listed the mean inclination and mean declination, (east of the true north) for the magnetic vector in the three localities. From these data the ancient latitude and longitude of the North magnetic pole position have been calculated and also the ancient latitude of Nagpur (being a central point in India), ancient latitude of each site, ancient dip at Nagpur etc. These results are tabulated in table II. The calculated value for the ancient latitude of Nagpur is nearly 37° South of the equator in close agreement with the results obtained by the Tata Institute group.

The results of our investigation are very similar to those obtained by Deutsch, Radhakrishnamurthy and Sahasrabudhe (1958) for Deccan traps of Amba area and those of Clegg, Deutsch and Griffith (1956) for Khandala area near Poona. A comparison of these results is shown in Table III. The elevation of all these sites ranges from 500-2250 ft. above mean level. The distance between Chincholi and Amba is almost 385 Km.

It has been concluded by previous workers (Deutsch et. al, 1958) from the study of Deccan traps of Nipani, Khandala, Amba, Linga and Pavagadh that the lower Deccan traps are reversely magnetised while the upper Deccan traps are normally magnetised. In this classification the traps of the areas studied seem to belong to the lower Deccan traps.

Thermoremanent Vector Studies

A test of stability of the magnetic vector has to be applied to the rock specimens to ensure to some extent that the direc-

tion of magnetisation measured is the same as that due to the intrinsic field prevailing at the time of the formation of the rocks and that it has remained the same during the geological past.

A strong grouping of the points of the projection of the magnetic vector of various rock specimens collected from different places on stereographic net itself indicates stability of magnetisation, when this direction of magnetisation is quite different from that of the present day field. Laboratory tests for the stability of the magnetic vector have also been applied to a number of specimens. The results of few of these will now be discussed.

The rock specimen is heated in a specially designed non-magnetic furnace, the heating filament being of Platinum wire. The rock specimen is placed in the furnace and the change in the magnetic vector is studied at various temperatures, while it is being heated. Temperature is measured at suitable intervals using a copper-constantan thermocouple, calibrated for this purpose. The specimen is heated to a temperature of about 500° to 600°C and then cooled in the present earth's field in a fixed orientation. The direction of magnetisation and intensity acquired while cooling is also measured. During the process of each measurement the earth's field is neutralised by means of three sets of Helmoltz Coils.

Fig. 3a, 3b and 3c show the thermal demagnetization curve for specimen No. C_{28} d_2-Gulbarga. Following Wilson's (1961) technique Fig. 3a shows the change in the intensity of the vector in XY plane with temperature. Fig. 3b shows the same thing in XZ plane. It is seen that within the limits of observational error the direction of magnetisation is quite stable upto about 400°C which seems to be the Curie point of the ferromagnesian mineral contained in the rock. Fig. 3c shows the relative intensity of the vector *Vs.* temperature while heating, the specimen being cooled in the present earth's field. During the process of cooling the intensity is observed to be higher consistently for all specimens studied. The range of Curie temperatures observed for some of these rocks is from 250°C to nearly 600°C.

It has been found by various investigators (Nagata, 63) that the minerals in igneous rocks responsible for stable mag-

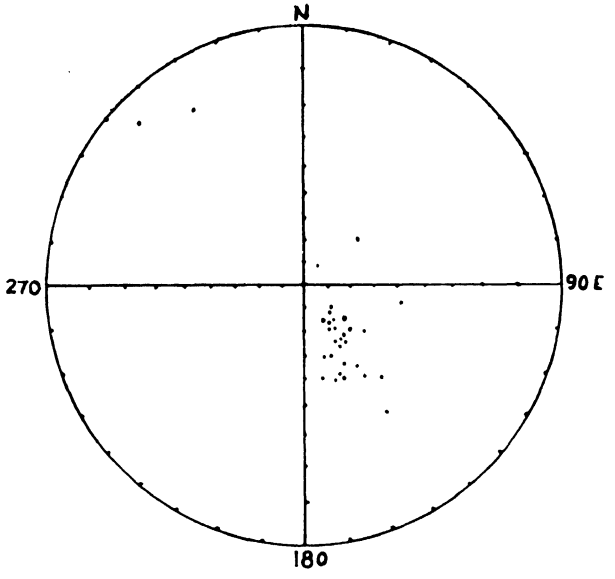

Figure (1)

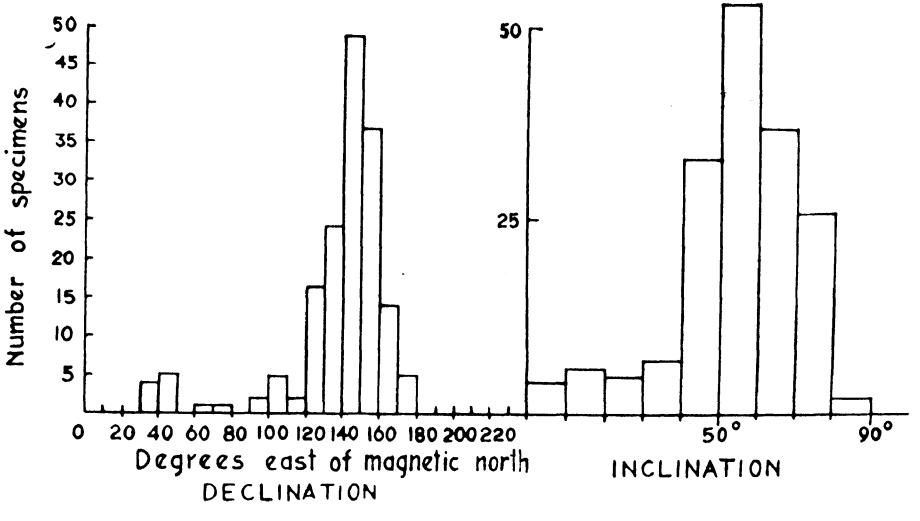

Figure (2)

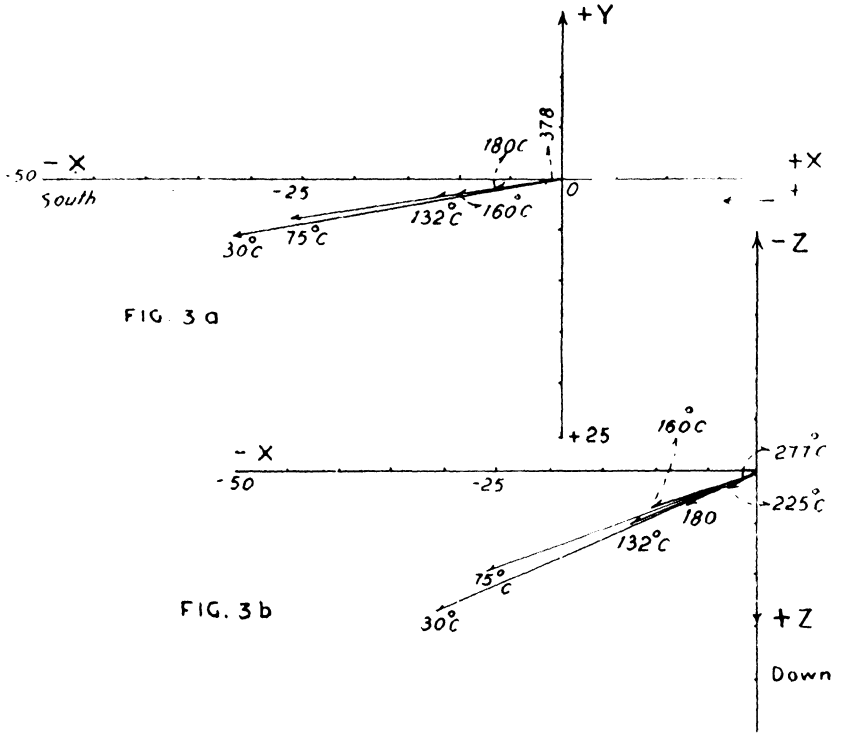

Figure (3a) **Magnetic vector plotted as a function of temperature in XY plane for specimen C_{28} d_2 Gulbarga area.**

Figure (3b) **Magnetic vector plotted as a function of temperature in XZ plane for specimen C_{28} d_2 Gulbarga area.**

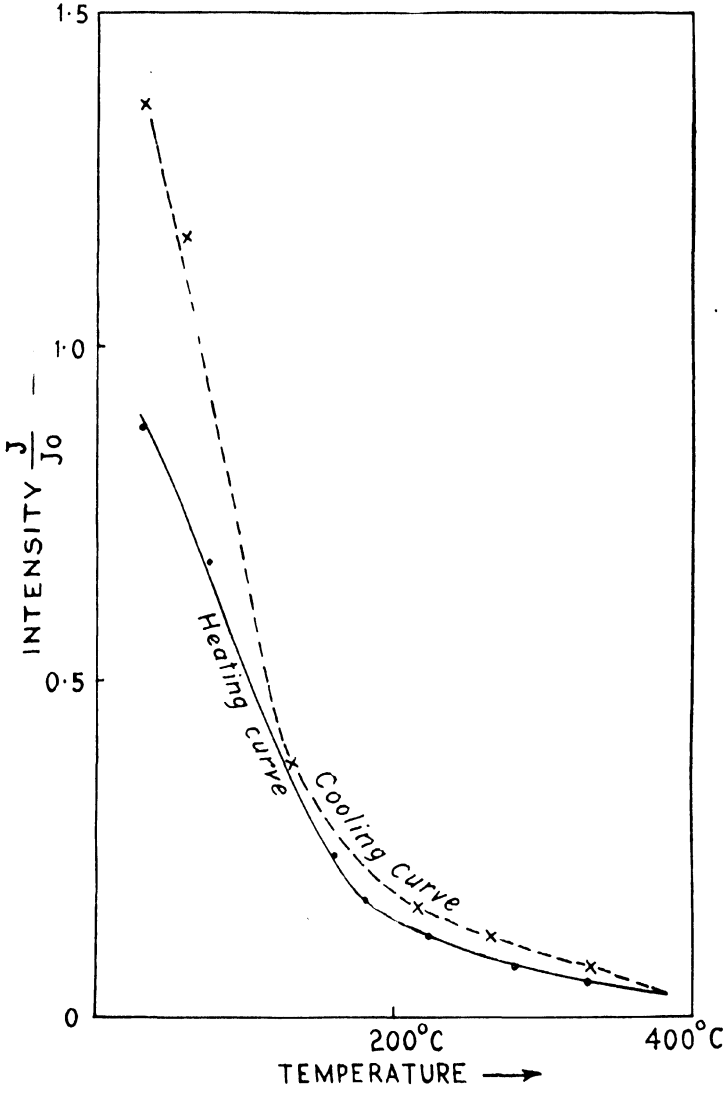

Figure (3c)

Thermal demagnetisation curves for specimen No. C_{28} d_2, Gulbarga area

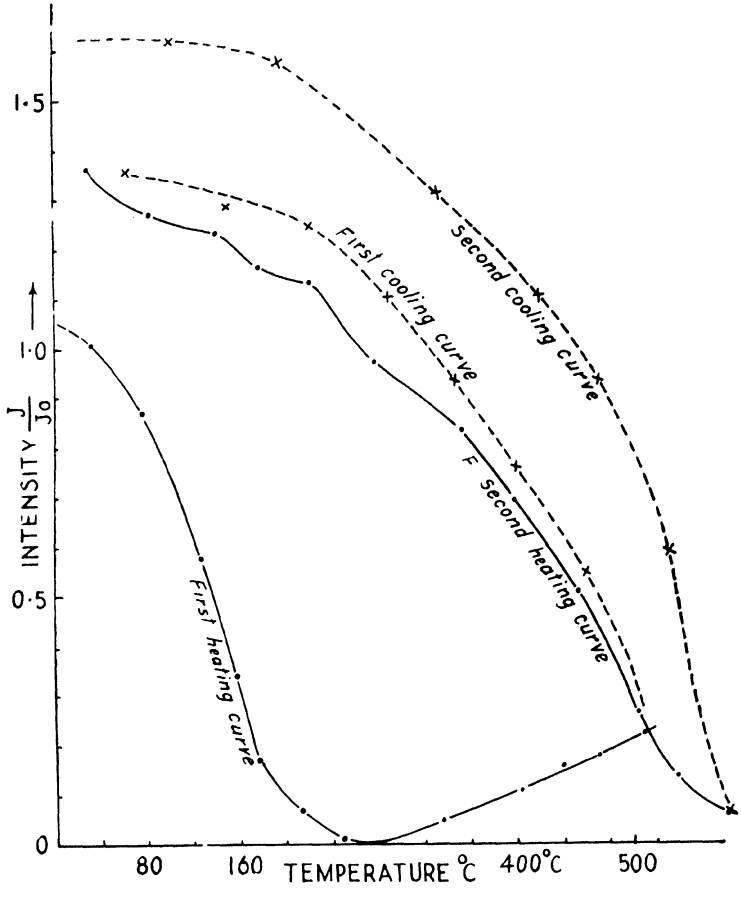

Figure (4a)

Thermal demagnetisation Curves for specimen No. C_{19B}, Chincholi area.

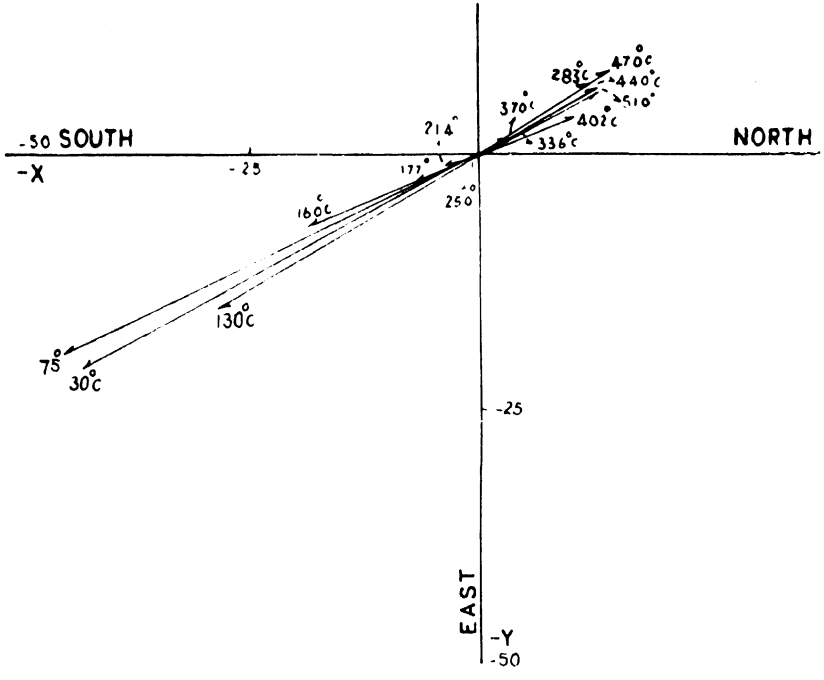

Figure (4b)

Magnetic Vector in the XY plane during thermal demagnetisation for Specimen No. $C_{19}B'$ (Chincholi area).

netism are titano-magnetites which are solid solutions of pure magnetite Fe_3O_4 ($\theta_c = 580°C$) and Ulvospinel (Fe_2TiO_4, non-magnetic) having crystal structure of the spinel type. The Curie point and intensity of magnetization decrease with the increase in the percentage of titanium oxide. In many basaltic rocks the amount of Ulvospinel is found to be quite appreciable.

Fig. 4a, 4b show the results of thermal demagnetisation studies of another specimen (C-19B). The interesting feature of the specimen is that the vector changes in direction and intensity during heating above a temperature of about 260°C. This change is almost opposite to the first and increases in intensity with temperature. This specimen was heated to about 510°C and then cooled in the present earth's field. It was reheated and recooled. It was noticed that the first cooling and reheating curves almost coincide. There was no reversal of the vector now.

It is probable that during each process of heating some irreversible change takes place in the magnetic minerals contained in the rock. This particular rock when examined in thin section shows a great deal of weathering and change in the ferromagnesian minerals. The minerals in the rock may have two opposite magnetic vectors, the predominant one being the original vector acquired due to thermoremanent magnetism. The secondary vector seems to have been acquired in the present earth's magnetic field by the minerals which have been produced by chemical changes in the rock. As the rock is heated, the thermoremanent vector loses its intensity and the secondary vector becomes dominant on account of higher Curie point of the secondary mineral.

Acknowledgement

We wish to express our thanks to Prof. M. S. Krishnan for his encouragement and providing us all facilities for doing this work and for reading the manuscript. We are very much indebted to the Rock Magnetism Group of Tata Institute of Fundamental Research for help in the construction of magnetometer as well as in other phases of the work.

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STRUCTURE AND TECTONICS OF EASTERN GHATS IN SRIKAKULAM DISTRICT, ANDHRA PRADESH.

BY

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Introduction

THE importance of the study of the structure of the Eastern Ghats in Srikakulam and Visakhapatnam districts was realised from the publications of Fermor (1936, 1940) and Krishnan (1953). Srikakulam district is being mapped structurally from 1956 onwards in conjunction with the work of the research scholars (Sriramdas and Rao, 1960) forming part of the study of the tectonics of the Eastern Ghats.

The Eastern Ghats area structurally mapped is in between 18° 15′ and 18° 45′, and 83° 30′ and 84° 15′ in G. T. Sheets Nos. 65 N/10, N/11, N/14, N/15 and 74 B/ and B/3. The area forms part of the Srikakulam District between the main Eastern Ghat ranges and the Coramandel coast (Fig. 1).

Previous Literature

Reconnaissance work has been done by King (1886), Smith (1899), Walker (1900) and Collins (1907), Fermor (1909), and Mahadevan and Krishnarao (1956). These studies were directed mainly to the Khondalite series or on manganese ores. Fermor (1936, 1940, 1950) drew attention to the general problems involved in the study of the Precambrian formation and dealt with a few 'provinces' among the Precambrians of Peninsular India. Sriramdas (1962) discussed the boundaries of these provinces in the coastal districts of Andhra Pradesh in the light of modern data. Holmes (1950, 1955), Mahadevan and Aswathanarayana (1955) have discussed the structure of the Precambrian formations of Peninsular India in detail while Krishnan (1953, 1961) has presented an uptodate picture of structure and tectonics of India.

Structural mapping of the area on one inch to a mile scale was carried out during 1956-1959 by Rao, R. J., and Murty,

V. N. (65N/10) Rao, V. R. (Southern part of 65 N/14), Padmanabhaiah, K. (Southern part of 74 B/2, Rao, M. M. and Narayana, L. S. (65 N/15) for their M. Sc. research theses. The author visited and studied parts of these areas with the scholars and mapped critical areas on four inches to a mile scale.

Acknowledgement

The author wishes to thank the late Professor C. Mahadevan who encouraged him to take up the study of the area, and Messrs. M. M. Rao, L. S. Narayana, K. Padmanabhaiah, V. R. Rao, R. J. Rao and V. N. Murthy for furnishing field and laboratory data collected during the progress of their work.

Topography

The main hill ranges in the area are Barnakonda, Antikonda, Palakonda and Kadagandi ranges with Gamatikonda having the maximum height of 2,706 ft. Higher hill ranges of the Eastern Ghats are towards north–west whereas low lying detached hills are towards south-east. A narrow plain runs in between the hills and the coast of the Bay of Bengal.

The major hill ranges and some of the detached hills show a distinct N.W.-S.E. trend. A few hills show E.W. and N.E. S. W. trends. Mulangakonda (18° 17′ 30″; 83° 47′ 45″) is crescent shaped with N. W.-S. E. trend changing gradually through E.-W. trend into N.E.-S.W. trend. Gangada Konda (18° 32′ and 83° 33′), Nagala and Suddula Kondas (18° 33′ and 84° 6′) and Antikonda (18° 38′ and 83° 47′) also show this crescent shape. The two major rivers Nagavali and Vamsadhara show a N.W.-S.W. trend for a major part of their course in the area.

Lithology

Khondalite series: The major rock types in the area are the Khondalite series consisting of garnet-sillimanite gneisses, feldspar-quartz gneisses, cordierite-sillimanite gneisses, garnetiferous quartzites, quartzites and the calc-granulites. The garnet-sillimanite gneisses and the feldspar-quartz gneisses occur throughout the area. The quartzites and garnetiferous quartzites occur as separate hills as well as alternating bands in gneisses. Cordierite-sillimanite-gneiss occurs as a small

patch near Sangam (Lat. 18° 35′ 30″; Long. 83° 38′ 15″). The calc-granulites are observed as thin bands in a few places but well developed in Rajayyapeta (Lat. 18° 31′; Long. 83° 49′ 45″). The calc-granulites consists of the diopside, plagioclase, scapolite, wollastonite and sphene.

Charnockite series: In the Srikakulam area the charnockite series consist of charnockite, diorite, gabbro and pyroxene amphibolite. The charnockite or hypersthene-granite has blue quartz and perthite, hypersthene and iron ores with or without garnets. The rock is black, massive, hard and compact. Diorite consists of the hypersthene, augite, hornblende, quartz and andesine. The gabbro has augite, labrodorite, hypersthene, iron ores with or without quartz and hornblende. The gabbro is fine-grained, dark green and gneissose on weathered surface. The pyroxene-amphibolite consists of hornblende, hypersthene, labrodorite, augite and iron ores.

Granites: The granites in the area consists of the massive and gneissose, porphyretic and hypidiomorphic types. The massive granite consists of quartz orthoclase and biotite with muscovite in some. The granite gneisses made up of quartz, orthoclase, biotite and iron ores. Garnet and in a few types hypersthene are found in them. The porphyretic granite gneisses consist of the euhedral orthoclase laths in a ground mass of orthoclase, quartz, biotite with or without garnet and hypersthene. The orthoclase laths are 2 to 12 cm. in length and 1 to 4 cm. in width with the three well developed pinacoids.

Structure

Bedding and foliation: The planes separating the quartzites and garnet-sillimanite gneisses when they occur in alternate bands are taken as bedding planes. The trend of the bedding and the foliation in gneisses are observed to be parallel. The main trend of bedding and foliation in khondalite series in N.W.-S.E. with a dip towards south-east. The hills in Srikakulam, Palakonda and Viraghatam areas show this trend. The next in importance is the E-W. trend shown by many of the small hillocks. The N.E.-S.W. trend which is dominant in the Eastern Ghats, N. E. of the area is of very minor importance. The strike and dip of bedding and foliation in the khondalite series of Mulanga Konda is of special significance. The north-western end of the crescent shaped hill

shows N.W.-S.E. trend, changing through E. W. trend in the middle, to N.E.-S.W., N. S. and N. N. W.-S. S. W. trends in north-eastern end.

The charnockites are mostly massive but show discontinuous foliation especially on the weathered surfaces of the basic members. The foliation is highly variable. The granite gneisses show well developed foliation. The euhedral laths of feldspar in the porphyretic granite gneisses show fair alignment in a few outcrops. The strike of foliation in granite gneisses and charnockite series shows remarkable parallelism with that in the khondalite series. The dominant trend is N.W.-S.E. varying to by E-W. and N.E.-S.W. trends. The diagram prepared by Mr. Padmanabhaiah for 620 foliation planes in granite gneisses on Tekkali area of Srikakulam district, showed the maxima in S. W. and N. E. quadrants confirming the observation that the general strike is in N.W.-S.E. direction (Fig. 2).

Lineation : In the khondalite series lineation is shown by the elongated garnets, axis of the drag and minor folds and slip directions. In the granite gneisses the elongated garnets as well as the feldspar laths show lineation. The feldspar laths are broken and aligned parallel to the gneissosity with biotite and garnet wrapping around the feldspar giving rise to the augen structure.

Joints: All the rock types in the area and in particular the garnetiferous granites are traversed by numerous joints. They trend in numerous directions but invariably with steep dips. Contour diagrams of 426 joints in granite gneisses of Tekkali area by Padmanabhaiah and 397 joints in Palakonda area by Ramana Rao reveal the presence of the following sets. The most dominant set strikes N.E.-S.W. followed by E-W., N.W. S.E. and finally N.S. The dip is very nearly vertical in all the sets.

Folding: Major folding of the khondalite series can be inferred from the trend of their bedding and foliation. Minor folds and drag folds in the khondalite series are observed in several outcrops. The trend of bedding and foliation in Mulanga Konda showing N.W.-S.E. trend, changes to other directions locally and reveals the existence of a major fold. There are other folds inferred from the foliation planes.

Several small bands of calc-granulite are present in the garnet sillimanite-gneisses of the khondalite series. These calc-granulite bands display folds with axial planes and axis trending in all directions. In the same outcrop the variation in the trend is observed. These folds are observed in the calc-granulite band at Rajayyapeta. The quartzite bands also show minor folds with the axial plane striking N. 35° W., that is parallel to the foliation in the adjacent gneisses.

Faulting: Pure quartz veins of considerable size occur in this area. The important occurrence is near the 12/7 milestone (Long. 18° 19′; Lat. 83° 46′ 30″) on the Ponduru-Srikakulam road. It is a white, massive vein quartz, with vitreous lustre. It is highly fractured. The fracture planes show dendritic marks. It extends for a length of about 3 to 4 furlongs. Another vein occurs along the north-eastern flanks of the three garnet-sillimanite gneiss mounds, south of the above occurrence. It extends in a N.W.-S.E direction for a length of about 1 furlong. The highly fractured quartz vein with voids and slip planes suggests that this may be a silicified zone deposited by silica-bearing solutions along weakness planes which resulted from faulting. These may be taken as indirect evidence of faulting.

On the northern flanks of the hill 297′ (Lat. 18° 16′ 15″; Long. 83° 52′ 50″), east of Sutta Gurayapeta, a quartz vein cuts across the garnet-sillimanite gneisses. The vein strikes N 68° W.-S 68° E. and dips 80° north. It has a width of about 60 ft. to 70 ft., and extends for a distance of about half a mile in the direction of strike, and finally gets covered by soil. The quartz vein permeated the garnet-sillimanite gneiss as thin veins. The thickness of the quartz bands varies from 2 mm. to 5 cm. Some bands contain quartz crystals grown from the two walls of the bands towards the centre.

The garnet-sillimanite gneiss is very hard and compact. The intimately impregnated nature of the quartz vein and garnet-sillimanite gneiss indicates the pre-existence of a plane of weakness in the garnet-sillimanite gneiss. The existence of voids in this weak plane of the garnet-sillimanite gneisses, resulting from the movements is indicated by the crystallisation of quartz with well developed faces, from the walls towards the centre. Of course, the voids can also result from the solution of pre-existing material. Or there may be several

closely spaced joint planes that formed a zone of weakness which facilitated the deposition of silica from the solutions. From all these considerations, it is clear that there is a zone of weakness and it may be a fault.

Discussion

In Srikakulam area, variation in trend of folding and faulting from N.W.-S.E. through E-W. to N.E.-S.W. is noticed. The N.E.-S.W. trend typical of the Eastern Ghats is noticed to a minor extent. This may be due to the fact that the present area lies on the border of the Eastern Ghats. The western boundary between the Eastern Ghats and the Mahanadi type rocks is supposed to be faulted (Crookshank, 1938) although clear cut evidences are lacking. The eastern boundary of the Eastern Ghats show evidences of some amount of faulting and folding. One may therefore expect the presence of Mahanadi type rocks east of the eastern boundary of the Eastern Ghats.

In addition to the khondalite series and charnockite series typical of Eastern Ghats, the Srikakalam area shows porphyritic granite–gneisses, granites, garnetiferous granites and pegmatites. The structural features referred to above invariably are associated with these granites and pegmatites. This may be taken to emphasise the fact that the area is on the border of Eastern Ghats and Mahanadi type rocks. This may also indicates that tectonism is associated with plutonism by way of emplacement of granites.

The recently recorded minor earth tremors in this area show that the eastern border of the Eastern Ghats is somewhat unstable. The earth tremors, the faults, folds and variation in trends lend support to the view of Fermor (1936) that the Eastern Ghats have faulted boundaries.

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REVIEW OF STUDIES IN MARINE GEOLOGY (ALONG THE EAST COAST OF INDIA) AT ANDHRA UNIVERSITY, WALTAIR

BY

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Introduction

FOR the first time in India, a systematic study of various branches of oceanography including marine geology was started in the Andhra University under the guidance of Dr. E. C. La Fond (of the U. S. Navy Electronics Laboratory, San Diego, California) while he was visiting Professor of Oceanography in Andhra University during 1952-53 and 1955-56. Professor La Fond brought from United States equipment for the collection of sea floor sediments such as Phlegar corer and La Fond-Dietz snapper and other tools needed for carrying out different aspects of oceanographic research.

The Geology Department of Andhra University, which had been carrying out researches on the black sand concentrates along the east coast, found an excellent opportunity for the extension of the lines of research to the adjacent sea floor and sediments of the Bay of Bengal under the direction of late Professor C. Mahadevan.

Fifty-four cruises, each lasting from one day to about one week, have been made in the Bay of Bengal on mine-sweepers of the Indian Navy. Five hundred samples of sea floor sediments were collected, using La Fond-Dietz snapper and Phlegar corer, from the continental shelf of the east coast of India from Madras (Long. 80° 21′ E., Lat. 13° 11′ 5″ N.) to the Ganges delta (Long. 89° 41′ E., Lat. 21° 25′ N.). The author along with other members of the staff of Geology Department, participated in a number of these cruises for the collection of marine sediments and worked on the various aspects of these sediments in the laboratory.

The area covered is divided into there regional units namely, Visakhapatnam area, Visakhapatnam-Madras area and

Visakhapatnam-Gangetic delta area. Considerable amount of work has been carried out off Visakhapatnam coast during different cruises, utilising the material from a large number of stations, parallel as well as perpendicular to the coast. A profile of the sea floor off Visakhapatnam coast was also obtained by an echo-sounder traverse. The sea floor sediments from each of the above regional units have certain physical and mineralogical features which are distinctive and throw light on the source, distribution, mode of transport and conditions of their deposition.

Laboratory Studies and Results

Preliminary examination of all the samples was made and representative samples from strategic positions were selected for a more detailed study. The methods of study included observations on such physical properties of sediments as colour, plasticity, texture and lithological composition and the microscopic character of the sediments. Chemical studies, such as the determination of calcium carbonate, manganese content and organic matter were made. The clay minerals were studied by Differential-Thermal and X-ray analysis. The detailed results of these studies were reported in earlier publications and referred to here at relevant places.

Among the important features revealed, the following may be mentioned: (1) The delineation of the shelf off Visakhapatnam coast into five zones namely, sand zone, clay zone, shell zone, oolith zone and mud zone beyond the continental shelf, depending upon the dominant presence of particular constituents in each zone; (2) Occurrence of coarse sediments in the outer shelf; (3) Occurrence of ooliths in the outer shelf particularly off Visakhapatnan coast beyond 40 fathoms; (4) Association of shallow water benthonic foraminifera with the outer shelf sediments; (5) Presence of black sand concentrates in the inshore sediments and (6) The relationship between the detrital minerals of the sea floor sediments and the source rocks, namely, coastal formations and the rocks of the drainage basins of rivers flowing into Bay of Bengal (Mahadevan and Poornachandra Rao, 1954).

Visakhapatnam Area

The studies made on the nature and distribution of the shelf sediments off Visakhapatnam coast facilitated the divi-

sion of shelf into five convenient zones (Mahadevan and Poornachandra Rao, 1954, 1956; *sand zone*, *clay zone*, *shell zone*, *oolith zone* and the *mud zone* beyond the continental shelf. Though there is some overlapping, the zones are distinctive enough for definite delineations.

The near shore sediments corresponding to a distance of 2½ miles from the coast or 15 fathoms, are composed of sand, and this zone was named as *sand zone*. The sand in this zone appears to be graded and sorted, the fineness of the grains increasing with distance from the shore. In the sand zone are found the heavy minerals such as zircon, garnet, monazite, ferromagnesian and dark brown opaque minerals which are common in the black sand concentrates of the east coast beaches. The occurrence of the black sand concentrates in the near shore sediments is interesting and a detailed study may bring out the relationship between these and the black sand concentrates along the beach (Mahadevan and Poornachandra Rao, 1953).

The second zone extends from 15 fathoms down to about 30 fathoms, corresponding to a distance of roughly 10 miles from the coast (*clay zone*). Here the sediments consist of clays and fine grains of sand. The fine sand continues to decrease in size and amount with distance from the coast, together with a corresponding increase in the clay proportion. Shell fragments are rare in this zone.

The next sedimentary zone is called the *shell zone*. It extends from about 30 fathoms (33 fathoms, exactly) out to 70 fathoms corresponding to a distance of roughly 20 miles from the coast. The maximum shell content occurs between 58 and 70 fathoms. In the shell zone the sands are coarser than those found in the preceeding clay zone or beyond 70 fathoms. This interesting zone disproves the old concept of progressive diminution of grain size with distance from the coast (Poornachandra Rao, 1954).

The next deeper sediment zone overlaps the shell zone and extends from about 40 fathoms to the continental shelf. This zone is termed the *concretion* or *oolith zone*. Although the sediments in this zone are composed of clay, fine sand and shell fragments, the unique feature is that much of the material consists of oval shaped concretions or 'ooliths'. They vary in

size from microscopic dimensions upto about 1 mm. in diameter. The formation of 'ooliths' is a very important aspect of sedimentation in the shell along the east coast of India.

The last zone beyond continental shelf is termed the *mud zone* and consists of plastic blue muds containing foraminifera such as *Globigerina* etc.

Evidences of Lowered Sea Level during Pleistocene Time

The zonal pattern of sediments off Visakhapatnam coast has already been described. The peculiar character of the sediments here is the presence of coarse sand in the shell zone at depths greater than 30 fathoms. In the preceeding clay zone at lesser depths, progressive diminution of fine sand was observed. This type of discontinuity in the progressive diminution of grain size of sediments across the shelf has been observed in other parts of the world by different workers.

Shepard (1948) and Emery (1952) are of the opinion that the old concept of progressive diminution and gradation of grain size in sands with distance from the coast does not always hold good.

The break in the progressive gradation in the size of the sedimentary constituents like sand off the Visakhapatnam coast may be accounted for mainly in two ways: one explanation is by the current transport, which may bring sand from distant sources other than from the coastal area in proximity.

There are many evidences such as bathythermographic observations, salinity variations, transparency changes etc., pointing to the existence of currents in the shell zone (Mahadevan and Poornachandra Rao, 1954, 1956).

But the presence of agglutinations over the sand grains and shells, aggregates consisting of smaller ooliths, sand and shell material, fresh and smooth appearance of many of the ooliths, and lack of abrasional rounding and delicate ornamentation in shells indicate a quiet condition at the bottom at present, where the coarse sand is present in association with shell material and ooliths.

The occurrence of coarse sand in the shell zone may also be explained as due to eustatic changes of sea level and effects of Pleistocene glaciation. Lowered sea levels in most continental shelves are well recognised as pointed out by Shepard (1948).

There is coarse sand in the bottom samples collected along 40–50 fathom line south and north of Visakhapatnam. The observations on samples indicate that the coarse sediments in the outershelf occur along the coast upto Godavari delta in the south and upto Mahanadi delta in the north, in which places the deposits on the whole shelf are covered by the clay and silt brought by those rivers.

The coarsening of the sediments being a wider phenomenon applicable to several shelves of the world, the author attributes this to eustatic level changes and lowered sea levels during Pleistocene time rather than to current transport. In support of this conclusion the following evidences are given.

During his stay at the Scripps' Institution of oceanography (University of California) in the year 1956-'57, the author studied the foraminifera of the sediments of the continental shelf off Visakhapatnam coast and had discussions about them with Dr. Fred B. Phlegar and Robt. R. Lankford of Marine Foraminifera Laboratory of Scripps. There is abundance of shallow water benthonic foraminifera such as ***Rotalia beccarii*** warm Miliolidae, principally ***Quinqueloculina***, ***Elphidium*** cf. ***chrispum***, ***Rotalia***, ***Amphistegina***, etc., at depths greater than 40 fathoms and upto 97 fathoms. This shows that the sea level over the present outershelf was successively lower at different periods in the Pleistocene time and facilitated the deposition of the above shallow water benthonic foraminifera. Their abundance suggests that there has been very little sedimentation after the Pleistocene time in this area.

Probably the currents over the outershelf and the swell prevent the deposition of terrigenous material (clay and silt) on the predominantly calcareous outershelf sediments and facilitate deposition in the mud zone beyond continental shelf.

Occurrence of Ooliths in the Outershelf

The occurrence of ooliths in the sea floor sediments off Visakhapatnam coast is a significant fact revealed during the

study of these sediments (Poornachandra Rao and Mahadevan, 1955, 1957).

The occurrence of ooliths is of special significance restricted to few localities in the world such as Bahamas (L.V. Illing, 1954), Great Salt Lake, Utah (Eardley, 1938) etc. In these localities the ooliths are found on the beach or near shore and are forming at present due to the prevalence of suitable conditions of deposition of calcium carbonate in the form of ooliths. Off Visakhapatnam coast they occur between 40 and 100 fathoms in the outershelf and their abundance in the sediments varies from place to place. It is believed that these ooliths in the outershelf were formed at a time of lowered sea level during Pleistocene, as we do not find the ooliths in the near shore sediment at present.

The ooliths range in size from a fraction of a millimeter to 1 mm. They are of ovoid, spherical, and irregular shapes and are coloured creamy white or white with shades of brown and grey. The surface of ooliths is smooth and shining in some cases, while it is rough, pitted and dull in other cases. The optical examination of the thin sections of ooliths showed the concentric nature of the precipitated material around nuclei of quartz, feldspar, shell fragments and fecal pellets. The X-ray analysis of ooliths in the Scripps Institution revealed that they consist primarily of aragonite (95% and more); calcite (about 1%); dolomite (1 to 2%) and quartz (less than 1%). The microscopic and X-ray studies of ooliths and the evidences gathered so far indicate that they are formed by the inorganic precipitation of calcium carbonate, in the form of argonite.

Chemical Studies

Calcium carbonate:– From the results of calcium carbonate determination, a zone of calcareous sediments has been recognised on the outershelf off east coast of India which appears to reach its maximum extent off Visakhapatnam (Subbarao, 1958). The calcareous sediments seem to be replaced by terrigenous deposits off the river mouths and their deltaic areas. Evidence has been gathered from the nature of the mechanical make up of the sediments and the association of ooliths with shallow water benthonic foraminifera to show that these lime sediments, chiefly in the form of ooliths, shell material, and foraminifera, were deposited at a time of lowered sea level, probably in the Pleistocene glacial period.

Manganese content: The manganese content in the shelf sediments is 0.059 percent on an average (Subbarao, 1958). The source of the manganese content in the shelf sediments has been traced to the rocks in the drainage basins of various rivers emptying their waters and sediment load into the Bay. The brown coloured and fine-grained sediments are rich in manganese and poor in calcareous sediments. The sediments brought to the sea by Godavari, Krishna and Vamsadhara and deposited just off the coast generally are richer in manganese content than those found elsewhere.

Organic Matter: On an average, organic matter constitutes 1.33 percent of the sediment (Subbarao, 1960). It has been observed, that generally the fine-grained sediments are richer in organic matter than the coarse-grained. The sediments of the continental shelf are poor in organic matter as compared with the world's average (2.5%) for near shore sediments. The low content of organic matter in these sediments is probably due to the low plankton production in the overlying waters of the Bay of Bengal.

Clay Mineral Studies

Clay mineral studies by differential thermal analysis indicated that montmorillonite forms the important constituent of the clays from Krishna delta, whereas montmorillonite, illite and kaolinite are present, of which kaolinite seems to be the least abundant (Sastry et al, 1958), in the Godavari delta area.

Beach Studies

Mahadevan and Prasada Rao (1958) studied the beach evolution and erosion at Kakinada Bay and Uppada beach north of it. They examined the available charts of the British Admirality of the region of Kakinada Bay of the last 100 years and found that a sand spit has grown north of Godavari confluence and that the beach at Uppada is being eroded They opined that the emergence of the sand spit might have been due to an excess of sediment supplied by a flood which overloaded the littoral drift, which is of the order of a million tons, resulting in depositing sand and other sediments. The later growth of the sand spit is attributed to the changes in the Godavari basin such as deforestation which increased the soil erosion and rise in the quantity of the sediment supplied

by the river. The rapidly growing spit is exercising a profound influence on the coastal erosion further northwards at Uppada.

Prasada Rao (1956) studied the annual cycles of beach erosion on the Waltair beach and found that changes in wave height and currents are mainly responsible for the beach erosion cycles and concluded that Visakhapatnam-Waltair beach is essentially a coast line of erosion.

Venkataratnam and Poornachandra Rao (1963) studied the development of sand spit separating the Chilka Lake from Bay of Bengal. It is concluded that flat coastal gradient, small tidal range, an abrupt change in the direction of the coast, a dominant longshore drift in one direction, absence of a stronger current initially to erode the foundation and initial part of the spit, were the essential factors in the formation of the sand spit.

Conclusions

In the Visakhapatnam area on the basis of the study of the sediments, several zones such as sand zone, clay zone, shell zone and oolith zone have been delineated. In the sand zone the economically useful mineral black sand concentrates were noticed.

The occurrence of coarse sediments in the outershelf was discussed and two factors namely, role of currents and eustatic changes of sea level and lowered sea level changes are suggested as possible agencies, the latter being supported by different kinds of evidence chiefly from the shallow water benthonic foraminifera and the association of ooliths.

The physical, optical and X-ray characters of ooliths indicate that they are due to inorganic precipitation of calcium carbonate as aragonite from the sea water. It is believed that the ooliths were formed at a time of lowered sea level during Pleistocene time.

It has been observed that fine-grained sediments are richer in organic matter than the coarse grained and the low content of organic matter is probably due to low planktonic production in the overlying waters.

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STUDIES ON THE EASTERN MARGIN OF CUDDAPAH BASIN, ANDHRA PRADESH

BY

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Abstract

Recent studies on the eastern margin of Cuddapah Basin have yielded interesting results that call for re-examination of the Cuddapah Basin stratigraphy. The stratigraphic position of the Nallamalai Series poses a problem and the answer is probably to be found in their being considered as rocks older than Cuddapahs, possibly Dharwars.

It had so far been believed that the Nallamalai rocks are free from basic intrusives. A number of basic sills intrusive into the Nallamalai beds have been discovered. Whereas the trap rocks of the sills in the Lower Cuddapahs are fresh and unaltered, the sills in the Nallamalais show a highly altered dolerite. Another interesting feature noticed during the recent survey is the presence of granite and pegmatite that are intrusive into the Nallamalai rocks. A tourmaline bearing quartz vein cutting across these beds has also been observed in one locality. These observations coupled with the fact that Nallamalai sediments are much disturbed and have attained a higher grade of metamorphism compared to the Lower Cuddapah rocks lead to the inference that the Nallamalais may not be of Upper Cuddapah age but may possibly belong to Dharwars.

THE studies on the eastern margin of Cuddapah Basin in Krishna, Guntur and Nellore districts, Andhra Pradesh carried out during the last two field seasons have yielded some very interesting data and in the light of these observations the Cuddapah Basin stratigraphy has to be viewed in a different perspective. The stratigraphic position of the Nallamalai series poses a problem and the answer is probably to be found in their being considered as rocks older than Cuddapahs, possibly Dharwars.

King (1872) classified the Cuddapah rocks as Papaghani, Cheyair, Nallamalai and Krishna series, in this ascending order overlain unconformably by the Kurnool group. The Nallamalai series, comprising slates, phyllites and occasionally

schists with intercalated bands of quartzite and dolomite (and limestone) has suffered considerable amount of disturbance and the beds have generally acquired steep dips upto 80° on the eastern margin. These beds are intensely folded isoclinally along the margin.

Although King placed the Nallamalai rocks above the Cheyairs, nowhere is the Bairenkonda quartzite found resting directly over the Tadpatri shales. The stratigraphic position assigned to Nallamalais was based on the supposition that the Nagaris and Pullampets are the respective equivalents of Pulivendla quartzite and Tadpatri shales. Such a correlation is however rather of an arbitrary nature. Similarly, the view generally held that the entire eastern margin of the Cuddapah Basin is a faulted one, is without foundation. Though definite evidences of the faulted nature of the boundary are recognisable in the extreme north-east part of the Basin (Palnad area), they are no evidences whatsoever to suggest that the boundry in the north-central and central portion of the Basin is faulted. King himself had expressed considerable doubt whether the entire margin of the Basin was a fault. In the absence of any evidences it is extremely hypothetical to consider thrusting of the gneisses on the east over the Nallamalais, and thereby accounting for the considerable disturbance of these sediments at and near the margin.

It had so far been believed that the Nallamalai rocks are free from any basic intrusives and that the trap activity in the Lower Cuddapahs did not extend into the Nallamalais.* Recently, during detailed mapping of the Nallamalai strata in the area covered by toposheet Nos. 57 M/9 and 57 M/5, a number of basic sills were discovered in the area about eight km. north-west of Kurichedu in Nellore district. The rock comprising the sills is an epidiorite consisting of hornblende, plagioclase, epidote and iron ores. In contrast to the unaltered and almost fresh-looking traps of the lower Cuddapahs, the basic rock of the sills in Nallamalais is metamorphosed.

While it has generally been held that the Nallamalai rocks on the eastern margin are resting directly over the granites unconformably, no such definite unconformity is recognisable. On the other hand there is a general parallelism of strikes of

* Note: In his memoirs on Barytes and Asbestos of the Cuddapah basin Coulson has stated that the basic sills are of immediately post-Nallamalai or Kistna age.—Editor.

the Nallamalai sediments with the foliation of gneissic granite on the east. An interesting feature noticed during the recent survey is the discovery of a band of granitic material within the quartzite considered to be of Bairenkonda stage. This feature is observed in two localities; in the .534 hillock about 0.3 km. north-west of Agnigundala village (16° 11′: 79° 44′) 56 P/12, the other locality being Kalivelakonda about two km. west of Agnigundala. It is clear from the outcrops that granite is intrusive into the Nallamalai sediments. This view is further supported by the presence of pegmatites intrusive into the phyllites in the locality about 0.8 km. south-west of hill △ 1092 (15° 57′: 79° 33′) -57 M/9. In the same locality is observed a quartz vein cutting across the quartzite (of Nallamalai series). This vein-quartz is tourmaline-bearing, suggesting thereby the presence of granite younger than these sediments. Kenoliths of phyllites and quartzites within granite outside the Basin proper also lend support to this view. The sum total of all these evidences leads to the inference that atleast some of the granite, if not all, in this region is intrusive into and younger than the Nallamalai beds.

If the fact of the granite being intrusive into the Nallamalais is established, either a post-Cuddapah granite intrusion is to be accepted, or, the stratigraphic position of the Nallamalai beds is to be questioned. There is reason to believe that the Nallamalai rocks may not after all be upper Cuddapahs but that they are older than Cuddapahs, possibly Dharwars, and that their anomalous position is probably to be explained by tetonic movement. There are number of points which favour their correlation with rocks older than Cuddapahs. The degree of disturbance suffered by the Nallamalai rocks in contrast to the practically undisturbed character of Lower Cuddapahs and the higher grade of metamorphism attained by these compared to the apparently underlying Papaghani and Cheyairs are features which need consideration. Besides, the Nallamalai rocks are profusely traversed by quartz veins which are not so conspicuous in the Lower Cuddapahs. Whereas the trap sills in the Lower Cuddapahs are fresh and unaltered, the sills discovered in the Nallamalais are of altered basic rock.

The discovery of basic sills and granite and pegmatite intrusions into the Nallamalai rocks and also the presence of tourmaline-bearing quarts veins will be of help in solving the stratigraphy of the Cuddapah Basin. Work in this direction is in progress.

REVIEW OF GEOCHRONOLOGICAL KNOWLEDGE OF PENINSULAR INDIA

By

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Abstract

From the available geochronological data obtained by Pb-U-Th, alpha-helium, Rb-Sr, isotopic lead-Uranium and lead-lead methods, a tentative succession of pre-Cambrian orogenic cycles in Peninsular India has been delineated - Dharwar 2300±100 m. y., Eastern Ghats 1625±75 m. y., Mahanadi 1350±200 m. y., Satpura 955±40., Delhi 735±30 m. y. and Kishengarh 580±20 m. y.

As these results are obtained by different methods the degree of dependability of each determinations is indicated. Preliminary results of the lead isotope studies on Zangamrajupalley galena yielded for the Cuddapahs an age of 1400–1470 m. y. The implications of such an age are discussed. The age of 492 m. y. for Cheralite from Tranvancore is suggestive of the existence of a pegmatitic cycle of Cambrian age.

Introduction

ARCHAEAN rocks occupy about two-thirds of Peninsular India. Their correlation is difficult due to the fact that there are chemical, mineralogical, petrological and structural changes from one end to the other in each of the formations, stretching over hundreds of kilometres. Two different formations with geographical continuity (e.g., Khondalites and schistose formations of Nellore mica belt) affected by a single orogenic cycle exhibit the same regional trend. Sometimes the same formation is disturbed by more than one orogenic movement. These orogenic movements have been established to have taken place in Precambrian times at intervals. For these reasons it is necessary to study the structural relationships of the formations and determine the absolute ages for purposes of correlation of ancient formations.

The first systematic attempt to correlate the Precambrian schistose formations was made by Fermor (1936). M. S.

Krishnan (1943, 1953) tried to arrive at a succession of the orogenies which produced the characteristic regional strikes of the structural provinces.

Only recently has some work been done on the determination of absolute ages (Holmes, 1949, 1950, 1955; Mahadevan and Aswathanarayana, 1955, 1962; Mahadevan et al, 1957, 1958; Venkatasubramanian, 1953; R. S. Krishnan, 1960; Venkatasubramanian and R. S. Krishnan 1961; Pichamuthu, 1962; and Sarkar and Saha, 1962).

Significance of the Age Data

To utilise the age data on minerals for purposes of correlation it is desirable to decide which geological events they record and to what extent they are dependable.

Most of the geological events such as uplift and erosion, faulting and folding, involve metamorphism or recrystallisation of minerals and they may require millions of years for completion.

Pegmatites associated with magmatic activity and metamorphism originate at the closing phases of orogenic activity or crustal instability. Pegmatites belonging to different orogenic cycles may yield ages corresponding to the particular orogeny, but may give anomalous age due to loss or gain of radiogenic lead at the time or times of recrystallisation.

Kulp and Eckelmann (1955) concluded that detailed study of the uranium and lead isotopic content of a deposit may make it possible to evaluate the time of deposition despite successive alterations and to obtain some idea of the time or times of lead removal.

The geological history of the sample as well as the method of age determination govern the degree of dependability of the ages. The 207/206 ratio is the least sensitive to losses or gains of radiogenic lead during the geological history of a uranium sample and the correction on the 207/206 age for radon leakage is generally unimportant for minerals older than 1000 m.y. So the age calculated from this ratio would be closest to the true age of deposition or crystallisation (Mawdsley and Farquhar, 1955).

Radon leakage causes a lowering of the 206/238 age. But in cases of recent oxidation and leaching, the 207/235 ages are higher than the 207/206 ages. Due to the preferential leaching of Pb^{208} to the other lead isotopes as well as to the thorium, the 208/232 ages can be accepted if they show concordance with 207/206 ages (Kulp and Eckelmann, 1957).

The ages calculated from the isotopic composition of galena indicate only approximate age of mineralisation.

"The rubidium–strontium age values determined for separated minerals from the same rocks are internally consistent but are higher by 10 to 30 percent than the ages obtained for the same rocks by the uranium–lead methods" (Mawdsley and Farquhar, 1955).

Gastil (1960) suggests that potassium 40/argon 40 dates for micas and potassium feldspars of < 100 m.y. are reliable. Further, the dates determined for older feldspars and non–isotopic chemical analysis, common lead, helium and lead-alpha methods, while frequently are correct and useful as confirmations, are not considered reliable by themselves.

This paper reviews the available age data on the Peninsular India.

Age Data

The available age data are listed in tables I – IV. Only the more dependable ages are discussed.

Dharwar Cycle: The 207/206 age of monazite sample from the pegmatite of Yediyur is 2300 $\pm$ 100 after correction for the "inherited lead". (Holmes, 1955). The remarkable similarity of the ages (1, 2 and 3 in table I) suggest an age of 2300$\pm$ 100 m.y. for the Dharwar cycle.

The ages of microline, perthite and magnetite (4, 5 and 6 Table I) indicate the minimum age of metamorphism as 1870–1700 m.y. Phlogopite occurring near Punalur is associated with rocks whose general trend corresponds to Dharwarian strike (N.N.W-S.S.E) according to Subramanyam, (1941). Its age of 1630 m.y. (Venkatasubramanian, 1953) suggests that it has been formed at the time of Eastern Ghats orogeny.

TABLE I

Dharwar Cycle

Sl. No.	Name of the mineral or rock dated	Locality	Method of age determination	Age (in m.y.)	Remarks.	Reference
1.	Monazite	Yediyur, near Bangalore, Mysore.	Isotopic lead analysis.	2300 ± 100	207/206 > 208/232 > 207/235 > 206/238 2300 ± 100 1840 ± 40 1810 1430	Holmes (1955)
2.	Galena	Ingaladhal, Chitaldurg, Mysore.	Isotopic lead analysis.	2320 ± 120	Conventional age read from diagrams — 2450 ± 120 m. y.*	Russel (1954) *Holmes (1955)
3.	Monazite	Yediyur, Mysore.	Lead-alpha method.	2200 ± 100		Venkatasubramanian & Krishnan (1961)
4.	Microcline	Vasantapura, adjacent to Yediyur, Mysore.	Argon method.	1920	The mean standard deviation is ± 6 percent.	-do-
5.	Perthite	Yediyur, Mysore.	-do-	1870	-do-	-do-
6.	Magnetite	Holenarasipur, Mysore.	Alpha-Helium method.	1700		-do-
7.	Phlogopite	Punalur, Travancore.	Rb-Sr. method.	1630	The mean standard deviation is ± 8 percent.	-do-
8.	Allanite	Kamalapur, Madura dist., Madras.	Pb-U-Th method.	1860	Chemical age.	Aswathanarayana (1953b)

TABLE II

Eastern Ghats Cycle

Sl. No.	Name of the mineral or rock dated	Locality	Method of age determination	Age (in m. y.)	Remarks.	Reference
1.	Deterital monazite.	Satbhaya, Cuttack Dist., Orissa.	Isotopic lead analysis.	1570 ± 70	206/238 > 207/235 > 207/206 > 208/232 4300 3100 1600 ± 40 540 for the 207/206 age correction for inherited lead was applied.	Holmes (1955).
2.	Muscovite I	Nellore.	Argon method	1560	The mean deviation is ± 6 percent.	Venkatasubramanian & Krishnan (1961).
3.	Muscovite II	Nellore.	–do–	1600	–do–	–do–
4.	Biotite	Nellore.	–do–	1620	The mean deviation is ± 8 percent	–do–
5.	Cyrtolite	Sankara Mine, Nellore.	Lead-alpha method.	1490	–do–	–do–
6.	Quartz-magnitite rocks.	Kanjamalai, near Salem, Madras.	Alpha-helium method.	1500		–do–
7.	–do–	Ongole.	–do–	1350		–do–
8.	Vanadium bearing magnetite.	Mayurbhunj, Orissa.	–do–	1200		–do–
9.	Phlogopite.	Borra, Visakhapatnam Dist.	Rb-Sr. method.	1490	The mean deviation is ± 8 percent	–do–
10.	Samarskite.	Nellore, Andhra.	Pb-U-Th method.	1550	Chemical age.	Aswathanarayana (1953a)
11.	–do–	–do–	–do–	1765	Chemical age.	Nandi & Sen (1950a).
12.	–do–	–do–	–do–	1615	Chemical age.	Karunakaran & Neelakantam (1948).
13.	Allanite.	Anakapalli, Andhra.	–do–	1585	Chemical age.	Aswathanarayana (1956).

TABLE III

Satpura Cycle

Sl. No.	Name of the mineral or rock dated	Locality	Method of age determination	Age (in m. y.)	Remarks.	Reference
1.	Uraninite.	Singar, Bihar.	Isotopic lead analysis.	955 ± 40	208/232 > 207/206 > 207/235 > 206/238 1003 995 912 883	Holmes (1950)
2.	Lepidolite.	Monghyr, Bihar.	Argon method.	1040	The mean deviation is ± 6 percent.	Venkatasubramanian & Krishnan (1961)
3.	Muscovite.	Ghatsila, East Singhbhum, Bihar.	-do-	905	After Kulf.	Sarkar & Saha (1962).
4.	-do-	-do-	-do-	934	After Polkanov.	-do-
5.	Lepidolite.	Monghyr, Bihar.	Rb-Sr. method.	950	A second sample yielded an age of 870 m. y. The mean deviation is ± 8 percent on two samples.	Venkatasubramanian & Krishnan (1961).
6.	-do-	Hazaribagh.	-do-	1050	-do-	-do-
7.	Magnetite	Chaibasa, Singhbhum, Bihar.	Alpha-helium method.	970		-do-
8.	Monazite	Gaya, Bihar.	Pb-U-Th method.	965	Chemical age on a second sample also gave an age of 965 m. y.*	Sarkar (1941) *Sarkar (1952)
9.	-do-	Pichchli, Bihar.	-do-	970	Chemical age.	Nandi & Sen (1950).
10.	Allanite	Ranchi, Bihar.	-do-	980	Chemical age on a second sample also gave an age of 980 m. y.	Sarkar & Sarma (1946).
11.	-do-	Bahea, Near Singar, Bihar.	-do-	880	Chemical age.	Nandi & Sen (1950b).
12.	-do-	Purulia, Bihar.	-do-	880	Chemical age. Analyst - Ch. Leelanandam.	Aswathanarayana (1956)
13.	Monazite	Hazaribagh, Bihar.	-do-	950	Chemical age: Analyst - K. Sreenivasulu.	-do-
14.	-do-	Monghyr, Bihar.	-do-	980	Chemical age: Analyst - D. Purushottam.	-do-

TABLE IV

Delhi Cycle

Sl. No.	Name of the mineral or rock dated	Locality	Method of age determination.	Age (in m. y.)	Remarks.	Reference
1.	Uraninite.	Bisundni, Rajputana.	Isotopic lead analysis.	735±5	208/232 > 207/206 > 206/238 > 207/235 935 740 735 735	Holmes (1949).
2.	Monazite.	Soniana, Rajputana.	-do-	700-865	207/206 > 207/235 > 206/238 > 208/232 865 700 660 615	-do-

Travancore and Ceylon

1.	Monazite concentrate.	Beach sands, Kerala.	Isotopic lead analysis.	600	206/238 > 207/235 > 208/232 > 207/206 700 630 615 380+360	Holmes(1955).
2.	Zircon.	Manavalakurichi, Kerala.	Lead alpha method.	1025	Spread of ages on 4 different samples 1025-965.	Venkatasubramanian & Krishnan (1961)
3.	Detrital monazite.	Beach sands, Kerala.	-do-	775	Spread of ages on 2 different samples 775-735.	-do-
4.	Cheralite.	Kerala.	-do-	445		-do-
5.	-do-	Kuttakuzhi, South Travancore.	Pb-U-Th.	492	Chemical age.	Bowie & Horne (1953).
6.	-do-	-do-	-do-	490	Chemical age.	Holmes (1955.)

Iron Ore Orogeny : Sarkar and Saha (1962) on the basis of A 40/K 40 data on potash feldspars from Singhbhum granite pegmatite from Onlajori, Mayurbhanj, have given an age of 2000 m.y. to the Iron Ore orogeny.

Eastern Ghats Cycle : The remarkable similarity of the ages determined by several methods permits to adopt 1570 ± 70 m.y. as the age of Eastern Ghats cycle. From the available age data it can be established that magmatic or metamorphic activity (pegmatites) common to both Nellore mica belt (ages 2–6 and 10–12 – Table II) and Eastern Ghats (ages 1, 7–9 and 13–Table II) was prevalent at the closing phases of Eastern Ghats orogeny. This constitutes additional evidence in favour of the surmise of Mahadevan (1949) that the Nellore mica belt is a continuation of the Khondalitic belt.

Mahanadi Cycle

M. S. Krishnan (1943, 1953) distinguishes a "Mahanadi strike" (NW–SE) from the "Dharwarian strike" (NNW–SSE). Venkatasubramanian (1957) reported 1350 ± 200 m.y. as the age of Bastar lepidolite. Later on an age of 1400 ± 120 m.y. was adopted as the age of the lepidolite (Venkatasubramanian and R. S. Krishnan, 1916). This single determination does not warrant to confirm the existence of a separate orogenic cycle. From the age data, it is however indicated that the magmatic activity following the tectonic disturbances of the Eastern Ghats orogeny came to an end earlier than that of Mahanadi. Detailed structural mapping of this area and several age determinations are necessary to validate these opinions.

Satpura Cycle

The ages on different minerals from Satpura orogenic belt do not deviate much from each other (Table III). The accepted age for Satpura orogenic cycle is 955 ± 40 m.y.

Aravalli and Delhi Cycles

It is not yet clearly established whether the Aravalli trend gradually turns round and merges into the Satpura strike or continues under the trap cover linking up with the Dharwars of Mysore. This will eventually be resolved by the application of radioactive methods of age determination on minerals from the various pegmatites and granitic rocks.

The Delhi orogenic belt is superimposed on the Aravalli belt which overlies gneissic complex and has the same regional trend NE–SW except in the southwest. So far only two age determinations from the pegmatites belonging to Delhi orogeny are available and 735±5 m.y. is accepted as its age (Table IV).

Aswathanarayana (1959) determined the age of samarskite from post–Delhi pegmatite of Kishengarh, Rajasthan and obtained remarkably concordant ages after correction for "inherited lead."

$$\frac{206/208}{587} > \frac{207/206}{579} > \frac{207/235}{578}$$

An age of 580 ± 20 m.y. is given as the age of this particular post–Delhi pegmatite.

The Cuddapah and Vindhyan Systems

From the isotopic analysis of Zamgamrajupalle galena, Cuddapah, Aswathanarayana (1962a) calculated the age as 780–840 m.y. and later revised it to 1400–1470 m.y. (1962b). This age is only of approximate nature since it is calculated from the isotopic composition of galena. So far, the Cuddapahs are considered to be equivalents of Delhi system but Aswathanarayana (1962b) on the basis of his age data arrived at the same inferences as Holmes (1955) that the Cuddapahs belong to the end of the Eastern Ghats cycle and the period immediately following. Holmes argues that if the Aravallis had a floor of ancient Gneiss equivalent to Peninsular Gneiss, the Eparchaean interval of Andhra would probably be represented in Rajputana by the unconformity at the base of Aravallis. The Cuddapahs might then be contemporaneous with the Aravallis and are perhaps older than Delhis.

The interpretation of the age 1400–1470 m.y. for the Zamgamrajupalle galena (occurring as veins in the Cumbum shales, Nallamalai Series) requires a knowledge of its genesis. If the lead from unknown source rocks is disseminated in shales at the time of deposition and concentrated later during the igneous activity, (without any lead contamination by the igneous body) then the age of galena approximately corresponds to the age of the source rocks.

The Morar stage of the Gwalior series which may be considered as equivalents of Vindhyans indicated on the basis of helium ratios of basaltic rocks, an age ranging from 500–200 m.y. (Dubey, 1930). To what extent there has been loss of helium from the material investigated is not known.

Travancore and Ceylon

It may be pointed out that minerals of beach concentrate of Travancore (Kerala) belong to more than one age. The age of a placer mineral deposit may correspond to any of the orogenic cycles that source area had experienced or may yield a "composite age" which does not coincide with the age of any one of the established orogenic cycles.

Age data are at present quite scanty. Until a large number of new data can be accumulated, no reliable conclusions can be drawn on the age relationship of the several Archaean and Precambrian provinces of India.

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EXPERIMENTAL STUDIES ON ELASTIC PROPERTIES OF SOME INDIAN ROCKS

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Abstract

Determination and study of elastic properties of rocks in the laboratory under simulated conditions of pressure and temperature that normally exist in the crustal regions, will enable us to decipher the nature of the earth's crust. Modern techniques involving the measurement of the resonance frequency, critical angle at the liquid solid interface, measurement of travel time in a rock specimen (of the order of micro-seconds) have been set up using Piezo Electric Transducers. From a knowledge of the above it is possible to calculate the velocity of sound in rocks in the high frequency (Mega-cycle) region. The transmission of sound in rocks is intimately connected with certain geological features, viz., granular structure, porosity mineralogical assemblage, chemical composition, deformation and history of the specimen. In the present paper an attempt is made to discuss the dependence of physical properties of rocks on certain geological features in the case of some typical Indian rocks.

Introduction

ROCKS, which are essentially polycrystalline aggregates where individual crystallites composing the aggregate are usually randomly oriented, will be elastically isotropic exhibiting only two elastic constants. Experimental studies on elastic properties of rocks involve measurement of these two constants. They can indirectly be calculated if the elastic wave velocity values, both longitudinal and torsional are determined. Many investigators for the past three decades are engaged in developing modern and refined techniques for measuring elastic wave velocities. These techniques are broadly divided into two groups viz., field and laboratory. Laboratory techniques are fur-

ther divided into static and dynamic(Low frequency, High frequency and pulse techniques). Mention may be made of Hughes (1956), Birch (1956); Shimozuru (1960); Bayuk (1960); Levykin (1962) who did extensive work on measurement of wave velocities in rocks. In India some techniques have been developed and successfully employed to measure ultrasonic velocities in rocks in the laboratories of Prof. Bhagavantam. Bhagavantam and Bhimasenachar (1944) developed 'wedge method', the main feature of which is the realisation of a source which gives an ultrasonic beam of continuously varying frequencies. Krishnamurthi and Balakrishna (1953) developed a pulse technique involving the phenomenon of total internal reflection. Balakrishna and Ramana (1963) developed a pulse technique involving the measurement of travel time across a given length of rock specimen in terms of equivalent length of mercury column. All these methods have been very successfully employed by the author and his colleagues very extensively to measure ultrasonic wave velocities in various rocks of Peninsular shield. In this present paper a brief review is made of the results obtained in case of some Indian rocks and the various special features are discussed in detail.

Elastic Constants of Some Typical Rocks

The following table gives the density (ρ) gms/Cm^3; ultrasonic velocities both longitudinal (V_l) and Torsional (V_t) in Km/Sec; Young's modulus (Y), rigidity modulus (n) in 10^{11} dynes/Cm^2; and Poisson's ratio, in the case of some typical rocks belonging to Peninsular shield. Individual localities are not given since we are discussing very broad results. Most of the values given here are verified by the three different high frequency methods viz., Wedge method, Rotation reflection technique and Pulse technique; and the best result is given. Again for each rock type an average value of at least ten samples is given. As such values given here are representative but not of any isolated cases. An accuracy of less than 1% is aimed at the velocity values. In some cases the possible range of values in a rock type is also indicated.

Ultrasonic Velocities in some Typical Rocks

Rock Type	ρ	V_l	V_t	Y	n	σ
1. Hyderabad Granite	2.6	6.4	3 3	7.9	3.9	0.31
2. Hyderabad granite (Pink)	2.6	6.0	2.4	4.2	1.5	0.39
3. Hyderabad Granite (Grey)	2.7	6.7	3.3	7.4	2.7	0.34
4. Podili Granite	2.6	6 2	3.0	6.7	2.5	0.35
5. Errimpura Granite	2.7	6.2	2.9	6.4	2.4	0.35
6. Bundelkand Granite	2.6	6 0	2.8	6 5	2.4	0.35
7. Ranchi Granite	2.6	6.2	3.0	6.2	2.3	0.35
8. Closepet Granite	2.6	6.5	3.2	6.9	2.5	0.35
9. Kondapalli Charnokite (Acid)	2.6	6 1	3.1	6.2	2.5	0.33
10. Pallavaram Charnokite (Basic)	3.0	6.2	3.2	8.2	3.1	0.32
11. Kondapalli Charnokite (Ultrabasic)	3.0	6.6	3 5	9.9	3.7	0.32
12. Deccan trap	3.0	6.6	3.2	8.3	3.1	0.34
13. Deccan trap	3.1	6.8	3.2	8.6	3.2	0.36
14. Deccan trap	2.9	7.2	2.9	6.0	2.7	0.36
15. Dolerite	3.1	8.3	4.0	13.6	5.1	0.35
16. Dolerite	2.9	7.4	3.6	12 9	5.0	0.35
17. Dolerite	3.0	8.0	4.1	13.8	5.2	0.32
18. Ryolite	2.7	6.9	3.2	7.6	2.8	0.36
19. Ryolite	2.7	7.0	3.1	7.6	2.8	0.36
20. Schist	2.9	6.0	2.9	6.5	2.4	0.35
21. Schist	2.6	6.2	3.0	6.7	2.5	0.35
22. Khondolite	2.6	4.9	2.2	3.2	1.2	0.39
23. Gneiss	2.7	6.7	3.1	7.3	2.7	0.38
24. Gneiss	2.7	7.1	2.9	6.7	2.4	0.39
25. Nephelene Syenite	2.7	6.2	2.7	5.6	2.1	0.37
26. Nephelene Syenite	2.7	6.3	2.8	6.4	2.2	0.39
27. Sodalite Syenite	2 7	6.4	2.7	5.4	2.0	0.38
28. Peridotite	3.0	7.5	2.9	7.1	2.5	0.39
29. Quartzite	2.6	6.6	3.4	8.0	3.0	0.32
30. Quartzite	2.6	6.4	2.8	5.6	2.0	0.38
31. Marble	2.9	6.8	3.4	8.8	3.3	0.34
32. Marble	2.9	6.2	3 0	7.3	2.7	0.34

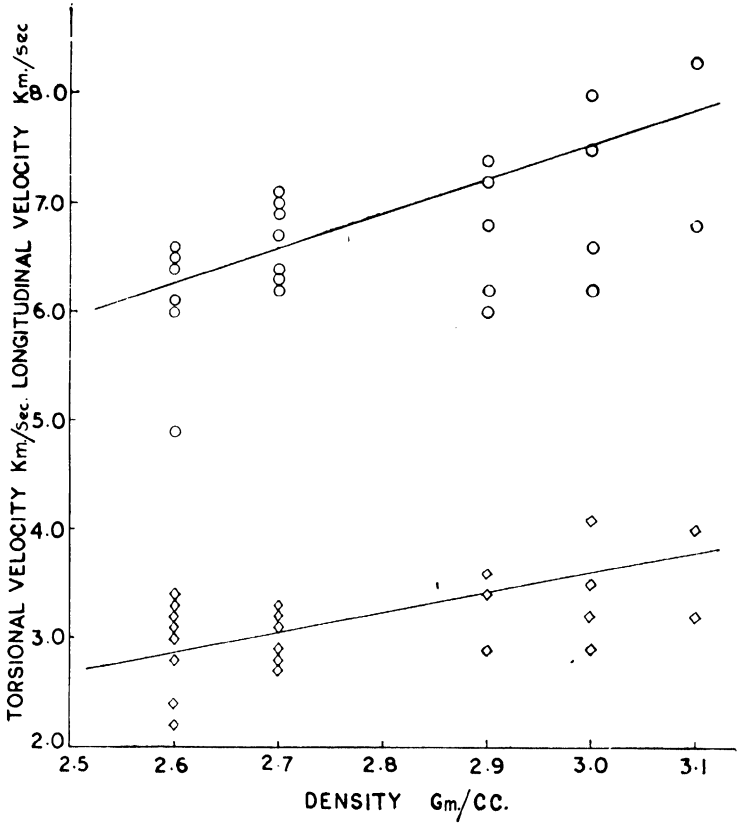
TORSIONAL VELOCITY Km/Sec. LONGITUDINAL VELOCITY Km./sec
8.0
7.0
6.0
5.0
4.0
3.0
2.0
2.5
2.6
2.7
2.8
2.9
3.0
3.1
DENSITY Gm/CC.

Figure (1)

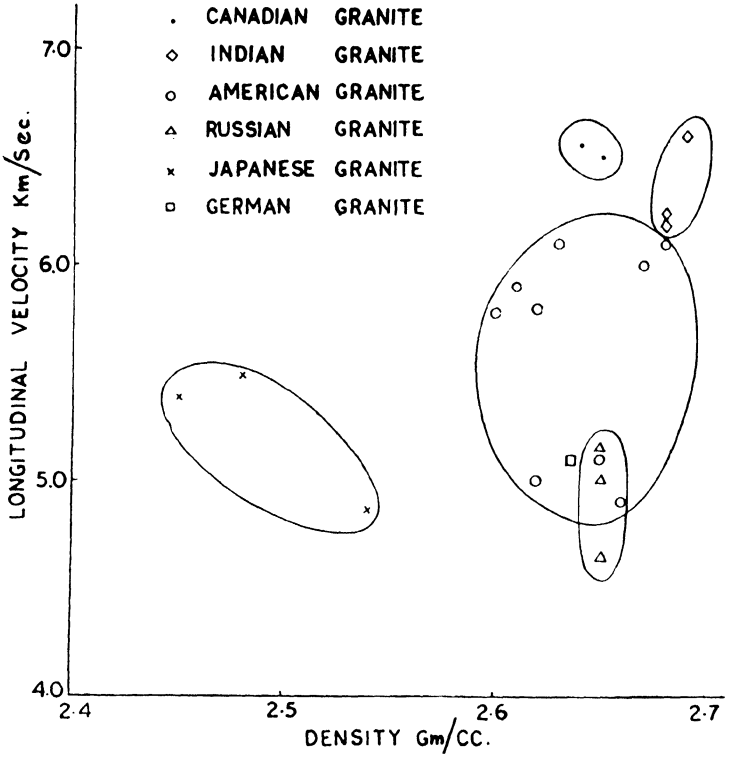
CANADIAN GRANITE
INDIAN GRANITE
AMERICAN GRANITE
RUSSIAN GRANITE
JAPANESE GRANITE
GERMAN GRANITE
LONGITUDINAL VELOCITY Km/Sec.
7.0
6.0
5.0
4.0
2.4
2.5
2.6
2.7
DENSITY Gm/CC.

Figure (2)

Fig. (1) shows the variation of ultrasonic wave velocities both V_l and V_t with density. In general as density increases the velocities increase.

Some Special Features in Indian Granites

Granite represents a typical rock in the Peninsular shield area and is also a well understood rock throughout the world. It has been observed in the course of a detailed investigation that Indian granites exhibit high ultrasonic velocity values in contrast to the specimens obtained from other countries. Table II gives the comparison of elastic wave velocities, longitudinal, in granites obtained from different localities in the world. An analysis of the literature shows that the velocities in rocks depend on the petrogenetic history of the rock, on the method which is employed and consequently on the size and shape of the sample. Care has been taken to see that results on granites obtained by employing pulse techniques are compared.

TABLE II

Comparison of Elastic Wave Velocities in Granites

Locality	ρ	V_p (O)	*Author*
Rock Port	2 62	5.00	Birch (1960)
Chemsford	2.63	4.21	Birch
Barre	2.65	5.10	Birch
Englehart	2.68	6.10	Birch
Sacred Heart	2.66	5.90	Birch
Minnesota	2 67	6.00	Birch
Quincy	2.62	5.80	Hughes (1956)
Westerly	2.61	5 90	Hughes
Texas Pink	2.63	6 10	Hughes
Texas Grey	2.60	5.78	Hughes
Hachimura, Japan	2.54	4.86	Shimozuru (1960)
Kyoto, Japan	2.45	5 38	Shimozuru (1960)
Japan	2.48	4.09-5.89	Kubotera (1962)
U.S.S.R.	2.65	4.64	Fai-Wei-Ching(1960)
U.S.S.R.	2.65	4.4 -5.9	Vasilov (1962)
U.S.S.R.	2.65	5.00	Silaeva (1959)
Germany	2.64	5.10	Muller (1954)
Canada	2.64	6.56	Balakrishna (1955)
Canada	2.65	6.50	Balakrishna (1955)
Hyderabad Pink	2.68	6.25	Balakrishna (1963)
Hyderabad Grey	2.68	6.25	Ibid
Closepet	2.69	6.60	Ibid
Podili	2.68	6.20	Ibid

A plot of density versus longitudinal velocity at atmospheric pressure and room temperature (Vp°) is shown in Fig. (2) for granites of different countries (Table II). It can be clearly seen that Peninsular granites (Indian and Canadian) show higher velocity values when compared to other granites (Japan, Russian) presumably because of their distinct petrogenetic history and long geological time that has gone by. American rocks are intermediate and very well fit into the spectrum.

A large scattering in the Poissons ratio σ for granites is noticed. It is again interesting to notice that Indian granites show high Poissons ratio. Table III gives the average values for poissons ratio for granites and the range of values.

TABLE III

Average Values for Poissons Ratio

Values of σ *for granites*	*Mean*	*Author*	(*Year*)
0.18 to 0.31	0.245	(Molotova)	1960
0.17 to 0.25	0.21	(Silaeva)	1960
0.19 to 0.28	0.23	(Kubotera)	1954
0.23 to 0.24	0.236	(Birch)	1938
0.29 to 0.32	0.310	(Hughes)	1956
0.31 to 0.39	0,35	(Balakrishna)	1962

A large scater in velocity values themselves at atmospheric pressure and a dissimilar behaviour with pressure in granites of different countries have been noticed. Hayakawa and Balakrishna (1961) discussed the variation of velocities in rocks and offered a tentative explanation for the high ultrasonic velocities in Indian rocks. It has been concluded that in the case a granite the depth of original formation as well as its age are high, we should expect it to exhibit high velocity values. At the other end of the spectrum will be cases of granites in which the depth of original formation as well as age are low, consequently exhibiting low velocities. Intermediate cases are bound to come up with either of the parameters or both taking intermediate values. One of the main conclusions is that under higher pressure a lot of stress energy can be stored i.e., the initial velocity becomes high when the rock is found at great depths while at shallow depth less stress energy can be stored and consequently the velocity is less.

Table IV gives the comparison of velocities in typical rocks of distinctive localities in the world as obtaind by different workers. It generally suggests that rocks from Peninsular shield (India) show higher velocity values.

TABLE IV

Comparison of Ultrasonic Velocities in Indian and other Countries Rocks.

Rock	*Jai-wei-Ching* (1961) U. S. S. R.		*Shimozuru* (1960) Japan		*Birch* (1960) U.S.A.	*Hughes* (1956) U.S.A.		*Muller* (1954) German		*Balakrishna* (1963) India	
	V_p	V_s	V_p	V_s	V_p	V_p	V_s	V_p	V_s	V_p	V_s
Granite	4.6	3.0	4.6	3.0	5.1	5.5	3.0	5.1	2.9	6.4	3.3
Basalt	5.5	3.3	5.5	3.5	6.5	5.4	3.2	6.4	3.2	6.8	3.0
Limestone	5.1	2.8	5.6	3.2	5.1	5.9	2.8	5.0	2.6	6.5	3.1
Schist	4.8	2.9	5.0	2.7	5.7	—				6.0	3.2
Gneiss	—		4.6	3.0	3.4	—				6.7	3.1
Marble	—		5.8	3.3	5.6	5.8	2.8			6.6	3.2
Quartzite	—		5.6	3.0	5.6	5.9	3.8	4.3	2.9	6.3	3.0

In order to confirm this high velocity values in the rocks of Peninsular shield and also to test the reliability of the experimental technique employed, results are obtained on the same sample by different methods set up in the laboratory. Table V gives the compressional wave velocities (V_p) obtained on the same sample by different methods.

TABLE V

Determination of V_p by several Methods

Rock	*Wedge*	*Critical transmission*	*Pulse transmission*	*Mean*
Pink Granite	6.56	6.11	6.00	6.22
Grey Granite	6.74	6.52	6.59	6.62
Charnokite	6.24	6.70	6.20	6.38
Basalt	6.36	6.70	6.25	6.45
Marble	6.83	6.83	6.93	6.88
Sandstone	4.20	4.60	4.09	4.12
Limestone	6.60	6.40	6.70	6.56
Dolerite	7.40	7.70	7.61	7.75
Quartzite	6.40	6.30	6.50	6.40

In granites, chief constituents are quartz and felspar. Many types of granites contain these two minerals in different proportions. An attempt is made here to tabulate the modal composition of granites and longitudinal velocities to study their dependence.

TABLE VI

Modal Composition and Variation of V_p in Granites

Sl. No.	V_p	*Quartz*	*Total felspar*	*Other accessories*
1.	5.7	24.8	67.1	8.1
2.	5.8	26.1	70.1	3.8
3.	6.1	26.4	56.0	17.6
4.	5.9	27.6	68.4	4.0
5.	5.7	27.8	64.6	7.6
6.	5.4	28.2	67.1	4.7
7.	6.0	28.6	62.0	10.0
8.	6.2	28.9	66.2	4.9
9.	6.5	32.9	64.4	2.7
10.	6.7	34.5	56.6	8.9
11.	6.5	35.6	61.3	3.1
12.	6.3	36.0	56.6	7.4
13.	6.1	36.1	56.3	17.6
14.	6.5	37.9	58.5	3.6
15.	6.5	37.2	60.2	2.6
16.	6.7	38.2	52.6	9.2
17.	6.7	38.5	58.1	3.4
18.	6.1	41.8	53.1	5.1
19.	6.9	42.0	55.2	2.8
20.	6.2	44.7	55.9	0.2

Fig. 3 shows a variation of ultrasonic velocity value (V_p) with increasing quartz content in granites. The relationship is more or less linear.

Isotropy or Anisotropic behaviour of Rocks

A study of variation of elastic properties with direction is of great importance to seismologists, specially in the light of the assumption that earth's crust and the materials composing the crust are elastically isotropic. Divergent results have been obtained by many workers in the laboratory regarding the

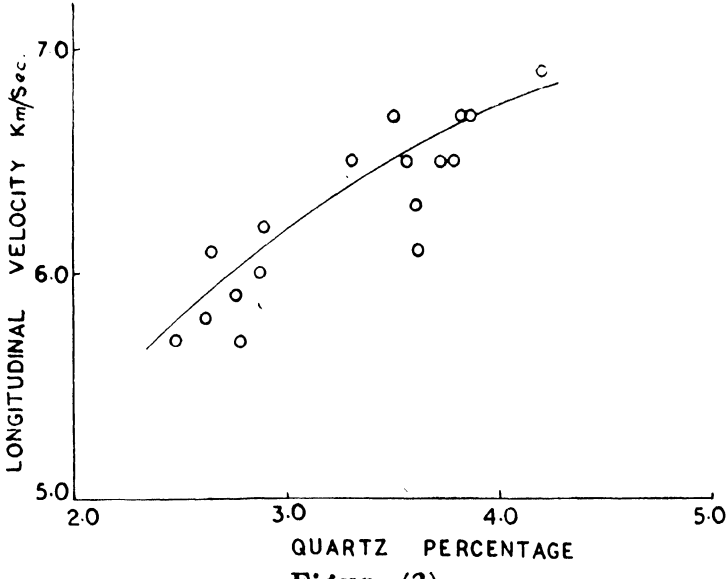
LONGITUDINAL VELOCITY Km/Sec.
7.0
6.0
5.0
2.0
3.0
4.0
5.0
QUARTZ PERCENTAGE

Figure (3)

isotropy or otherwise in the case of rocks. Employing the direct transmission technique, the velocities (V_l) are measured in terms of travel times across a given length of specimen. The specimens used here are rectangular bars and permit measuring velocities in three mutually perpendicular directions by changing the position of specimen each time. Table VII gives the velocity values (Km/Sec) in a specimen measured in three mutually different perpendicular directions (A, B and C). The mean value is also given to indicate the departure, if any, from perfect isotropy.

TABLE VII

Isotropic behaviour of Rocks (V_l)

S, No.	*Rock*	*A*	*B*	*C*	*Mean*
1.	Granite	6.77	6.77	6.76	6.77
2.	Granite	6.15	6.20	6.12	6.16
3.	Granite	6.56	6.58	6.52	6 55
4.	Granite	6.56	6.59	6.62	6.59
5.	Granite	5.94	6.10	6.01	6.02
6.	Charnokite	6.39	6.46	6.49	6.45
7.	Charnokite	6.24	6.41	6.72	6.45
8.	Charnokite	6.28	6.97	6.56	6.54
9.	Charnokite	6.59	6.64	6.38	6.54
10.	Charnokite	6.29	6.00	5.73	6.00
11.	Deccantrap	7.36	7.53	7.33	7.40
12.	Deccantrap	6.85	7.06	6.99	6.96
13.	Deccantrap	6.99	6.69	6.91	6.86
14.	Deccantrap	6.52	6.37	6.73	6.54
15.	Deccantrap	6.22	6.12	6.04	6.13
16.	Dolerite	7.77	7.78	7.90	7.82
17.	Dolerite	7.60	7.65	7.75	7.66
18.	Dolerite	7.93	7.85	7.70	7.83
19.	Quartzite	6.03	5.01	6.20	6.05
20.	Quartzite	5.91	6.26	6.16	6.11
21.	Quartzite	6.32	6.00	6.18	6.16

The following table gives velocity values in mutually perpendicular directions to a specific reference plane viz., foliation, schistosity, bedding plane and lineation. One section was cut parallel to the reference direction and velocities are measured in the direction perpendicular to the reference (a)

while the other is cut perpendicular to the reference direction and velocities measured in parallel to the reference (b). The results are given in table VIII.

TABLE VIII

Dimensional Orientation and Anisotropy

			a		b	
S. No.	*Rock*	*Reference Direction*	V_l	V_t	V_l	V_t
1.	Gneiss	Foliation	7.0	2.5	6.2	2.4
2.	Gneiss	,,	6.7	2.4	6.1	2.3
3.	Schist	Schistosity	6.5	2.7	5.9	2.6
4.	Schist	,,	6.4	2.6	6.0	2.4
5.	Schist	,,	6.8	2.7	6.1	2.5
6.	Granite	Lineation	6.5	3.1	6.2	2.9
7.	Granite	,,	6.3	3.0	5.7	2.7
8.	Granite	,,	6.1	2.9	5.9	2.7
9.	Charnokite	,,	6.9	3.2	6.3	2.8
10.	Charnokite	,,	6.3	—	5.7	—
11.	Charnokite	,,	6.2	—	5.5	—
12.	Deccantrap	Flowplane	6.8	2.9	6.3	2.6
13.	Deccantrap	,,	6.7	3.2	6.1	2.8
14.	Deccantrap	,,	7.4	3.3	6.4	2.7
15.	Limestone	Bedding Plane	7.4	3.3	6.6	3.0
16.	Limestone	,,	6.6	3.2	6.1	2.9
17.	Limestone	,,	6.9	3.3	6.4	2.8
18.	Limestone	,,	7.3	—	6.6	—
19.	Quartzite	Elongation	6.0	2.8	5.7	2.5
20.	Quartzite	,,	5.9	2.6	5.4	2.4

Preferred orientation of rock components, which is a record of the fabric that has responded to the vectors of movement suggests the degree of deformation that the rock has suffered. Where the deformation has been sufficiently penetrating, the preferred orientation of rock components, whether it be a grouping according to grain shape (dimensional orientation) or an arrangement of the space lattic (crystallographic or lattic orientation) of ten reflects the megascopic structure of the rock and also the kind of movement that caused the development of structure. Dimensional orientation can best be studied in the field by measuring the foliation planes, schistosity and lineation directions, while crystallographic orientation be studied by the universal stage technique.

Rocks in table VIII have a definite dimensional orientation and the velocities are influenced by these and hence the anisotropy is noticed. This is to be expected in these types of rocks because more compaction has taken place in the direction perpendicular to the reference plane and also because of the varying stresses acting on them. It is interesting to note that both the velocities V_l and V_t vary in a similar manner in all the cases. Another significant feature is that the elastic anisotropy is considerable in gneisses, schists, limestones, and Deccantraps while granites, dolerites, charnokites and quartzites show almost perfect isotropy. Granites whose origin itself is controversial exhibit elastic isotropy presumably because of their plutonic origin and others exhibit anisotropy because of the deformation they have undergone during their petro-genetic history.

Conclusion

The discussion in this paper is restricted to rocks from Peninsular Shield in India. Ultrasonic velocities in rocks are found to be around 6.0 Km 7.0 Km, (V_l) and 2.6 to 3.2. Km (V_t). These values are found to be higher when compared to similar rock types found in other countries. Presumably the depth of formation and old age are responsible for such a high value in the rocks of Peninsular Shield. Generally rocks of igneous origin and fine grained metamorphic rocks are found to be elastically isotropic while dimensionally oriented rocks exhibit anisotropy.

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PETROFABRIC STUDIES IN THE PRE-CAMBRIAN ROCKS OF YELLANDLAPAD AREA, ANDHRA PRADESH

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Abstract

The Pre-Cambrian rocks of Yellandlapad area which include the Pakhals and the associated high grade metamorphites, show intense deformation. The major structure in the area may be roughly decipharable into three isoclinal anticlines with corresponding synclines, all of which plunge either to the north or north-east. Studies have been made on structural elements like foliation, lineation, joints, minor-folds etc., in both the high grade metamorphics (in the cores of anticlines) as well as the Pakhals (in synclines). Petrofabric diagrams have been prepared from oriented specimens collected in type localities within the area. All these studies show that the Pakhals and the high grade metamorphic rocks have undergone the same tectonic history. Further, the whole region was subjected to one period of deformation, the stresses acting along east-west direction. But subsequently, there was a shift in stress direction. This second phase may have operated from the south-east and not from north-west. Both the phases of tectonic activity may not belong to two independent periods of deformation but to a single period in which there was a shift in tectonic drive during the later part.

Introduction

THE plutonic rocks around Yellandlapad area present a number of problems regarding their structure and metamorphism. It was William King (1882) who first mapped the Pakhal group of rocks and correlated them with the Cuddapahs on the basis of certain lithological similarities and moderate degree of metamorphism. Around Yellandlapad, however, he observed the intense deformation to which the rocks have been subjected. The Officers of the Hyderabad Geological Survey considered the Yellandlapad area to be folded into three anticlines with corresponding synclines, the

anticlines being occupied by Peninsular granite (according to them) and the synclines representing the intervening Pakhals. Heron (1949) regarded the syncline to the east of Yellandlapad as an isocline. Barring Mahadevan's (1949) and Heron's (1949) work, no published material is available on the tectonics of this extremely interesting area of Andhra Pradesh. In this paper, an attempt is made to present a preliminary report based on the petrofabric studies in the area. These studies are carried out both on the anticlinal 'bay' rocks and the synclinal Pakhals.

The anticlinal 'bay' rocks include a wide variety of lithological types ranging from green schists to granulite facies. The Karepalli 'bay' includes hypersthene and hornblende granitic granulites, feldspathised greenschists etc. The Yellandlapad 'bay' contains quartz - oligoclase - biotite gneisses and granitic gneisses with schist enclaves. The Bethampudi 'bay' includes quartzo - feldspathic gneisses, hornblende schists and amphibolites with anorthosite pockets, calc-granulites etc. The aim of the investigation has been not merely to follow the tectonic history of the Pakhals and the high grade plutonic rocks of the bays separately but to establish the unity of their tectonic history and to draw inferences regarding their respective ages.

The approximate geographical limits of the area are long. 80° 12′ - 80° 35′; lat. 17° 27′ - 17° 38′. About two summers were spent in the field determining the various structural features. The structures include strike and dip of bedding, foliation, lineation, joints, folds etc. 10 specimens have been analysed for optic axes orientation and to understand the general movement picture of the area.

In the field investigation of the structures of the area, it is noticed (see map) that both the Pakhals and intervening granitic rocks consistently dip towards the east, south-east or north-east. Hence, most of the folds could be of isoclinal or semi-isoclinal type. From a study of the outcrop pattern, as shown in the map, a number of conclusions may be drawn tentatively regarding the major structure.

(1) The Karepalli 'bay' represents a nearly vertical isoclinal anticline as shown by the marble bands on either side. The axis of the anticlinal fold which strikes roughly N. S.

must plunge north as revealed by the closure of the folds towards the north.

(2) The syncline between the Karepalli and Yellandlapad 'bays' part of which is covered by the Gondwanas, is complementary to the Karepalli fold and closes towards the south.

(3) In the Yellandlapad granite 'bay', the strike of foliation is no longer N-S as in Karepalli rocks but shows a change from NE around Taltalgudem (80° 22′; 17° 33′) to N near Dandagundala (80°24′; 17°37′) and NW or WNW near Manditog 80°20′; 17°38′). It is interesting to note that the adjacent Pakhals also show corresponding changes when traced from south to north. This must be a second isoclinal anticline which is plunging approximately north-east.

(4) To the east of this anticline is a complementary isoclinal syncline as shown by the repetition of marbles and quartzites on either side. This is called the Yellandlapad isocline.

(5) The Bethampudi 'bay' represents the third anticline. This cannot be an isoclinal fold since, towards the east, the dips gradually decrease in amount. Hence it may be regarded as an asymmetrical anticline. The eastern limb of this anticline does not fall within the investigated area.

The conclusion regarding the major folded structure is not based on outcrop pattern alone but is corroborated by a study of small scale features. These features are cleavage schistosity, lineation etc. The major structure of the Pakhal basin itself has not been investigated, though it is likely that it appears to be in a rift valley.

Cleavage and Schistosity

The dominant foliation in the rocks of the bays is parallel to banding. But whether this banding represents original bedding is a controversial problem. Turner (1941) has described the development of pseudo-stratification by metamorphic differentiation in the schists of Otago, New Zealand. Homogeneous rocks that have been thoroughly recrystallised under high metamorphic intensity would certainly show meta-

morphic differentiation. But the author is of the opinion that banding in the plutonic rocks of the 'bay' undoubtedly represents original bedding planes for the following reasons:

(1) The remarkable consistency with which the banding occurs over wide areas of many square miles.

(2) The wide variety of lithological types that are involved in all the three 'bays'. Metamorphic differentiation itself may not act uniformly over such diverse rocks, invariably giving the same directional pattern of banding everywhere.

(3) Further, the alternating bands of amphibolites, and quartzo - feldspathic gneisses in Bethampudi 'bay' are many feet thick and not merely a few inches. Similarly, the alternation of granulites and feldspathised green schists in Karepally 'bay' also cannot be due to metamorphic differentiation alone.

Due to the above reasons, the author is of the opinion that banding in the metamorphic rocks of all the three 'bays' represents original bedding planes. But in the subsequent phase of granitisation metamorphism, metamorphic differentiation played a considerable part and this was greatly facilitated by the dominant S plane, i.e., bedding. During deformation, due to isoclinal folding and mimetic recrystallization along the bedding planes, the resulting schistosity also became parallel to the bedding planes.

In the Pakhals, bedding can be easily recognised and the dominant cleavage is parallel to this bedding. If slaty cleavage is parallel to axial planes of folds, then the foliation direction in the rocks of the bays and the Pakhals represent axial planes of folds.

In the Pakhal phyllites near the 6th milestone on the Y-B road, there are arenaceous bands in which there is a fracture cleavage besides the usual bedding cleavage in the pelitic bands. This fracture cleavage dips to the west at about 60°. By detailed studies in the relative shear movements, it is established that the Pakhals between the Yellandlapad and Bethampudi 'bays' is a syncline. Simila rstudies in the Pakhals to the east of Karepalli also confirm this view.

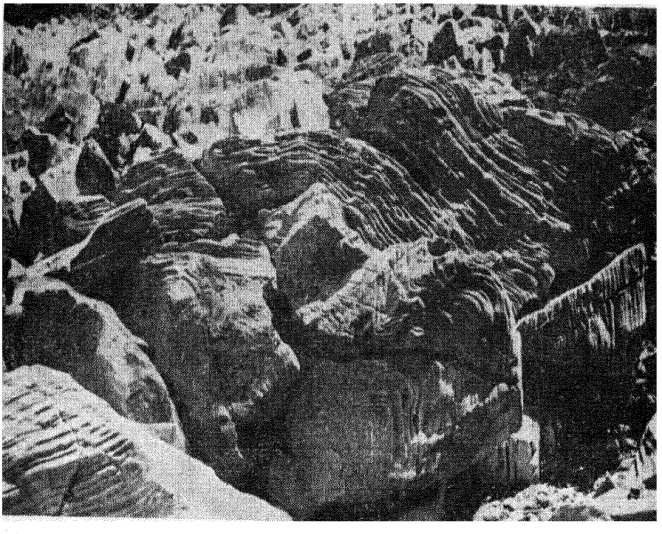


Figure (3)

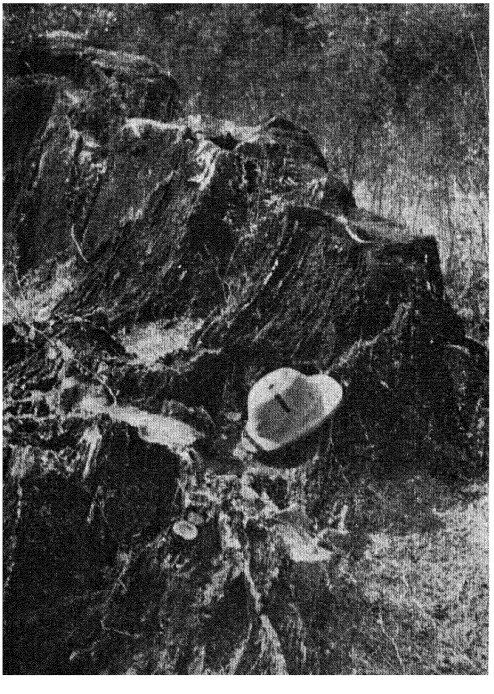
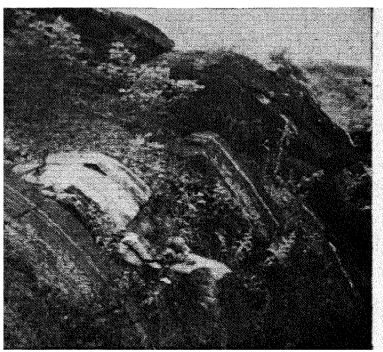


Figure (4)



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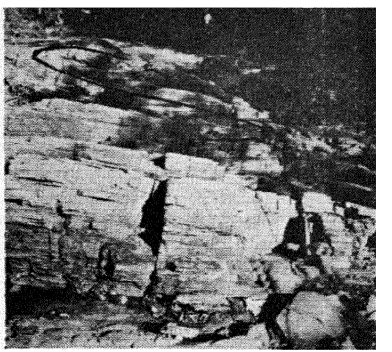


Figure (7)

Lineation

In structural investigation of Yellandlapad rocks, lineation trends could be traced at several places but the plunge of lineation could be determined at very few localities. Some of those have been mapped.

The kinds of lineation that are noticed differ in the three bays. Thus, in the Bethampudi 'bay' the lineation in the rocks is excellently shown by elongated prisms of hornblende which an megascopically visible and give rise to the streaky quartzo-feldspathic gneisses. Even in amphibolites, lineation is marked by the hornblende streaks. This lineation invariably coincides with schistosity. The plunge of lineation could be determined at some places and this ranges between 15° to 20° consistently towards the NE or rarely ENE. Mineral lineation of this type associated with major folds is supposed by the author, following Cloos (1946) and others, to be parallel to the fold axis. If so, in the Bethampudi area, it is safe to infer that the axial planes of the major folds trend northeast and that the axes of the folds plunge at 15° to 20°.

In some of the quartzo-feldspathic gneisses of the Bethampudi bay, along foliation planes, biotite is shown by circular or ovoidal plates which may exhibit a preferred orientation giving rise to a lineation. But this is generally very poorly expressed and cannot be relied upon.

In the Yellandlapad area proper (both the granite bay region aud the synclinal part) two kinds of lineation are recognised.

(1) Elongate grains of quartz. This is shown in the quartzites and in the grey gneisses. They show a plunge of 10° to 15° towards the NE again confirming the belief that the fold axis must be plunging in that direction.

(2) Minor corrugations or crinkling of the foliation planes in the schists and marbles. The parallelism of the axes of these small crinkles give a kind of lineation. Such lineation in the schist supports the above views regarding the major structure.

Besides these two kinds, occasionally the intersection of fracture cleavage with bedding in some of the Pakhal semi-

pelites gives a lineation. But such lineation was determined at very few places, the results are variable and the author does not wish to rely greatly on these meagre data.

In the Karepalli rocks, foliation has very high dips nearly 75° to almost vertical and is marked by biotitic elements in the biotite 'granulites' and chlorite in the green schists. Megascopic lineation is visible in the granulitic rocks marked by ellipsoidal grains of quartz. It is not possible to determine the plunge of lineation. The pink feldspar augen in the green schists also give a kind of lineation. In the quartz-hematite schists which are occurring as enclaves in the Karepalli area, besides the main schistosity, there is a secondary fracture cleavage. The intersection of both give lineation. In the few cases where it could be determined, the plunge of lineation is about 15° to 20° towards north.

Minor Folds

Besides the major folded structure, a number of minor folds are seen throughout the area. The trends of these folds are in general parallel to the major structure with the axes showing close correspondence. Ptygmatic folding is common in the pegmatitic bands of the granite gneisses of Yellandlapad bay. The contortions in the marble band of the Pakhals near Bethampudi are characteristic, but too complicated to give an idea regarding the major structure. Besides these, a number of minor folds show cross trends. For example, the quartzite hill near the 7/5 milestone on Y-B road reveals that the rock has been folded along the strike of the bedding. This feature is persistently seen both in the Yellandlapad and Bethampudi 'bays' but not in the Karepalli 'bay'. If the major structure is formed due to compressive force acting in east-west direction, these folds may represent either a second period of deformation or both may belong to a single period with the tectonic forces changing from initial EW to a subsequent NW-SE direction. Some of the minor recumbent folds which are very common in Bethampudi area, with fold axes perpendicular to major structure, may be due to this deformation. This may incidentally explain their low dips.

Joints

Though joints are common throughout the bays, they are best seen in quartzites, quartzo-feldspathic gneisses and amphi-

bolites. Invariably two sets of joints are seen, one set perpendicular to the strike of the rocks and the other set, which are equally important, are parallel to the strike. The former may be regarded as *ac* tension joints which are one of the commonest in metamorphic terraines. They are roughly perpendicular to lineation trends. The strike joints may be regarded as release joints and includes both those which are due to tension, as well as, shear. In the gneisses of Bethampudi 'bay' a third set of joints which may be regarded as OKL joints are often noticed. These are present in Yellandlapad bay but not in Karepalli bay.

Micro-fabric

As already stated, the aim of this study is to get an outline of the picture of movement of the rocks undergoing deformation, to demarcate any possible boundary lines in the tectonic history of Pakhals and the rocks of the 3 bays so as to indicate their relative ages and to establish the time relationship between the tectonic episode and granitization process which the author (Janardan Rao, 1963) has described earlier.

In the structure map (Fig. 2) attitude of bedding cum foliation, lineation and joint trends have been marked. Fold axes have not been recorded since in most cases they are parallel to the lineation trends. Only in the Bethampudi and Yellandlapad gneisses and quartzites, the presence of cross folds makes the earlier lineation perpendicular to the fold axis of the minor folds. Ten specimens were chosen for fabric study. Six of these belong to the rocks of Yellandlapad bay (along with the adjacent Pakhals), two of these are from Bethampudi bay and two from Karepalli bay. The author is aware that in structural studies more detailed work based on many more fabric diagrams is necessary to fully understand the different episodes of the tectonic history. However, an outline of the regional tectonics can be traced on the basis of the present studies.

Ten diagrams have been prepared from sections cut perpendicular to the strike of foliation and nearly normal to lineation wherever the latter could be observed. Out of these ten, one is of quartzite, one of quartz schist and one of marble all belonging to Pakhals. Five of the diagrams are of granite gneisses and gneisses. One is of granulite and another of

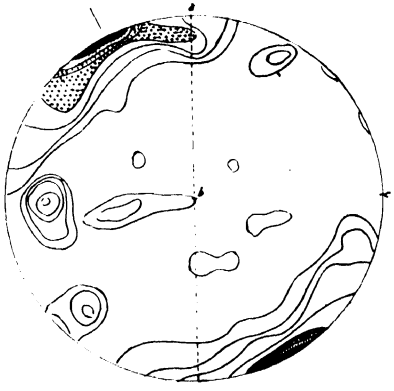
schistose granite both belonging to Karepalli bay. The location of the samples is shown on the map. All diagrams represent the lower half of sphere of projection. In all the other cases, except the marbles the optic axes of quartz have been measured. The number of measurements vary between 200 to 250.

The fabric axes *a,b* and *c* could be recognised in most cases and accordingly they are shown in the diagrams. Besides the lineation parallel to *b*, in a few cases, *a* lineation also is noticed, particularly in the gneisses of Yellandlapad and Bethampudi bays somewhat complicating the picture. The dominant megascopic foliation coinciding with bedding is the only visible S plane. Thus, it includes both the conventional S_1 (bedding) and S_2 (flow cleavage). Fracture cleavage S_3 is not traceable in the ten specimens that have been examined.

In his work on Applachian quartzites, Fellows (1943) suggested that "selectivity in measurement is the most important single factor in determining what fabric pattern will result". In the rocks under consideration, though several kinds of quartz are recognised, in any single section only two types are seen: (a) the coarse type which may represent recrystallised quartz or introduced quartz which has undergone a lot of deformation; (b) the fine grained quartz which could be either the granulated crush quartz or quartz of the original schistose ground mass. The diagrams are based on measurement of the optic axes of the coarse grained quartz only and in that respect they are partly selective diagrams. This may incidentally explain the high frequency of quartz maxima in all the diagrams. Diagram I shows the fabric of a quartzite collected from the hill near 7/5 milestone on the Yellandlapad -Burgampahad road. It is pinkish in colour and shows a visible lineation due to elongate grains of quartz. Its strike is N 22° E and dip is 65° SE. The diagram shows an incomplete *ac* girdle with a maximum of 5% near thc periphery. These maxima are located about 20° from the *a* fabric axis. The symmetry of fabric is monoclinic.

Diagram 2 is that of a quartz-schist near the Puballi tank (80°23′; 17°38′) Its strike is N 65° N and dip is 70° NE. Both schistosity and lineation are very prominent and the rocks give evidence of much higher deformation than in the quartzites. The section is cut perpendicular to the *b* fabric axis. The diagram shows a more or less complete *ac* girdle. The *ab*

PLATE I



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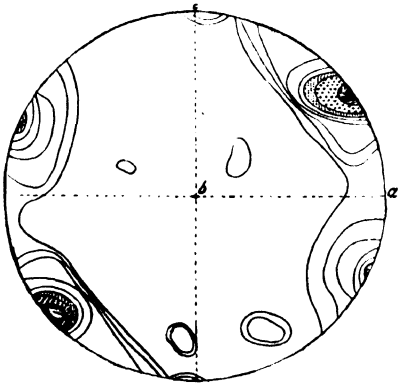

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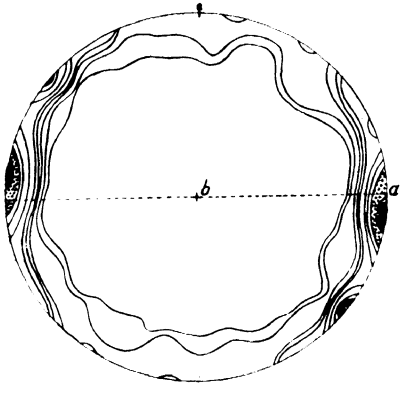

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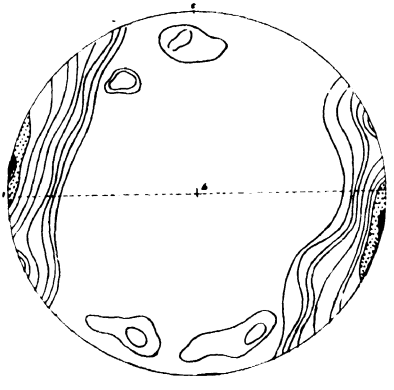

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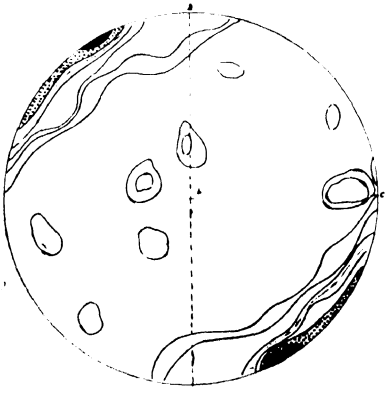

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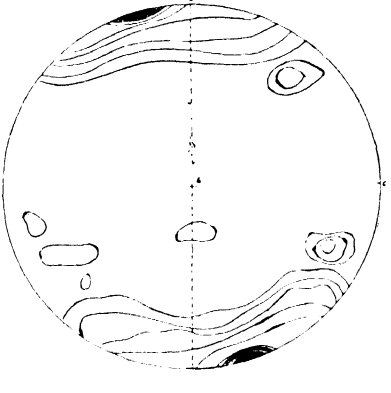

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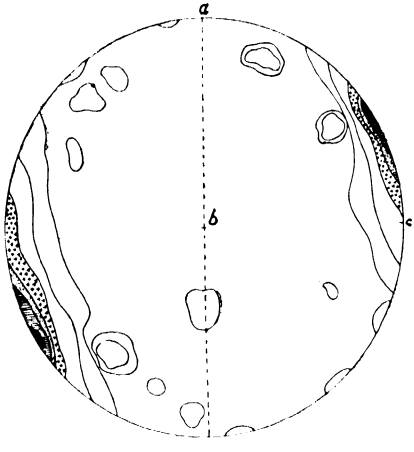
PLATE II



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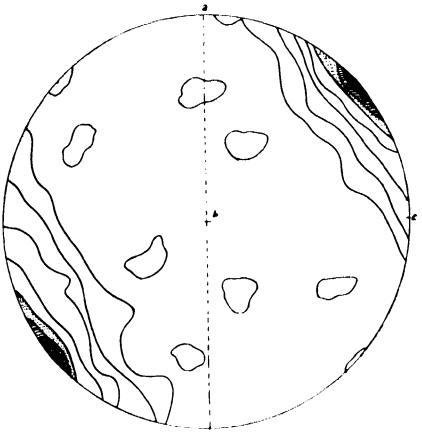

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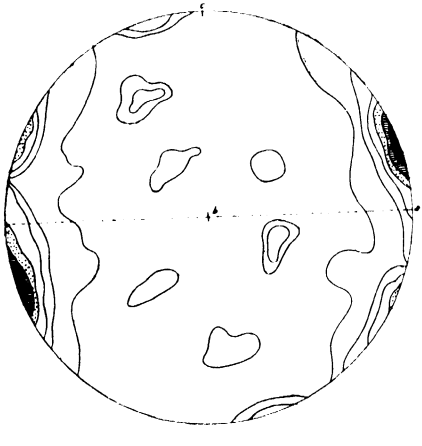

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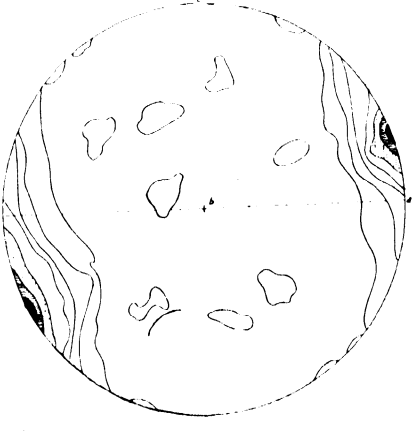

10

plane marks the plane of schistosity. Two maxima are symmetrically located and either side of the foliation plane. One is a 7% maximum and the other is a subsidiary maximum of 4%. Other maxima are absent. The symmetry of the fabric is roughly orthorhombic.

Diagram 3 is that of a marble near Manditog (80°20′: 17°38′). The strike and dip are similar to that of quartz schist mentioned above. Lineation is not evident and the *b* at the centre is inferred. This diagram shows a more or less complete *ac* girdle with two maxima both of which are near the periphery. One of these showing 9% maximum i.e., the chief maximum is almost near the fabric axis *a*, the other is slightly away in between *c* and *a*.

Referring to the significance of fabric details in orientation diagrams Turner and Verhoogen (1960) say: "Interpretation of individual maxima in orientation diagrams depends to a large extent upon hypothesis (of which there may be many) relating to orienting mechanisms of the minerals concerned. For example in the case of quartz, there are at least five and possibly a dozen, observed relations between c-axis maxima in orientation diagrams and schistosity of the corresponding rocks.....until more experimental data on development of the fabric under controlled conditions become available, this remains the most speculative aspect of petrofabric analyses." In spite of such criticism, as they themselves admit, the preferred orientation patterns in relation to schistosity and lineation should be able to provide considerable information regarding the tectonics of an area. In this paper, since the author has bestowed considerable attention on the macro-fabric studies such as foliation, lineation, minor folds etc, correlation of these with the micro-fabric data as revealed in orientation diagrams and drawing tentative conclusions from them regarding the tectonic history of the region in a broad outline, may not be far-fetched. Till such time as experimental proof is forthcoming, we have to rest content with whatever data is available. Accordingly, the author takes the liberty of drawing the following conclusions regarding the interpretation of the orientation diagrams.

All the three diagrams described above belong to typical Pakhal metasediments. It is interesting to note that the quartzite showing only 5% maximum is in the heart of Yellan-

dlapad isocline whereas the quartz schist near the Puballi tank borders the granite 'bay'. The quartz schist shows 7% maximum and has obviously been subjected to increasing deformation. The 4% subsidiary maximum within this girdle may represent some amount of rotation of slip planes (or creation of new slip planes) within the rock. This may be possibly due to a shift in the directional trend of tectonic deformation. Such a conclusion is not entirely unwarranted when we noticed that in diagram 1 the subsidiary maximum is absent. The existence of such a rotation of slip planes in the rocks (or glide planes of minerals) is further revealed in the Manditog marble in which the 9% maximum may represent the main directional movement and the 6% subsidiary maximum may indicate a shift in tectonic drive.

Diagram 4 gives the fabric data for a quartz-oligoclase-biotite gneiss (grey gneiss) two furlongs to the south of Puballi tank. The strike of foliation is similar to those given for specimens 2 and 3 above. The diagram again shows an incomplete *ac* girdle with two peripheral maxima, 8% near *a* fabric axis and another 4% slightly away. It is significant that this diagram very much resembles that of the marble described above. This rock belongs to the rocks in the Yellandlapad granite 'bay'.

Diagram 5 is that of a migmatite, a partially granitized gneiss. The striks is N 20° E and dip is 70° SE. The characteristic incomplete *ac* girdle is shown with a single 7% peripheral maximum. This maximum is located about 20° from *a* fabric axis.

In diagram 6, the fabric data for a typical granite gneiss collected near Hanumantalpad (80°22′: 17°36′) are shown. The strike is NS and dip is 75° E. A partial *ac* girdle with a single 8% peripheral maximum near *a* fabric axis is noticed.

Diagrams 5 and 6 are very much similar, in that, they not only show incomplete *ac* girdles but the lattice orientation with a single 7% to 8% peripheral maximum near *a* fabric axis is also very identical. This differs markedly from diagram 4 (least granitized gneiss) which resemble the marble and quartz schist (diagrams 3 and 2) in showing subsidiary maxima. The locality from which the specimen (represented by diagram 4) was collected is very near the place from where the quartz-

schist was collected, as shown on the map. This suggests that towards the mouth of the bay, the lattice orientation was wholly controlled by a single direction of tectonic transport roughly corresponding to *a* fabric axis unlike the rocks in the noses of folds which might have undergone some amount of rotation.

Diagram 7 shows an incomplete *ac* girdle for a quartzo-feldspathic gneiss collected near 18th milestone on the Y-B road. Lineation is quite prominent marked by hornblende streaks. A single peripheral maximum of 6% situated symmetrically between *a* and *c* is the characteristic feature. Subsidiary maxima are shown which are not peripheral. The symmetry of the fabric is monoclinic. This gneiss has a strike of N 50° E and has low dip of 35° SE.

Diagram 8 is that of a similar quartzo-feldspathic gneiss but towards the mouth of the 'bay'. Its strike is N 40° E and dip is 75° SE. The fabric diagram is identical to that of 7. The single peripheral maximum is 7%.

The two gneisses represented by diagrams 7 and 8 belong to the Bethampudi bay and a comparison of the diagrams with the first six shows that within the *ac* girdle, the optic axes maxima of quartz have shown considerable shift. It is no longer chiefly along the *a* fabric axis, but away from it, toward *c*. This again means a shift in the direction of tectonic movement. Such a shift was indicated in 3 out of 6 diagrams of Yellandlapad rocks but the *a* fabric axis still controlled the lattice orientation. But in the Bethampudi rocks its exclusive effect is obliterated to a considerable extent, possibly suggesting a second phase of deformation.

Diagram 9 is that of a hypersthene (granitic) granulite near Karepalli railway station. The strike of foliation is roughly NS and has a high dip of 80° E. It shows an incomplete *ac* girdle with two peripheral maxima of 7% and 3% located symmetrically on either side of the foliation plane *ab*.

Diagram 10 represents the fabric of schistose 'granite' near Regulagudem (80°13': 17°29') whose strike is again NS with very high dip of 85° E. An incomplete *ac* girdle with a

single peripheral maximum of 8% is characteristic. This is located about 20^0 from *a* fabric axis.

Conclusions

It is significant that in all the ten diagrams, there are characteristic *ac* girdles, either partial or complete, Such *ac* girdles are most common in B-tectonites as described by many workers (Sander 1930: Phillips 1937: Cloos and Hietanen 1941). Some of the peripheral maxima around *a* in the girdles correspond to maximum *I* of Fairbairn (1948).

Rigid classification of all the metamorphic rocks around Yellandlapad into B and S-tectonites is rather difficult. From the megascopic structure, a single foliation plane which coincides with the bedding is the dominant S-plane in most rocks of the area. Following Sander's (1930) and Knopf and Ingerson's (1938) definitions, such rocks should be regarded as S-tectonites. The rocks of the Karepally 'bay may be considered as a fairly good example of S-tectonites since foliation is the most dominant single S-plane with lineation relatively inconspicuous. In the rocks of gneisses of Bethampudi 'bay' the same type of folliation is still present, but then, a characteristic type of lineation marked by hornblende streaks is the dominant structural feature and the rocks may be regarded as excellent examples of B-tectonites. From field evidence, the rocks of the Yellandlapad 'bay' and intervening Pakhals may be considered as transitional from the western Karepalli S-tectonites to the eastern Bethampudi B-tectonites. But the evidence furnished by the orientation diagrams is slightly different. The *ac* girdles with peripheral maxima suggest that almost all the rocks are B-tectonites. However the incomplete nature of the *ac* girdles in most diagrams may indicate a transition from S-tectonites to B-tectonite fabric. Examination of all the 10 diagrams in a comparative manner reveals that *ac* girdle are more complete in the rocks of Yellandlapad 'bay'. This suggests considerable rotation of the fabric elements in the rocks of the central bay. This is consistent with field observation that the Pakhals around Yellandlapad take a swing in strike and show cross-folds etc. besides the major folds. With the exception of diagram 2 (quartz schist) and diagram 9 (granulite of Karepalli bay) which show to some extent an orthorhombic symmetry this symmetry of fabric may be correlated with the symmetry of movement, of slip and/or rotation along the *b* fabric axis.

From all the above data, the following conclusions are drawn regarding the regional tectonics.

1. The Pakhals (as shown by the marbles, quartzites and quartz schists) and the rocks of the bays have undergone the same tectonic history. This is confirmed both by field studies as well as by preferred orientation data.

2. The whole region has been subjected to one period of deformation, the stresses acting roughly along east-west direction. But there was a shift in stress direction towards the eastern parts subsequently. This is again shown both by the field studies and fabric data. Thus in the Karepalli rocks, the bedding schistosity strikes N-S. The axial planes of the folds coincide with this strike. Following Turner (1960), the author is of the opinion that this type of S-tectonite fabric "must have evolved during compression by a force acting normal to the plane of schistosity" i.e., the compressive stress must have acted in roughly E-W direction.

3. However, towards the eastern parts of the Karepalli bay they already show indication of a subsequent deformation acting along NW-SE direction. In the Yellandlapad bay, if we imagine the rocks to have originally a N-S strike, they should have been subsequently bent due to this second phase of deformation, as shown by their change in strike. The Bethampudi rocks give further indication of this second period of deformation. The second phase of tectonic activity may have operated from the south-east direction and not from noth-west since, in the later case, the Karepalli rocks should have been affected. The petrofabric data supports these ideas as already indicated above.

4. The granitization reported by the author earlier (Janardan Rao 1958, 1963) was syntectonic, at least in its main phase of activity. It is proved by the similarity in the diagrams of granitic gneisses and the schistose rocks of the 'bays'. Field evidence also supports this conclusion.

5. Since the Pakhals and the granitic rocks of the 'bays' show identical tectonic history, it is likely that the bay rocks are also Pakhals; only, they have become high grade metamorphic rocks because of selective granitization in anticlinal cores (Janardhan Rao 1963).

5. The tectonic history of the Yellandlapad area may show a distinctive individuality of its own and may not reflect parallelism with the tectonics of the main Pakhal basin. The intense deformation of Pakhals around Yellandlapad area may be a local phenomena.

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EXPLANATION OF FIGURES

Fig. 1. Sketch Map Showing Location of Investigated Area.

Fig. 2. Structure Map of Yellandlapad Area, Khammam Dist. A.P.

Fig. 3. Contorted Marbles in the Pakhals Near Bethampudi.

Fig. 4. Migmatite in Yellandlapad 'Bay' Showing Almost Vertical Dips. Note the Joints in the Quartzitic Band.

Fig. 5. Steep Folding in Banded Gneiss of Bethampudi Bay (1 Furlong South of 16/4 Milestone on Y-B Road).

Fig. 6. High Dip in the Quartzo-feldspathic gneiss of Bethampudi 'bay' Near Thadkalpudi.

Fig. 7. Joints and Minor Recumbent Folds in the Gneiss of Bethampudi 'Bay' (Near 18/4 Milestone on Y-B Road).

PLATE-I

1. Orientation diagram of 205 Quartz axes from Quartzite near 7/5 milestone on Y-B road (Location 1 on map). Contours. 5–4–3–2–1.5–1–.5 Percent.
2. Orientation diagram of 250 Quartz axes from Quartz sehist near Puballi Tank (Location 2 on map). Contours 7-6-4-5-3-2-1-.5 Percent.
3. Orientation diagram of 255 calcite axes from marble near Manditog (Location 3 on map). Contours 9-8-7-6-5-4-3-2-1-.5 Percent.
4. Orientation diagram of 209 Quartz axes of gneiss south of Puballi tank (Location 4 on map). Contours 8-7-6-5-4-3-2-5-2-1-1-.5 Percent.
5. Orientation diagram of 220 Quartz axes from migmatite 6 furlongs north-east of Yellandapad (Location 5 on map). Contours 7-6-5-4-3-2-1-.5 Percent.
6. Orientation diagram of 210 Quartz axes from granite gneiss near Hanumantalpad (Location 6 on map). Contours 8-7-6-5-4-3-2-1.5-1- .5 Percent.

PLATE–II

7. Orientation diagram of 215 Quartz axes from Quartzofeldspathic gneiss near 18th milestone on Y-B Road (Location 7 on map). Contours 6-5-4-3-2-1 Percent.
8. Orientation diagram of 250 Quartz axes from Quartzofeldspathic gneiss 6 furlongs north of Thadkalpudi (Location 8 on map). Contours 7–6–5–4 3–2-1 Percent.
9. Orientation diagram of 200 Quartz axes from hyporsthene granulite near Karepalli railway Station (Location 9 on map). Contours 7–5–3–2-1-.5 Percent.
10. Orientation diagram of 230 Quartz axes from schistose 'granite' near Rangulagudem (Location 10 on map). Contours 8–6–4–3-2-1-.5 Percent.

PALAEOMAGNETISM AND THE GEOLOGY OF THE DECCAN TRAPS*

By

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Abstract

Palaeomagnetic studies carried out over the last seven years on oriented samples from the Deccan traps of Cretaceous to Eocene age and from Rajmahal traps of presumably Jurassic age have given significant evidence in favour of the hypothesis of Continental Drift and of reversal of the geomagnetic field in the past. These studies have already been described elsewhere. In addition, the studies on the Deccan traps have been found to be useful for the elucidation of the geological problems connected with this formation.

Palaeomagnetic studies show that the Deccan traps may comprise two zones, Lower and Upper traps, having reversed and normal remanent magnetic directions respectively. This division is based purely on the magnetic directions and therefore, refers to the time of cooling of the lavas; it also applies to dykes and sills found in different areas. Further, it also permits us to fix the relative stratigraphic positions of flows and dykes in widely separated areas which have hitherto presented great difficulties. Such a characterization also yields important information on the relationship between the dykes and the flows in various localities.

The geological studies of the Deccan traps and the Rajmahal traps based on the palaeomagnetic method are discussed in this paper. The writer believes that the method may be useful for dating, on a relative basis, igneous rocks formed between the Jurassic and Miocene times.

Introduction

PALAEOMAGNETIC studies deal with the natural remanent magnetism of rocks formed at different times in the past. It is known that certain rock types acquire, at the time of their formation, a permanent magnetization in the direction

*Based upon a thesis submitted for the degree of Ph.D., Banaras University, 1963.

of the prevailing geomagnetic field, and retain the same over periods longer than the geological ages of the rocks; this magnetic record can also undergo modification as a result of physical or chemical processes which occur during the life of rock. Suitable rocks having unmodified "magnetic fossil" records in them exist on the earth's surface. Palaeomagnetic studies carried out on such rocks make it possible in principle to trace the history of the earth's magnetic field such as changes in the orientation of the geomagnetic field in past, and since the latter depends on the latitude of the observation point, the movements of geographical poles (i.e. of the earth's crust as a whole which is referred to as "Polar Wandering") and of continents (i.e. of the various landmasses relative to each other which is referred to as "Continental drift").

The manner in which a particular rock type acquires a permanent magnetization depends on the mode of rock-formation. Igneous rocks acquire a thermoremanent magnetization (TRM), when they cool from high temperatures which prevail at the time of their eruption. Nagata (1960) has shown that the (TRM) is highly stable and in favourable cases can be expected to be retained by rock for periods much larger than the geological ages of the rocks. However, subsequent to formation, rocks are subject to the influence of a number of natural phenomena such as geological movements, metamorphism, weathering and the like, and these may affect the magnetic properties of the rocks so as to render them unsuitable for palaeomagnetic studies. Nevertheless, it is often possible to ascertain with the help of geological *in-situ* conditions, and standard laboratory tests, if the rocks from a given formation have been so affected physically or chemically during their history. Also, rocks subsequent to their formation may acquire secondary induced remanent magnetization, (IRM), owing to the long-continued influence of the geomagnetic field on them. This is also often called viscous magnetization and is generally present in the rocks of all types. However, this secondary magnetization is relatively unstable and can be removed by suitable magnetic cleaning techniques of alternating field demagnetization and thermal demagnetization.

Palaeomagnetic studies of Indian rocks were started in the Tata Institute of Fundamental Research, Bombay in 1955, at the instance of Professor P. M. S. Blackett, F. R. S., to test the hypothesis of continental drift propounded by Wegener

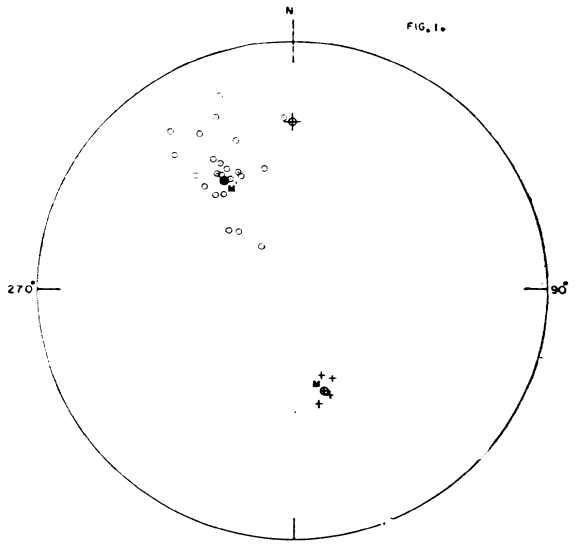
(1925) and DuToit (1937). According to this hypothesis, which rests on the admirable analyses of a great variety of geological and palaeoclimatological evidence, the landmass of India is believed to have drifted to its present position from a position it occupied in high southern latitudes as a part of the huge Gondwana land comprising of Australia, India, South America and Africa during the Corboniferous times. The palaeomagnetic results obtained thus far from the Deccan traps and the Rajmahal traps have given significant support to the above hypothesis. These results also indicate a complete reversal of the earth's magnetic field from the normal during the eruption of Rajmahal traps, reversed during the laying down of the lower 2000 feet of basaltic flows in the Deccan traps and normal again during the formation of the younger Deccan traps. These results have already been published elsewhere. (Clegg et al 1958), Deutsch et al (1958), (1960).

In addition to above, the pattern of remanent magnetic directions obtained in the various flows and dykes from a number of localities in the two rock-formations, Deccan traps and the Rajmahal traps, throw light on a number of geologically important problems connected with the two formations; this aspect of palaeomagnetism forms the main body of the present discussion.

Results

The remanent magnetism in oriented samples from sequences of flows, as well as from dykes from a large number of localities in the Deccan trap area was determined using an astatic magnetometer. This instrument and the measurement procedure commonly adopted have been described in detail, (Blackett 1952). The stability of remanent magnetization in the Deccan trap lavas has been critically examined, for the first time, using the recently developed techniques of alternating field demagnetization and thermal demagnetization. The apparata used for these stability tests and the concerned experimental procedure have been described by Athavale, Radhakrishnamurty and Sahasrabudhe (1962).

The results of palaeomagnetic studies made earlier on samples from sequences of flows at Khandala, Linga, Amba, Nipani, Pavagarh and Mahabaleshwar have already been published [(Clegg et al, (1956), Deutsch et al (1958), (1960) and Sahasrabudhe (1963)]. Additional results obtained from studies



MEAN DIRECTIONS FOR SAMPLES FROM BOMBAY AREA

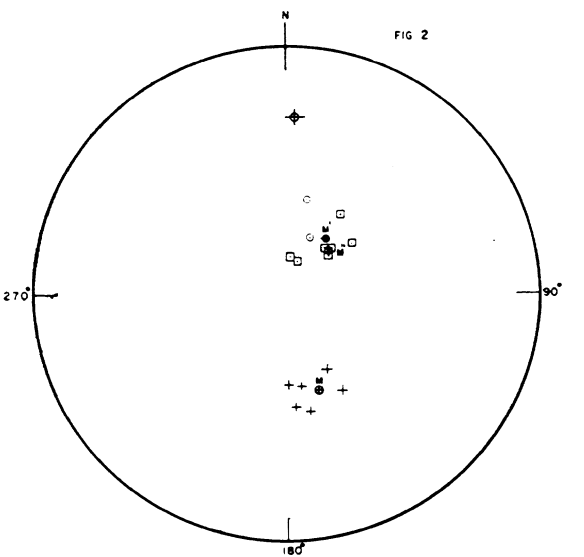
+ DIP DOWNWARDS (+IVE) LOCAL TRAPS AT KALYAN

⊖ DIP UPWARDS (−IVE) FROM BOMBAY ISLAND AND ONE DYKE AT KALYAN.

MEAN DIRECTIONS

PRESENT DIPOLE FIELD (+IVE)

Figure (1)



MEAN DIRECTIONS FOR SAMPLES FROM AJRA-GARGOTI AREA

○ DIP UPWARDS (FLOWS AT GARGOTI)

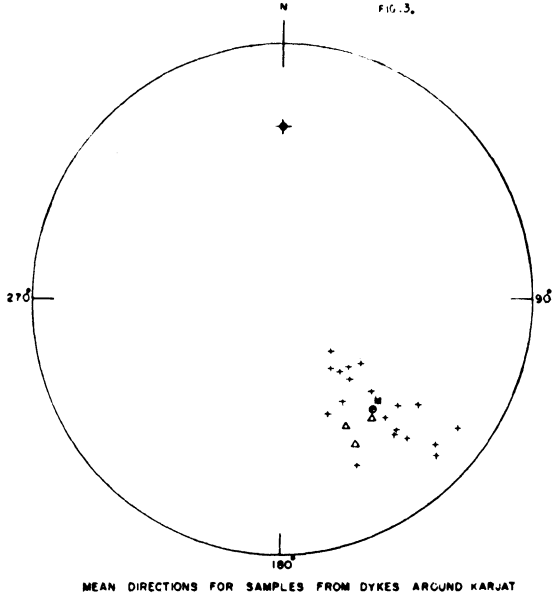
□ DIP UPWARDS (FLOWS AT AJRA)

+ DIP DOWNWARDS , FLOW AT GARGOTI

MEAN DIRECTIONS

PRESENT DIPOLE FIELD

Figure (2)



MEAN DIRECTIONS FOR SAMPLES FROM DYKES AROUND KARJAT

+ DIP DOWNWARDS (+IVE) 6 DYKES

△ DIP DOWNWARDS (+IVE) LOCAL TRAPS

● MEAN DIRECTION

✦ PRESENT DIPOLE FIELD (+IVE)

Figure (3)

on trap flows at Bombay and trap–flows and dykes in areas between Bombay and Poona, and around Panchmarhi are presented here.

Bombay Traps

The few flows of basalt and Trachyte exposed at sea level at Bombay are considered by geologists (Wadia, 1953) to belong to the latest phase of the Deccan trap activity. A total of 35 blocks of rock from 6 fresh exposures in greater Bombay have been studied. Ten samples, five from the local traps and five from the dyke intruding them at Kalyan have also been examined. An equal-area projection plot of mean direction in all these samples is shown in Fig. 1. All the samples from the island and the ones from the dyke at Kalyan are normally magnetized whereas those from the local traps at Kalyan have reversed magnetization.

Traps from Ajra-Gargoti Area

Fig. 2 is a stereogram showing mean directions in samples from the small section comprising of 5 flows between elevations 1700′ to 2200′ m.s.l. in the Ajra–Gargoti area (Deccan traps). The flows having mean elevations of less than about 2000′ m.s.l. are magnetized reversely whereas those at higher levels have normal magnetization. The single flow at Ajra which has a mean elevation of 2100′ m.s.l. and is exposed over-lying the much older Kaladgi sandstones of pre–Cambrian age has also been found to be normally magnetized with a comparatively steeper inclination (–70° up). The section studied here is small and has a supplementary value to the ones studied in other localities.

Dykes in the Deccan traps

The Deccan trap flows are intruded in many localities by a large number of dykes which often appear to form clusters or swarms. Some representative dykes in areas between Bombay and Poona, and around Panchmarhi in Central India have been analysed.

Dykes around Neral and Karjat

In Fig. 3 is shown a stereogram of mean remanent directions obtained in samples from 5 dykes well exposed around Neral and Karjat. The directions in samples from local traps at Karjat are shown separately for comparison. All the dykes and local traps sampled are exposed at altitudes of around

100′ m.s.l. and have been found to be reversely magnetized. The general mean directions for all the dykes and local traps and the direction of the present earth's field are also shown in the figure.

In Table 1 are given the mean directions for the dykes and the local traps separately. The numbers corresponding to the dykes are the ones used by Gupte (1963) in his survey of this area. Only those specimens which showed stable magnetization have been utilised and shown in the Table.

TABLE I

Mean magnetic direction for the dykes around Neral and Karjat (Lat. 18°57′ Long. 73°19′)

Dyke No. (after R. B. Gupte)	Number of samples	Number of specimens	Mean Direction		Polarity
			Azimuth E of N	Dip — ive (up)	
1	2	3	4	5	6
110	3	9	148	+50	R
111	6	18	135	+61	R
118	2	5	130	+13	R
121	2	5	132	+28	R
140	9	31	141	+39	R
Local traps at Karjat	3	12	148	+40	R

TABLE II

Mean magnetic directions for dykes around Panchmarhi Latitude 22°27′ Longitude 78°26′

Dyke No. (Arbitrary)	Number of samples	Number of specimens	Mean Direction		Polarity
			Azimuth E of N	+ ive (downwards)	
1	2	3	4	5	6
1	5	12	159	+ 33	R
2	3	3	337	− 15	N
3	4	9	143	+ 49	R
4	9	20	337	− 36	N
5	2	4	345	− 48	N
6	2	6	167	+ 62	R
7	4	11	164	+ 52	R
8	5	15	152	+ 51	R

Dykes around Alandi

In Fig. 4 is shown a stereogram of mean directions in samples from dykes and local traps at Alandi about 10 miles from Poona on the Poona-Nasik highway. The exposures sampled here occur at elevations of about 2000′ m.s.l. The dykes are normally magnetized with negative dip whereas the local traps intruded by the dykes are reversely magnetized with a downward dip. The contact zones of dykes in general have very close splintery jointing and it is rather difficult to obtain fresh samples from the contacts. These dykes have been mapped by Agashey (1956).

Dykes around Panchmarhi

A total of 45 samples have been analysed from 8 dykes providing fresh exposures around Panchmarhi. Two big coarse-grained dykes intruding the Gondwana sandstones South West of Panchmarhi are reversely magnetized, and out of the six dykes sampled north-east of the Panchmarhi mountains three are magnetized reversely and the remaining three normally. The mean directions obtained in all the samples in this area are shown in Fig. 5, along with the general means of the two groups of dykes and the local direction of the present dipole field.

The mean directions for the dykes are separately given in Table 2, the numbers representing the dykes being arbitrary.

Test Samples

In addition to the areas described above and the ones studied earlier, test samples from dykes and flows in many localities have been analysed from time to time to check the general pattern of results. Test samples analysed from flows exposed at altitudes of less than around 2000′ m.s.l. in ghat sections at Buldana, Kambatki and Igatpuri have all been found to be reversely magnetized. Samples from dykes at Bombay and Kandala have shown normal magnetization whereas the one dyke sampled in Gir forest (Saurashtra) has been found to be reversely magnetized. In general, it is often difficult to get fresh exposures of dykes to collect suitable samples and this is one of the main reasons why it has not been possible so far to study them extensively.

Summary of Results

The results obtained from palaeomagnetic studies made earlier on the samples from sequences of flows in various localities are reproduced here (Tables 3 and 4 and Fig. 6), along with the results presented in the foregoing.

In Table 3 are listed the flow-wise mean remanent directions against mean elevations (m.s.l.) for the various sequences studied so far. This is an attempt to compare the flows in different localities on the basis of their mean magnetic directions.

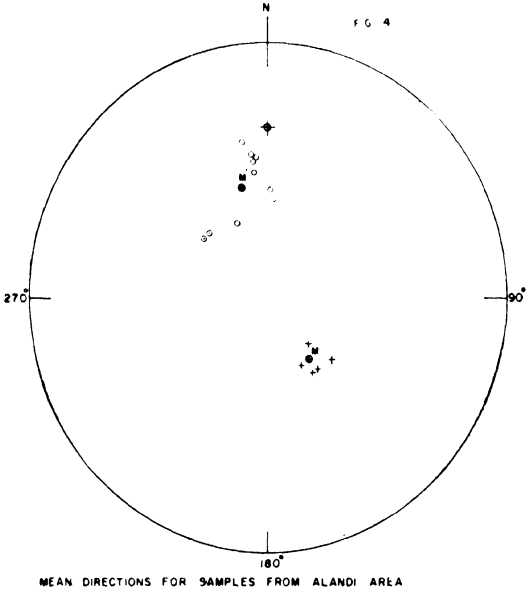
The final mean directions of normal and reversed flows and dykes from all the localities are given in columns 7 and 8 in Table 4. The elevations covered by the exposures sampled are given in column 6 of this Table.

In Fig. 6 is shown a stereogram of mean directions in all the normal and reversed flows and dykes. Each point in this figure represents a mean direction for the individual flow or dyke and is a mean of about 20 to 40 specimens obtained from 5 to 10 samples in it. A double cone having a minimum angle has been drawn to include the maximum number of points. It is reasonable to expect that more studies made on samples from this formation would yield directions lying within this cone.

These results may be summarised as follows:

(a) the remanent magnetic directions obtained in the Deccan traps are highly stable and widely different from that of the present earth's dipole field at the sampling sites, the mean directions being 20° to 50° W of N, or E of S with upward or downward inclination respectively;

(b) the lava flows occuring upto altitudes of around 2000′ m.s.l. in all localities, except in Bombay, are magnetized reversely with downward inclination and the ones above this height have a polarization which is normal and upwards ;



MEAN DIRECTIONS FOR SAMPLES FROM ALANDI AREA

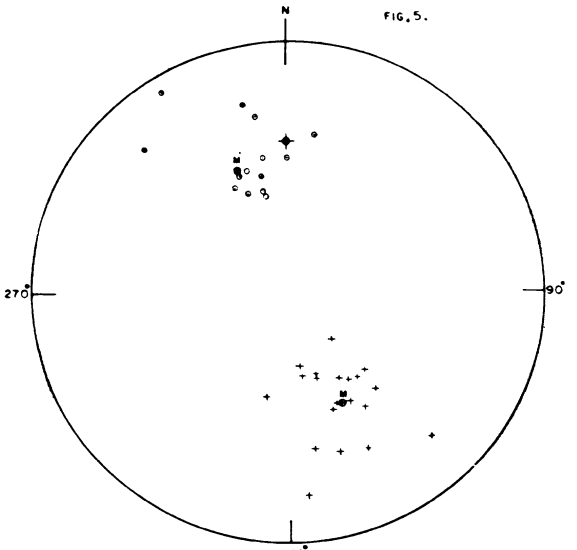
+ DIP DOWNWARDS (+IVE) LOCAL TRAPS

○ DIP UPWARDS (-IVE) DYKES

MEAN DIRECTIONS

PRESENT DIPOLE FIELD (+IVE)

Figure (4)



MEAN DIRECTIONS FOR SAMPLES FROM DYKES AROUND PANCHMARHI

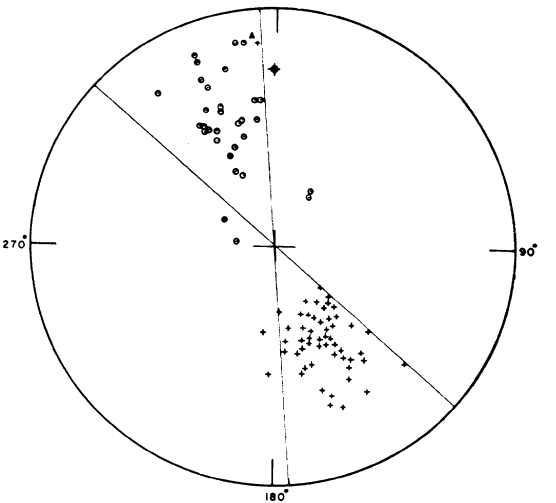
+ DIP DOWNWARDS (+IVE) 5 DYKES

○ DIP UPWARDS (− IVE) 3 DYKES.

MEAN DIRECTIONS

PRESENT DIPOLE FIELD (DOWNWARDS)

Figure (5)



MEAN REMANENT DIRECTIONS FOR FLOWS AND DYKES FROM ALL LOCALITIES IN THE DECCAN TRAPS.

○ DIP UPWARDS UPPER TRAPS.

+ DIP DOWNWARDS LOWER TRAPS

PRESENT DIPOLE FIELD (MEAN)

Figure (6)

TABLE III

Comparison of flow-wise mean directions from different localities in the Deccan trap area. A = Azimuth, R of N; D = Dip

Elev. above m. s. l. ft.	Ajra		Gargoti		Nipani		Amla		Mahabaleshwar		Khandala		Linga	
	A	D	A	D	A	D	A	D	A	D	A	D	A	D
3700									344	-25				
									328	-43				
2500					322	-22			338	-54				
					337	-19								
					333	-37	328	-41						
					344	-51	337	-30	352	-39				
			349	-15	345	-45	338	-40	354	-39				
									277	-77				
									298	-71				
2100	35	-70	33	-68					150	47	150	68	139	41
									166	46	150	62	188	51
									168	57			165	39
					170	61			157	27	130	70	170	55
1800			159	56	173	57	160	60	146	42	130	64		
											149	57		
											140	63		
									182	45	154	54		
							157	58	159	65	150	53		
									147	28	139	58		
1200											150	36		
									136	62	140	40		
									154	52	154	54		
800									187	60	175	67		
							148	55	159	54				
							148	44	163	47	131	68		
							143	63	160	29	149	51		
500									144	57				

TABLE IV

Mean remanent directions from different localities in the Deccan trap area

Locality	Mean		No. & types of exposures	No. of specimens	Elevation above m. s. l.	Mean Azimuth R of N.	Mean Dip + ive downward
	N-Lat	E. Long					
1	2	3	4	5	6	7	8
Mahabaleshwar	17° 55′	73° 38′	7 flows	175	2000–3500	339	— 57
Amba	16° 59′	73° 46′	3 flows	54	2000–2100	335	— 26
Nipani	16° 26′	74° 22′	3 flows	74	2300–2500	338	— 32
Gargoti	16° 19′	74° 10′	2 flows	35	2150	11	— 46
Ajra	16° 3′	74° 3′	1 flow	22	2100 ft.	35	— 70
Alandi	10° 34′	73° 35′	2 dykes	41	2000	346	— 53
Bombay	18° 58′	72° 49′	3 flows	71	Sea level	328	— 47
Panchmarhi	22° 27′	78° 26′	2 dykes	25	—	338	— 47
Pavagarh	22° 28′	71° 33′					
Mahabaleshwar	17° 55′	73° 38′	20 flows	339	200′–2000′	157	52
Khandala	18° 45′	73° 22′	16 flows	233	400–2000	147	58
Linga	21° 58′	78° 55′	4 flows	195	1700–2000	164	48
Amba	16° 59′	73° 46′	5 flows	109	500′–1800′	144	60
Nipani	16° 26′	74° 22′	2 flows	44	1800′–2000′	168	60
Neral	18° 57′	73° 19′	5 dykes	65	0–150′	139	43
			1 flow	11	0–150′	148	40
Alandi	18° 34′	73° 53′	1 flow	12	2000	141	66
Buldana	20° 33′	76° 12′	2 flows	20	1600–1900	149	53
Panchmmarhi	22° 27′	78° 26′	4 dykes	52		156	50
Kalyan	19° 13′	73° 7′	1 flow	15	Sea level	164	56
Gargoti	16° 25′	74° 14′	1 flow	28	1800′	159	56

(c) all the dykes sampled so far fall into two groups, (a) reversely magnetized (R), and (b) normally magnetized (N). The dykes which can be established in the field as being younger than all the R traps (i.e. exposed at altitudes of about 2000′ or more) are all normally magnetized whereas those which are exposed among the R traps at lower altitudes are either normal or reversed; the magnetic directions in the (R) and (N) types of flows and dykes are almost exactly opposite to each other;

(d) the magnetic directions in a system of dykes, or in flows from a sequence vary from one member to another, in a somewhat irregular manner, although the sense of magnetization, either (N) or (R), strictly prevails in the corresponding groups; when in the same sequence of flows the sense of magnetization changes from R to N it changes suddenly and the line of demarcation is at an altitude of around 2000′ $\pm$ 200′ m.s.l.

Discussion of Results

Assuming that the earth's field averaged over periods of the order of a 1000 years or so has always been that of an axial dipole, which has been borne out by studies made by Johnson et al (1948) and Runcorn (1955), (1959), the result (a) can be interpreted as indicating that the landmass of India occupied a position 30 to 40° south of the equator around Cretaceous times and has since drifted northwards to its present position, and rotated 30 to 40° anti-clock-wise. This evidence for the hypothesis of continental drift has already been published elsewhere, Clegg et al (1956), (1958), Deutsch et al (1958), (1960) and Athavale et al (1962).

The extensive studies made on the magnetic and mineralogical properties of the Deccan traps have thus far not revealed any magnetic self reversing property in the R traps, or any significant difference of magnetic or petrological characters of the N and R types of traps; and the results (b), (c) and (d) have been interpreted as indicating that the earth's field was in a direction opposite to its normal one during the time the R flows and dykes were formed. This indication of earth's field

having been reversed in past, is one of the main controversial problems in the field of rock-magnetism and is discussed in detail by Sahasrabudhe (1963) a, (1963) b. Result (d) namely the variation in directions among flows in a sequence has been interpreted (Sahasrabudhe, 1963 a) as indicating a secular variation of the earth's field during the period of formation of the Deccan traps.

In addition to providing a consistent evidence in favour of the hypothesis of continental drift, these results from Deccan traps taken together with those of the Rajmahal traps which have been shown by Clegg et al (1958) and Radhakrishnamurty (1963) to be normally magnetized with a steeper upward dip (– 64° up), provide a method for a detailed study of a number of geological problems connected with the two formations. Some of the geological deductions made concerning the two formations on the basis of magnetic directions will now be discussed.

Classification of the Deccan traps

The Deccan traps have been subdivided by geologists (see Wadia, 1953) into three groups, Lower, Middle and Upper traps–on the basis of the occurrence of intertrappean sediments and ash beds in a few localities. However, the occurrence of these indices is not very common, and since the traps in general show a remarkable uniformity in chemical composition, it is often very difficult to determine the relative stratigraphic position of a section of trap flows wherein the indices are wanting.

Accepting as established that neither N nor R rocks in the Deccan trap formation are self-reversed and, therefore, assuming that the earth's dipole field was reversed during the eruption of a part of the lavas, these traps can be subdivided into two groups having almost opposite magnetic directions. These groups are:

1. UPPER TRAPS: Comprising of flows and dykes having normal magnetization with upward (-ive) Dip.
2. LOWER TRAPS: Comprising of flows and the contemporary dykes magnetized reversely with a downward inclination.

The above subdivision is based purely on magnetic directions which represent the period during which the flows were erupted. We can, then easily determine, often without ambiguity, the stratigraphic position of an isolated outcrop of basalt from the sense of the observed remanent magnetization,(normal or reversed). Since the mean directions of flows in any section vary and flows having similar directions occur at more than one level (Tables 3 and 4), it is not as yet possible to trace or date on a relative basis the individual flows. However, the magnetic directions can be used to compare series of flows containing representations of all the flows. Thus, these palaeomagnetic studies are believed to contribute to the studies of stratigraphy of the traps. The method is rendered more effective by the fact that the Rajmahal traps of Jurassic age have been shown by Clegg et al (1958) and Radhakrishnamurty (1963) to be normally magnetized with a steeper inclination than found in the Deccan traps. The two series of traps are considered by geologists to belong to the great eruptive activity which started in Jurassic times in Bihar and Assam and continued with some periods of quiescence, up to Eocene. These basaltic rocks are almost devoid of any fossils and palaeomagnetism as a means of studying their relative stratigraphy assumes a great importance. The complete reversal of the earth's dipole field indicated by the rocks of the two trap series has the following order:

Deccan traps	Upper traps (Normal) Lower traps (Reversed)	} Cretaceous to Eocene age
Rajmahal traps	Normal, with steeper inclination	} Jurassic age

Rajahmundri Traps

The isolated outcrop of basalts exposed near Rajahmundri was hitherto regarded as an outlier belonging to the basal Deccan traps. However, their normal magnetization with steeper inclination suggests for them a stratigraphic position more akin to the Rajmahal traps. These studies are described in detail by Radhakrishnamurty (1963).

Dykes around Panchmarhi

The stratigraphic position of the dykes intruding the Gondwana sandstones north and south of the Panchmarhi mountains

in Central India has thus far been a matter of controversy (Crookshank 1936). It has not been possible to decide whether they belong to the Rajmahal traps or the Deccan traps. On the basis of magnetic directions in them, we can now say with some confidence that the reversely magnetized dykes, particularly the coarse-grained ones exposed in this area (dyke Nos. 1, 3, 6, 7 and 8, Table 2), are more akin to the Lower Deccan traps and may have fed lava to some of the flows occurring in the vicinity. However, the normally magnetized dykes on the north side of Panchmarhi (dykes Nos. 2, 4 and 5) present some difficulty in that they can be grouped with either Rajmahal traps or with Upper Deccan traps. Moreover, since dykes belonging to the same system often show a considerable variation in azimuth and dip, the ambiguity in position of these dyes cannot as yet be resolved on the basis of inclination in their direction. However, since the Upper Deccan traps do not occur that far towards East, it is more likely that these N dykes met with around Panchmarhi are older than Lower Deccan traps and represent an extension of the Rajmahal trap activity.

The Ajra Traps

The normally magnetized flow at Ajra, exposed at an elevation of around 2100 ft., (Table 3), has a rather steep inclination, namely -70°. A flow with similar dip but different azimuth has also been encountered at Mahabaleshwar (Flow No. 19) and Gargoti (Fig. 2), but not in the near sequence at Nipani (Table 3). The N flows at Amba and Nipani (Tables 3 and 4) have given comparatively shallower inclinations. It is possible that a flow with such a steep dip is either not represented in these sections, or that it existed earlier and has been eroded away. In general the normally magnetized flows in all the localities studied are too few to permit any definite comparison. This lack of data for the Upper traps is chiefly because of the non-availability of large sections. Even at Mahabaleshwar, flows in the upper trap sequence have been missed for want of suitable exposures. The interesting feature regarding the Ajra flow is that its normal magnetization puts it along with the Upper traps even though it is exposed overlying the Kaladgi sandstones of pre-Cambrian age.

Trap flows at Linga and Khandala

The trap flows exposed at Linga in Cental India and Khandala along west coast have been regarded by geologists to

belong respectively to the Lower and the Middle traps (Wadia 1953). The flow-wise analysis made of the remanent directions from these flows (Table 3), indicates that both these belong to the upper or middle portions of the Lower traps in the present classification. This analysis assumes that the flows in both the localities, particularly at Khandala, represent continuous sequences, so that as series of flows the comparison can be made.

Traps in Bombay Island

As mentioned earlier, (Table 4), the N flows in the traps generally occur, especially along the west coast, at altitudes of higher than about 2000 ft. The occurrence of N flows at sea level altitudes in Bombay, therefore, presents a puzzling problem. This anomaly can be attributed to any one of the following possibilities :

(a) If we assume that all the lava flows along the west coast have a general tilt of 5 to 10° due west then we can expect the upper flows occurring above 2,000′ inland, say at Khandala, to descend to sea level altitudes about 30 to 40 miles towards west.

(b) The Bombay traps were laid down at low altitudes simultaneously with the eruption of Upper traps at higher altitudes in other localities.

(c) The N flows at Bombay existed at much higher altitudes in ancient times and have been brought down to lower altitudes relative to others either by monoclinal flexure folding as suggested by Blanford (1867) or by a series of faults with downthrow on the western side.

A tilt of the order of 5 to 10° has been recorded by Sukeshwala (1953) in the flows exposed in Bombay island. However, the trap flows exposed everywhere, particularly in the higher western ghats, maintain their remarkable horizontality for hundreds of miles, and explanation (a) therefore appears to be unlikely. On the other hand, it is quite likely that the tilt observed in the Bombay flows themselves is a purely local feature resulting from geological events such as

faulting or local warping. The flat-lying nature of the flows indicates that the lavas must have been highly fluid and with very low viscosity and the occurrence of a sort of "island-eruptive activity" in Bombay appears to be very unlikely. Also, explanations (a) and (b) are made unlikely and explanation (c) likely by the occurrence of reversely magnetized traps exposed at sea level altitude at Kalyan a few miles east of the island on the main coast-line. The N dyke at Kalyan and the R dykes and local traps at Karjat and Neral further east in the same low level topography also support (c).

On the basis of a few cases of westward tilted flows, and topographic features indicative of a gentle westward tilt in few places, Blanford (1867) suggested the existence of a north-south flexure line through Panvel about 40 miles east of Bombay. According to Blanford, the horizontal flows developed a westward tilt along the flexure line and the younger traps occurring at higher altitudes in ancient times were thus brought down almost to sea level towards west in Bombay island. On the contrary, tilting in flows west of the hypothetical flexure axis is not a common occurrence, and topographic features indicating no tilt and in some cases a slight tilt in other directions have been observed at a number of places. The main objection to the flexure hypothesis is that such a huge monoclinal folding, involving some thousands of feet of lava flows, would have altered the whole topography in a major way. Alternatively, the relative vertical downward displacement of the Bombay traps could have been the result of a series of north-south faults, parallel to the coast-line, with a large downthrow on the western side. The occurrence of faulting has been recorded in a number of localities in the traps, particularly in the Bombay island (Sukeshwala 1953). Traps have been met with at large depths in the recent boreholes in Gujarat and these indicate presence of faults. The occurrence of steep vertical escarpments involving tens of flows is a very common feature in the traps and these could easily be a result of faulting.

Whether large scale tilting or faulting has occurred in the Deccan traps east of Bombay can be decided by studying the remanent magnetism in oriented samples from sub-surface traps in a few localities. However, this would involve a great effort in terms of time and money. Alternatively, a magnetic

variometer survey of the area, with a few east-west tracks, would yield important information on the sub-surface geology of the area. Since both the N and R traps occur in this area the magnetic survey, now in progress, can be expected to locate the hypothetical sub-surface fault planes or flexure axis.

Dykes around Neral and Karjat

The occurrence of dykes in the Deccan traps is very common and their relationship with the traps forms one of the important geological problems connected with this formation. The dykes are believed by geologists to mark the fissures through which the upwelling of the magma originally took place. On the other hand, Auden (1949) concludes that the dykes, particularly in Saurashtra Kathiawar and along west coast occur in certain definite patterns related to important plutonic masses and folded zones and, therefore, belong to a post-trappean hypabyssal activity.

However, the reverse magnetization of all the dykes studied around Neral and Karjat on the west coast, and one dyke in the Gir forest in Saurashtra from which three test samples have been analysed, indicate that these dykes are older than the Upper N traps. These dykes can, therefore, be considered as contemporary, or perhaps feeders, to some of the Lower trap flows. The foregoing conclusion is based on the assumption that there did not occur another reversal of the earth's dipole field during the later stages of this great eruptive and intrusive activity. This assumption is supported by the fact that the Rhyolites of Pavagarh which have been described by Mathur and Dubey (1934) as belonging to the last phases of this igneous activity have been shown by Deutsch et al (1958), (1960) to be normally magnetized. Thus it is extremely likely that these R dykes, and others having similar magnetic directions, were feeders of lavas. On the other hand, the N dykes exposed at altitudes of about 2000 ft. or so, as at Khandala and around Poona, are younger than the Lower traps and may be younger than or contemporary to the Upper N traps. It may be that these N dykes intruded through all the Lower R traps and either intruded through or perhaps fed some of the Upper trap flows which presumably existed earlier and have since been eroded away. In either case, it seems difficult to consider them as representing a truly hypabyssal activity.

The only objections in regarding the dykes in general as feeders of lavas to traps flows seem to be: (a), nowhere has a dyke abutted by a flow been so far observed in the whole of this formation, and, (b), these dykes appear to be inadequate as possible sources of such immense amounts of lava material. The mode of eruption of these lavas, therefore, presents a mystery. On the contrary, what happened to the lava upwelling through almost thousands of dykes is also an important one, and difficult to answer. Perhaps with increasing knowledge of the nature of lavas at source and their behaviour during eruption it may be possible to arrive at some definite conclusion.

Acknowledgments

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ON THE CHARACTER OF ISOSTATIC GRAVITY ANOMALIES IN PENINSULAR INDIA

BY

J. C. BHATTACHARJI

Abstract

The gravity anomalies used are based on the Airy's hypothesis of isostatic compensation for T= 30 km and are found to constitute a remarkable pattern in peninsular India. It is observed that although most of the outstanding land features over the stable peninsular block, that could escape the denudation of ages, are completely isostatically compensated, there are also regions of gravity-highs in Central India especially over the tectonic ranges of the Aravallis as well as of gravity-lows more predominant over the sedimentary rocks of the Cuddapah basin than in the deeply eroded region of the peninsular plateau. The positive anomalies are caused by the mountain roots of much thinner formation than are actually obtainable on the basis of the Airy's isostatic-floating theory; while the negative anomalies are interpreted in terms of undulations of a deep seated topography in the case of Cuddapah basin, and of a surface topography of mass-defects due to age-long denudation in the case of the eroded region. The undulations postulated here are estimated approximately on the basis of the Airy's hypothesis and their overall effects give results in fair agreement with the gravity material available. In the end the necessity of a more comprehensive gravity survey covering especially the mountainous region all over the peninsula, is stressed for a more detailed investigation.

Introduction

Gravity anomalies as given in the Survey of India Technical Paper No. 10 by B. L. Gulatee, are on the basis of free-air. Bouguer, Hayford's compensation for D=113. 7 km and Airy's compensation for T=30 km. The isostatic gravity anomalies in peninsular India are characterised by a positive belt over the tectonic mountain ranges in Central India followed by an extensive negative zone in the archaens of the South. Despite the fact that the peninsula is a stable crust-block lift undisturbed since the preCambrian times, the anomalies over this vast

rock expanse composed mostly of heavy rocks, are very negative. This has, since long, posed a delicate problem for geodesists.

Burrad's interpretations based on only fragmentary data were of a general nature. Glennie tried to interpret them in terms of interlacing series of downwarps by making use of his own crustal warping hypothesis. This has now been discarded by Glennie himself. Gulatee tried to explain this phenomenon as due to the choice of the normal thickness of the earth's crust as 30 km instead of 15 km in Airy's isostatic reduction. This, however, is not confirmed by the regression equations between station elevation and Airy anomalies obtained by the least-squares fitting.

In Peninsular India, the problem has thus remained unexplained. In the paper an attempt has been made to point out some factors which may account for this paradox.

Principal Structural Features

The Peninsular India is one of the oldest continental areas on the earth's surface. It is a rigid crust-block "which has lain undisturbed by orogenic movements of any intensity, at least since Palaeozoic times". In Dr. Wadia's words "This old crust-block, no doubt, was seamed with ancient mountains, now peneplaned and eroded almost to their roots and forming, in fact, the girders of its frame-work." The important mountain ranges of the peninsula, consist of the Aravallis, the Vindhyas, the Satpuras, the Western Ghats and the broken and discontinuous chain of elevations known as the Eastern Ghats. Of these, the Aravallis and parts of the Satpuras represent the only tectonic chains in the region, the rest being merely the outstanding remnants of the old plateau of the peninsula. Completely isolated from the rest of the block, lies the conspicuous feature of the Cuddapah basin which was "Originally a gulf of an ancient sea", but formed of the pre-Cambrian sedimentary rocks during the first part of its history.

Character of Isostatic Anomalies and their Studies

Chart I shows the existing gravity cover in Peninsular India, which is mainly confined to the important roads and

railway lines. There are thus wide gaps here and there particularly over areas south of Palghat and also in the Deccan Trap south-east of Bombay. The isostatic anomaly contours on the Airy's hypothesis for T=30 km, based on the existing data, are shown in Chart II against the topographical background of region. These anomalies, though largely negative, are found to follow exactly the same structural pattern as described in the preceding para, bringing out the following four distinct characteristics :

(a) a region of zero anomalies covering the outstanding land features over the peninsular plateau, that could escape the denudation of ages.

(b) a region of moderate positive anomalies, comprising the tectonic mountain chains in Central India.

(c) a region of strong negative anomalies over the sedimentary rocks of the Cuddapah basin.

(d) a region of moderate negative anomalies, covering the deeply eroded areas in the peninsular plateau.

Now in order to study the details of isostatic principle, particularly the mode and degree of the compensation, the isostatic anomalies in the region require to be analysed in detail. With this object in view, the Airy isostatic gravity anomalies: $\triangle g$ (in mgal) for various normal thicknesses T (in km) of the earth's crust, have been developed as functions of station elevation h (in Kilo feet) or HOLOPAINEN'S correlation factor r or i.e. $\frac{h.\ \triangle g}{|h.\ \triangle g|}$ by the least-squares method and the results given in Table I for the regions considered. In the above analysis the usual free-air and Bouguer anomalies have been taken as equivalent to the Airy isostatic anomalies for T=O km and T= ∞ km respectively, and the Hayford isostatic anomalies for D= 113.7 km have been assumed to correspond to the Airy isostatic anomalies for T=60 km. But the value of T for which the elevation term is zero or the correlation factor r or the quadratic anomaly sum is significantly small, is considered the most probable thickness of the earth's

Chart I

Gravity Cover in Peninsular India.

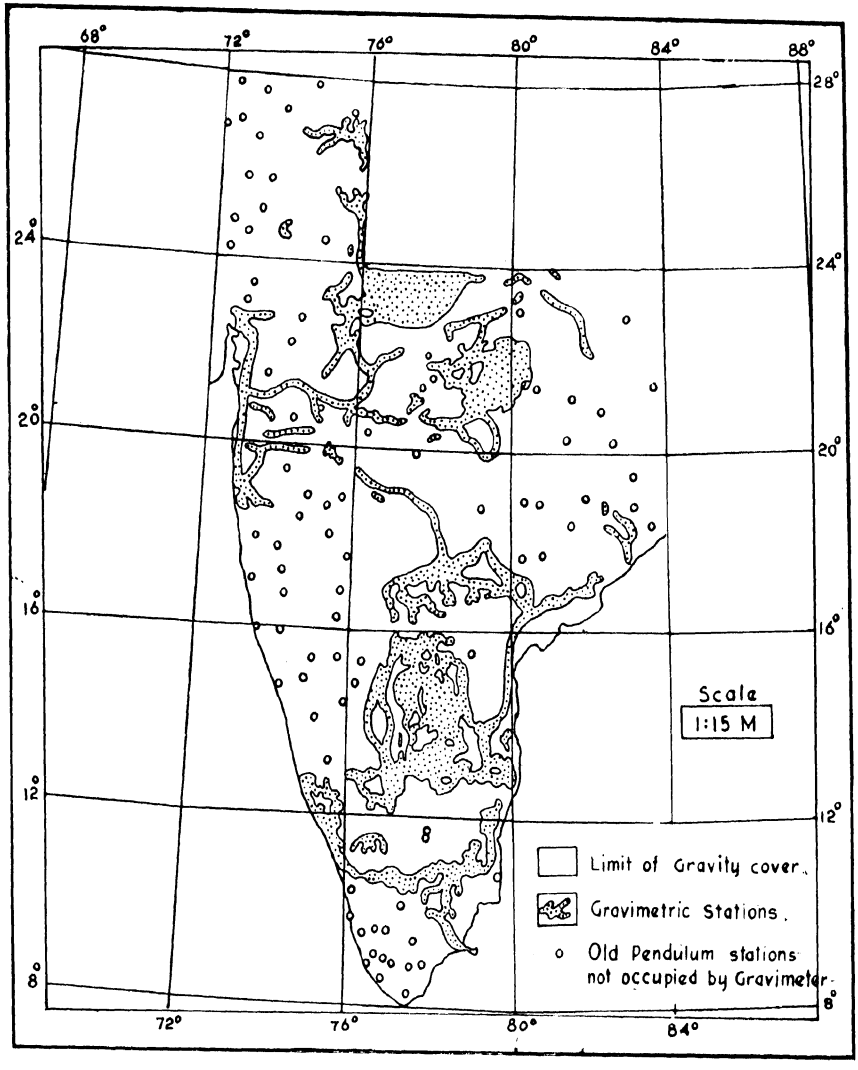
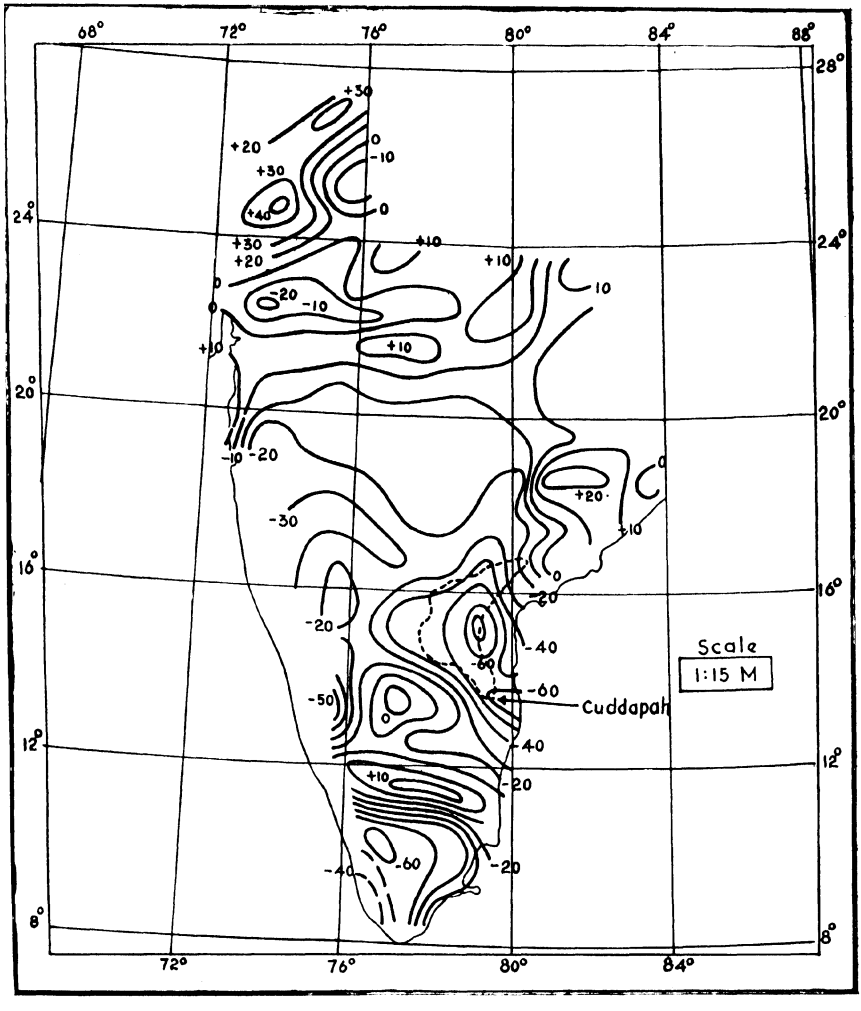


Chart II

Airy Anomalies for T = 30 Km. against Topographical background.



Broken contours are based on insufficient Gravity Data.

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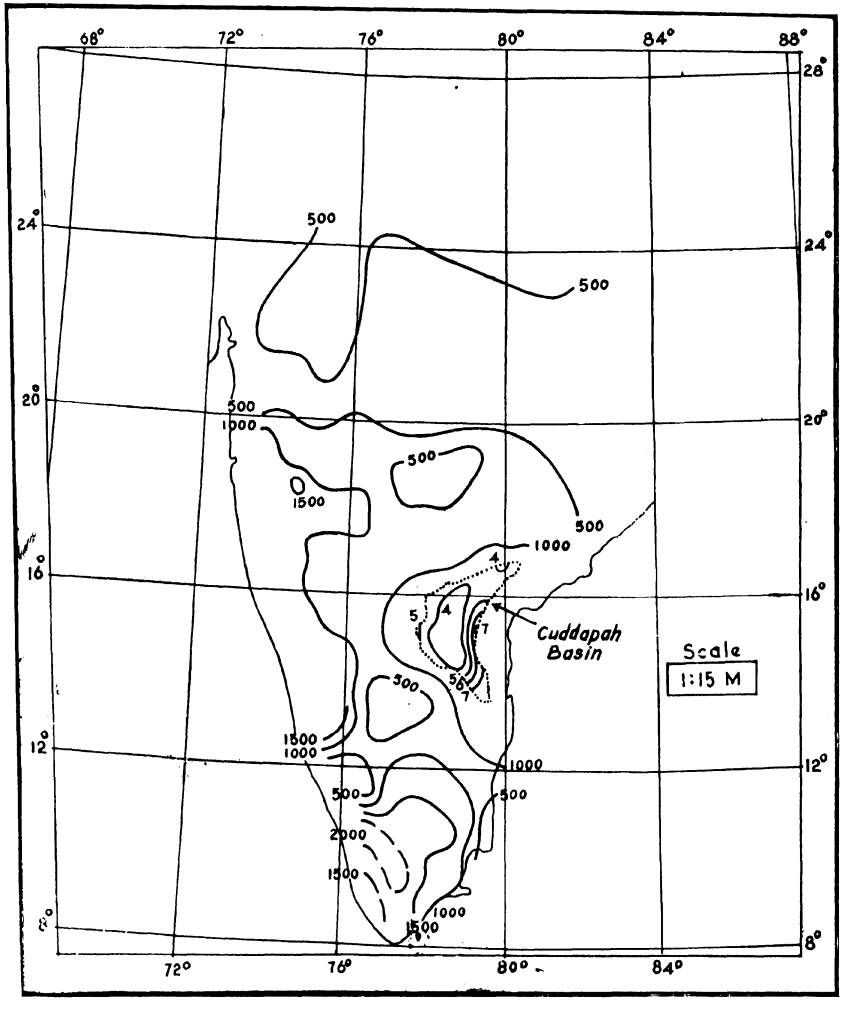
Chart III



Broken contours are based on insufficient Gravity Data.

*

crust for isostatic equilibrium. This in the case of region (a) is the same accepted value of 30 km. but as regards other regions there is practically no solution of T as such, showing thereby that there are actual deviations from isostatic equilibrium prevailing in the regions, which have been discussed in detail in the subsequent para. Moreover the regions being of low elevations, reductions on Vening Meinesz's regional hypothesis also do not seem to make much appreciable difference as illustrated by some stations given in the Survey of India Technical Paper No. 11 by B. L. Gulatee. Table II provides an interesting comparison of the performance of the mean Bouguer anomalies and mean Airy isostatic anomalies in different regions giving thus a more clear picture of the degree of the compensation prevailing in the regions.

Region of zero anomalies

As evident from Chart I, the gravity cover in region (a) is very limited. The overall anomaly picture obtained on the basis of the existing gravity material mainly confined to the level lands, cannot therefore be truly representative, especially because whatever characteristics the outstanding land features in region (a) may possess, are practically lost while considering the anomaly picture of the peninsular region as a whole. Moreover "if we are interested to decide whether an isostatic principle is right or wrong, we have to study not the level lands but the mountains and oceans". Thus any inference derived therefrom without giving due weight to the anomaly field actually prevailing in the mountainous region (a), as has previously been done, would be completely misleading. Apart from this, there are also difficulties in respect of gravity anomalies in the coastal areas where gravity disturbances in the form of complicated isostatic anomalies often occur for various reasons, viz. deposition of light sediments, bulging out of lighter continental matter under the edge of ocean floor and formation of tectonic belts along the coasts. These complicated anomalies are therefore better left out of consideration especially when studying details of isostatic condition in an extensive region. But when studied separately as in Tables I and II, the region (a) is found to reduce practically to a region of zero anomalies having the outstanding land features completely compensated, showing thereby that the stable peninsular block is broadly in a state of isostatic equilibrium.

Region of positive anomalies

As evident from Table II, the visible topographical features in region (b) are 125 per cent over-compensated. According to geological evidences, the Aravallis-"the only instance of a true tectonic mountain-chain" in Central India, though peneplaned and eroded to their roots in pre-cretaceous times, "has been since slightly upwarped" due to some Upheaval forces in the Mesozoic era, but the mass-load of the upwarped mountain ranges might prove "too small to force the earth's crust to sink into equilibrium. It therefore seems most probable that the Aravalli ranges have developed root formation much thinner than what is normally obtained on the basis of the Airy's isostatic floating theory, thus automatically giving rise to a region of over-compensation.

Region of Strong Negative Anomalies

The crescent-shaped area of the Cuddapah basin, as described by Glennie, "was evidently a gulf of an ancient sea, the floor of which steadily sank during the first part of its history, and during this period the sediments of the Cuddapah system were deposited". Moreover there are geological evidences, as indicated by Glennie, of earth movements from the east "pushing up the Nallamalais and other ranges of the Eastern Ghats over the east part of the basin", but keeping the western part practically undisturbed. These are the circumstances which have been considered most favourable for the development of the lateral compressive forces inside the earth's crust, which can sustain the deviations of isostatic equilibrium as prevailed in the Cuddapah basin on account of the strong negative anomalies therein. These deviations are not possible to be explained otherwise. The assumption of large mass-deficiencies below the basin is out of question as the actual crustal densities therein are found, according to Auden, to be generally above the normal. The lateral compressive forces again cannot be assumed to be below the elastic limit of the earth's crust; for in that case these would be limited to elastic compressions only which, as observed by Vening Meinesz, are of little significance in the case of large negative anomalies. The most probable explanation for the departures from isostatic equilibrium because of the strong negative anomalies in region (c), therefore, seems to be the lateral compression above the elastic limit of the earth's crust, leading as stated by Vening Meinesz, to plastic thickening combined

with downbuckling which presses the crust into a position inside the heavier subcrustal layer, considerably lower than that of its isostatic equilibrium, thereby causing strong negative anomalies in the region. The plastic downbuckling is, in effect, a deep-seated topography whose undulation is calculable in terms of linear depths by which the thicknesses of the crust of density 2.67 corresponding to the zero Airy anomaly, fall short of those of the same crust when considered to be pressed down in the heavier subcrustal layer of density 3.27 in order to account for the strong negative anomalies in the region (a). The method of estimation of the above depths based on the Airy's hypothesis of isostatic compensation for T = 30 km, as given in the appendix, has been utilised in the preparation of the contoured Chart III showing in blue the undulation of the plastic downbuckling of the earth's crust underlying the Cuddapah basin. It is however of interest to note that the downbuckling, as revealed in Chart III appears to go much deeper towards the eastern end-the less stable part of the Peninsular region, but have suddenly risen up forming a conspicuous shallow strip about the middle of the basin below the upwarped Nallamulai ranges.

Region of Negative Anomalies

The negative anomalies in region (c) are found to occur in areas wherever there are possibilities of large scale surface mass-depressions due to the age-long denudation over the old Peninsular plateau. It is also observed that the deeper the mass-depressions over the surrounding areas, the stronger are the negative anomalies. There is thus close relationship between the order of the negative anomalies and that of the surrounding surface depressions in the form of mass-defects whose compensation effects computed on the Airy's hypothesis are large enough to account for the negative anomalies in the region, the Bouguer effects getting automatically cancelled out on account of the negligible terrain of the considered depressions. Moreover, the Vening Meinesz's plastic downbuckling hypothesis does not fit well in the case of the old Peninsular block over such an extensive region, which, according to geological evidences, "has remained stable and has lain undisturbed by earth movements of any intensity, at least since Palaeozoic times". It therefore, appears quite justifiable from both geological and isostatic considerations to assume the negative anomalies over the extensive deeply eroded region (d)

to be due to the surfaced depressions in the form of negative loads over the stable peninsular plateau. The method of estimation of the depths of the above surface mass depressions based on the Airy's hypothesis of isostatic compensation for T = 30 km, as given in the appendix, has been utilised in the preparation of the contoured Chart III showing in red the undulation of the surface topography of mass-defects in region (d). The trend of red contours in Chart III is in general agreement with the existing surface mass–depressions over the old peninsular plateau and the average estimated depth of the eroded layer is of the order of 600 feet which is not too large.

Conclusions

It is observed that the outstanding land features over the old peninsular plateau, that could escape the denudation of ages, are isostatically compensated showing thereby that the stable peninsular block is, broadly, in a state of complete, isostatic equilibrium except for the tectonic Aravalli ranges which is overcompensated due to the thinner root- formations below, the Cuddapah basin which is a region of strong negative anomalies resulted from the plastic downbuckling of the earth's crust underlying the basin and lastly the deeply eroded parts of the peninsular plateau which is a region of negative anomalies caused by mere surface-depressions due to the age-long denudation.

It is, however, felt that the gravity cover in its present form, is very much limited and is, as such, unsuitable for a more detailed investigation. Recommendations are therefore made for a more comprehensive gravimetric survey covering the existing gaps especially the mountainous region all over the peninsula.

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APPENDIX

The Airy isostatic gravity anomalies for T = 30 km, are to be used to contour the regions (c) and (d) with condition that at any point within the regions, rigorous gravity reduction for the undulations of the deep-seated topography shown by red contours in region (c) and of the surface topography of mass-depressions shown by blue contours in region (d) of the same Chart III, will produce the Airy isostatic anomaly at that point. Use is, however, made of the fact that a large part of the gravity effects of both the deep-seated and the surface topography of mass-depressions will come from an area of less than 100 miles radius. Beyond that, the effects will rapidly diminish. Two stages are required to obtain the final result. The first stages is a preliminary one producing contours to be adjusted in the next stage. The approximate formulae to estimate the point values of depths required in stages I and II, have been derived with the help of "Fundamental Tables for Reducing Gravity Observed Values" by G. Cassinis, P. Dore and S. Ballarin, and are given as below :

Stage I (preliminary)

$$D_1 = - \frac{\triangle gCA}{6.F_1 + 11.F_2 + 3.F_3} \quad \text{for region (c).....(1)}$$

$$d_1 = - \frac{\triangle gCA}{9.f_1 + 15.f_2 + 4.f_3} \quad \text{for region (d).....(2)}$$

Where D_1=preliminary depth of deep-seated topography in km.

d_1=preliminary depth of surface topography of mass depressions in Kilo feet.

$\triangle gCA$ = Airy isostatic anomaly at a point in mgal

F_1, f_1 = fractions of regions (c) and (d) covered by zone (1) of radii:17 and 35 miles.

F_2, f_2 = fractions of regions (c) and (d) covered by zone (2) of radii : 35 and 60 miles.

F_3, f_3 = fractions of regions (c) and (d) covered by zone (3) of radii : 60 and 100 miles.

The values of depths at each point as obtained in stage I to the nearest 200 metres in the case of region (c) and 200 feet in the case of region (d), are utilised in preparing only preliminary contours in regions (c) and (d).

Stage II (final)

$$D_2, = - \frac{\triangle gCA - 9.d' - 15.d'' - 4.d''}{6.F_1 + 11.F_2 + 3.F_3} \quad \text{for region (c).....(3)}$$

$$d_2 = - \frac{\triangle gCA\ 6.D' - 11.D'' - 3.D''}{9.f_1 + 15.f_2 + 4.f_3} \quad \text{for region (d).....(4)}$$

Where D_2 = final depth of deep-seated topography in km.

d_2 = final depth of surface topography of mass-depressions in Kilo feet.

D', d' = average depths of deep-seated and surface topography and covered by zone (1)

D'', d'' = average depths of deep-seated and surface topography and covered by zone (2)

D″,d″ =average depths of deep-seated and surface topography and covered by zone (3)

The values of depths at each point as obtained in stage II to the nearest 100 metres in the case of region (c) and 100 feet in the case of region (d) are utilised in the preparation of the final chart.

TABLE I

	Reduction	method	g in mgal h in Kilo feet	Corr. factor	Square sum
	Free-air;	T= 0 km;	g= — 16+18.h	r=0.90	34600
Region (a)	Airy ;	T=30 km;	g= 1+ 0.h	r=0.20	2500
	,,	T=60 km:	g= — 4— 1.h	r=0.70	6200
	Bouguer ;	T= ∝ km;	g= — 18—15.h	r=1.00	88400
	Free-air ;	T= 0 km;	g= — 30+41.h	r=1.00	12600
	Airy ;	T=30 km;	g= 3+13.h	r=1.00	5300
Region (b)	,, ;	T=60 km;	g= 8+ 9.h	r=1.00	4400
	Bouguer ;	T= ∝ km;	g= —138+72.h	r=1.00	3700
	Free-air ;	T= 0 km;	g= — 5+ 2.h	r=1.00	28100
	Airy ;	T=30 km;	g= — 64+ 2.h	r=1.00	37500
Region (c)	,, ;	T=60 km;	g= — 36—49.h	r=1.00	53600
	Bouguer ;	T= ∝ km;	g= — 35—15.h	r=1.00	59600
	Free-air ;	T= 0 km;	g= — 45+15.h	r=0.91	43300
	Airy ;	T=30 km;	g= — 42+ 7.h	r=1.00	58600
Region (d)	,, ;	T=60 km;	g= — 50+ 4.h	r=1.00	111600
	Bouguer ;	T= ∝ km;	g= — 44—19.h	r=1 00	265600

TABLE II

	Mean elevation feet	Mean anomaly				Percentage of compensation Under compensation (—) Over compensation (+)
		With regard to sign		Without regard to sign		
		Bouguer mgal	Airy mgal	Bouguer mgal	Airy mgal	
Region (a)	1350	—37	+ 1	39	6	+ 3
Region (b)	1650	—20	+25	20	25	+125
Region (c)	560	—63	—52	63	52	— 17
Region (d)	1370	—71	—32	71	32	— 55

ABSTRACTS

ELASTIC WAVE VELOCITIES OF ROCKS UNDER A GENERALIZED STRESS FIELD

BY

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In this paper, the author deals with the elastic response of matter, to infinitesimally small stresses superposed over a large finite stress field of a general nature, a problem of importance in geophysical studies. This response is specified either by the modified wave velocities in the stressed medium, or equivalently by the elastic constants modified from their original values by the initial stress field. Formulæ for such modified or "effective" elastic constants for material of cubic or isotropic symmetry are presented in this paper and these are based on earlier work of Bhagavantam and Chelam, who employed the theory of nonlinear elasticity to connect the effective moduli with the second and third order elastic constants of a stress-free state and magnitude of the initial strain.

Due to extreme paucity of experimental data on third order elastic constants, the immediate application of the above formulæ is severely restricted. However, the available information has been utilized to discuss some simple cases like Birch's wave velocity data on granite placed under a uniaxial stress, the increase in wave velocities followed by a decrease as reported by Shimozuru in marble etc. The formulæ predict a decrease in most elastic moduli due to a finite shear, a result of significance in release of elastic strain energy in earthquakes, rockbursts etc. Some possible applications of this work to the orogenetic features in the peninsular shield are tentatively discussed.

A CORRELATION OF GRAVITY DATA WITH THE REGIONAL GEOLOGY OF THE SOUTHERN PENINSULAR INDIA

BY

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An analysis of Bouguer anomaly map of Southern Peninsular India prepared from the data published by the Survey of India and the Geological Survey of India is presented.

A gravity maximum with a northeasterly trend occurs over the Nilgiri Hills and Eastern Ghats. A gravity minimum almost parallel to this maximum extends northeastwards from Palghat through Salem to Gummidipundi. The northeasterly trend in the gravity contours prevails in the coastal areas of Central Madras, where local anomalies with steep gradients are found east of Vriddhachalam over the Tertiary and younger sediments.

A gravity minimum with a northwest trend occurs over the Dharwars of Mysore. Another feature of interest is a gravity low over the Cuddapah Basin of Precambrian age, which is filled with rocks of higher than normal density of 2.67 g/cm^3.

The near parallelism between the gravity contours and the Dharwar and Eastern Ghats structural strikes suggests that the gravity may be indicating the structural grain of the Peninsular Shield.

It is probably that the gravity maximum over the Nilgiris and the Eastern Ghats indicates the horst-like structure of these orographical features, although part of the anomaly is to be attributed to heavy rocks such as the charnockites and Khondalities that are present in the region of the gravity maximum.

It is not clear whether the gravity minima are reflecting downwards as postulated by Glennie, 'roots' of ancient mountains, local thickenning of the granitic crust, or grabens.

REMANENT MAGNETISM OF THE DOLERITE DYKES OF HYDERABAD

BY

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The remanent magnetic studies of about 25 samples of dolerites occurring around Hyderabad, have been collected from eight different sites. From each sample 4 to 6 specimens of 2.5 cms. diameter were cored and cut to 1.5 to 2 cms. length. Measurements of remanent magnetism has been carried out with an Astatic magnetometer of the sensitivity 10^{-4} C. G. S. Samples from two dykes showed very stable directions even after repeated measurements with considerable lapse of time. But other dykes showed large variation in the direction showing their unstability. A. C. demagnetisation test was carried out using solenoid method in field free region to avoid the anhysteric effects of magnetisation on the specimens. For further stability tests, thermal demagnetisation unit was constructed and used. The dolerite dykes found near Hyderabad have a rough East-West trend. These have been described as belonging to Precambrian age. The direction of remanent magnetisation of the stable samples on a stereographic net showed closed points while the unstable ones showed large deviation and also possessed mixed polarisations. The direction of remanent magnetisation of each dykes is different. After demagnetisation in A. C. field, the scatter diminished and showed constant and concordant directions. Similarly, thermal demagnetisation studies showed stable directions almost upto Curie temperature. The unstable ones on the other hand showed large deviation from the initial direction. Near the Curie point, consistant directions were noticed. Curves of magnetisation versus temperature and also against the specimen in zero field and cooling in the earth's field. The thermal studies showed that the original remanent magnetisation was of the thermo-remanent magnetic nature.

FACTORS GOVERNING THE ATTENUATION OF SEISMIC WAVES

BY

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This article is an attempt to present the current stage of understanding of processes which lead to attenuation of elastic waves in the Earth. A knowledge of the variation of their amplitude with distance, and with depth in the case of surface waves, would appear to be of considerable interest to seismology in general and to Earthquake Engineering in particular.

An advancing wave is normally attenuated by the spreading out of its energy with the enlarging wavefront and by partition of its energy at the elastic discontinuities. Other factors contributing to this include scattering, diffraction, and deviation from perfect elasticity. The short period shear waves and the long period surface waves are by far the greatest source of danger to structures. Scattering causes appreciable damping of the former, whereas elastico-viscosity and elastic after-working assume greater importance for longer period vibrations. More field and laboratory experiments are needed to help understand the actual physical mechanism responsible for the attenuation.

NATURE & ORIGIN OF MICROSEISMS AT COCHIN

BY

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The analysis of microseisms recorded by the east-west and vertical seismographs during the period 1958-60 by a new filtering technique showed the existence of three main types of microseisms at Cochin. They are $\frac{1}{2}$ - 2 second short period microseisms associated with the local rainfall, 2–6 second steady vibrations with varying amplitude related to the monsoon and 2–6 seconds regular storm-type microseisms. The general characteristics and the origin of these microseisms are described in this paper indicating the possibility of using microseisms for the study of monsoon in the southern peninsular and intense cyclones forming in the Arabian Sea or Bay of Bengal.

THE RELATIONSHIP BETWEEN TECTONICS AND METAMORPHISM IN SOUTH INDIA

BY

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The tectonic pattern of Peninsular India indicates a succession of orogenic belts. Mysore State, which contains the characteristic "Dharwar System" formations, constitutes the nucleus around which the younger tectonic units are disposed.

The Mysore Dharwars, comprising the Shimoga and Chitaldrug Schist belts, are folded into a huge anticlinorium which plunges north-north-west. The two main limbs of this fold have a general north-south trend, and the typical members of these formations such as the schists, limestones, quartzites, and ferruginous quartzites, yield abundant evidence of progressive regional metamorphism. The elongated ultramafic intrusion which is located in the axial zone of the Dharwar anticlinorium, has been progressively metamorphosed.

The Peninsular gneisses are also affected by this progressive metamorphism, for in the southern parts of Mysore State, they have been transformed into charnockites. Large scale folds have been recognised in the charnockite province of South India and it is for consideration whether these folds are inherent to the charnockites, or whether they were present in the original rock formations before their charnockitization. In the Biligirirangan area in south-east Mysore, however, it is clear that the structural trends and fold patterns of the charnockites are conformable to those of the gneisses.

The increasing grade of metamorphism from north to south in Mysore State is partly due to the fact that as a consequence of the Dharwar anticlinorium plunging northwards, successively lower sections of the crust are exposed as one proceeds south-wards; and party to a widespread intrusion of metamorphic charnockites.

TECTONICS OF GRANITE AROUND BOMMASAMUDRAM; CHITTOOR DISTRICT, ANDHRA PRADESH

BY

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Granite is the most extensive rock type around Bommasamudram (Lat: 13°0′ and 13°5′ and Long: 79°4′ 15°15″ and 79°15′) and is comprised of several members. It carries rafts of metasediments, metagabbros, granite gneisses and charnockite and is intruded by dolerite swarms. The acid dykes comprised of monzonite, syenite, aplite and quartz veins are of restricted occurrence and are the youngest rock types.

To trace the tectonics of Granite the structural map has been prepared. The flow structure which is well displayed along the contacts with country rocks is of one whole consistent pattern and to this, joints and other structures are geometrically related.

Flow structure is essentially due to primary banding and mineral orientation. The mineral alignment is fairly consistent in the banded varieties but is poor in the equigranular types. The plunge of lineation in the plane of foliation in the northern portion is gentle towards N. 10° E. but in the southern portion it is somewhat steep. The bands dip at high angles towards west and in some places they are vertical.

Four joint systems occur within the Granite mass, and the Q and S—joints constitute master system.

Slicken sides occur along the joint planes and are mostly confined to Q—joints. The inclination of the slicken sides is towards west at varying angles. It seems likely that the north south tension, accompanied or followed by east-west compression was responsible for normal faulting along the Q—joints with a relative downward displacement of the rocks to the West.

Petrofabric diagrams of the Granite and country rocks prepared in sections cut perpendicular to lineation show that rock types which have consistent foliation also possess consis-

tent petrofabric patterns. Therefore the foliation and petrofabric patterns are referable to powerful deformation during consolidation of Granite.

The field characteristics of Granite suggest that it is not of replacement origin. Though it occurs as sill like intercalations in the country rocks, it is in places voilently transgressive. The presence of trains of rafts of country rock in Granite indicates that the frame work has been opened owing to the accession of the magma. The display of swirling pattern by the xenoliths in granite suggests the turbulent flow of the magma. The occurrence of overfolded rafts of metasediments in granite and the trend of lineation in granite reveal the vertical rise of the magma and its flow from south to north beneath the cover of country rocks. During this flow perhaps it exerted hydraulic pressure on the confining walls and fragments and aligned them parallel to the trend of the Granite.

During consolidation crustal pressure operated along an approximately East-West direction and this was accompanied or followed by a tension in an approximately North-South direction and gave rise to Q and S—joints. The bending in the trend displays by the bands of quartz-magnetite rocks towards west may be attributed to east-west crustal pressure. After the Granite became essentially solid diagonal joints were evolved and probably during this period, the slicken sides were formed.

TECTONICS OF THE LAURENTIAN SHIELD

BY

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A study of what work has been done on other shield areas can be of great value in interpreting data in one's own area.

The Laurentian Shield is made up in part of sedimentary and volcanic rocks, now disturbed and metamorphosed in varying degrees, and impart of great masses of granite and other rocks of plutonic origin. All visible structures are of PreCambrian age and since the beginnings of Paleozoic time the shield has remained somewhat stable.

Most of the details in its history can never be deciphered because its record has been largely obliterated by metamorphism and by the removal of great masses of rock by erosion. As the shield rocks are void of fossils, they cannot be classified and correlated in the usual manner. Recent radioactive methods of age determination have provided a clue to the succession of tectonic events which are now thought to be approximately as follows :

The oldest rocks in southern part of the shield are those of the Timiskaming-Keewatin province north of Lake Superior where radioactive determinations on the granite intrusives show ages of 1,750 to 2,400 million years. Next in age are those rocks in the Grenville province bordering the St. Lawrence River, and those intrusives possess ages of about 1,100 million years. Located between the two above provinces are the younger sediments of the Huronian series which underwent deformation during the closing phase of the Grenville orogeny. And, in the Lake Superior region Keweenawan red beds and lavas with ages of 530 to 550 million years rest unconformably on the Huronian.