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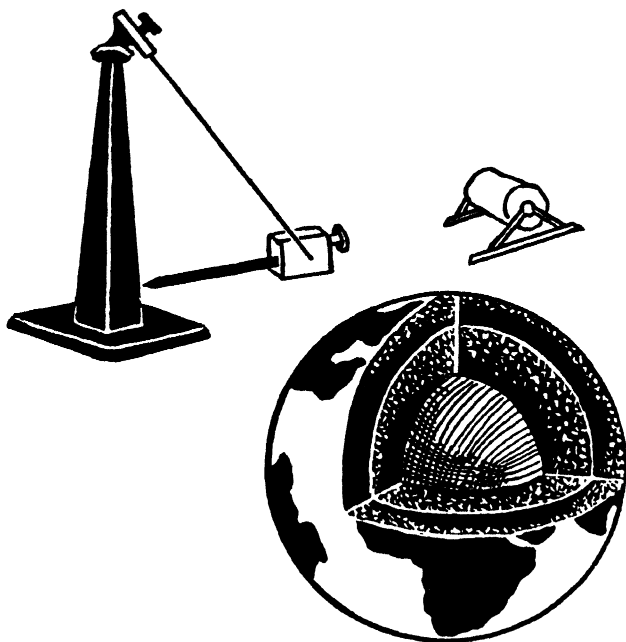
RESTLESS EARTH



Illustrations by Gerald Ames

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Introduction

Ever since the dawn of human history, a few individuals here and there have bent some of their energy toward the exploration of the universe. In recent years, the scientific explorers have provided themselves with many tools and implements, some of them extraordinarily complicated, to enable them to penetrate the secrets of the world about us. Objects on the surface of the earth, inanimate or living, small or large, have revealed their structure and much of their nature. What is happening in the air above us and in the sea around us is common knowledge to all who keep abreast of the expanding frontier of science. There remains one portion of our environment about which we have very little direct knowledge, a region that man has always taken for granted but which now is challenging his ingenuity as never before.

Much more is known about the materials in the atmosphere a hundred miles above our heads than about the materials in the earth only ten miles beneath our feet. The deepest wells drilled anywhere are less than four miles deep—less than one thousandth of the distance down to the center of the earth. In seeking knowledge about our terrestrial

abode we have been able to observe directly only the surface skin of a planet, the interior of which is beyond approach by means of any of our senses. But there are many fascinating, indirect approaches to knowledge of the earth's interior. Some of these are beginning to yield information that is both satisfying to the characteristically human trait of curiosity and significant to the equally characteristic craving for a more comfortable and secure existence. What happens in the depths of the earth has much to do with the formation of metalliferous ore deposits in its outermost skin where those ores become available for human use. The internal forces that crumple the surface into mountain ranges and oceanic troughs, or raise and lower continents and ocean floors, profoundly influence the surficial processes of erosion and sedimentation responsible for landforms and mineral fuels. For many reasons, it is highly desirable that the men who live on the surface of our planet learn just as much as they can about the forces and processes that make it truly a Restless Earth.

This book is essentially a non-technical account of some of the ways whereby men are beginning to understand those forces and activities. Volcanoes and earthquakes are surface expressions of deep-seated processes; they are discussed as effects of internal activities. Appropriate attention is given to the paradox that rock which is so firm and obdurate,

when observed in canyon wall or wave-cut cliff, is plastic and pliable under the conditions of pressure and temperature that are present at only moderate depths. The force of gravity accomplishes strange results within the body of the earth and some of these results are discussed in simple but accurate terms.

All in all, these readable and truly fascinating pages will serve the general reader as an admirable introduction to one of the oft-neglected aspects of earth science. They open up a new and important sector of the expanding horizon of knowledge about the world in which, or on which, we live.

KIRTLEY F. MATHER

Cambridge, Mass.
April 15, 1954

Foreword

The air has its storms; the ocean has its waves and currents. By comparison, the solid earth seems quiet, but it is a deceptive quiet. Earthquakes and volcanoes show that a lot of activity goes on inside our planet. Thousands of cubic miles of the crust move at one time. Rock oozes like putty or quivers like a harp string. Sometimes it explodes with power greater than that of an atom bomb.

Men have always wondered what forces drive the earth's activity. The question cannot be solved

by an expedition, for the interior is closed to us. Pressures and temperatures are so high that human beings cannot expect ever to penetrate the depths. The moon will be easier to explore. Today scientists are investigating the upper atmosphere, and they are learning the secrets of the ocean deeps. Meanwhile an unknown world lies beneath our feet.

Because scientists cannot get into the earth's interior they have devised indirect methods of exploring it. In this book we accompany them in their investigations. First we consider volcanoes and earthquakes, and other effects of the activities within. Then we take up the main problem of the earth physicist—how to understand the internal forces that change our restless earth.

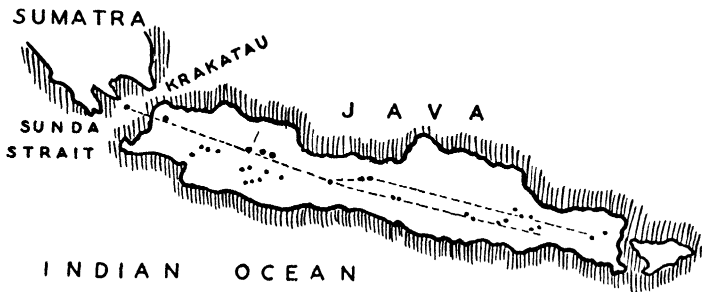
Volcanoes

I · *Exploding Island*

Millions of people live on volcanoes. In Java, one of the most densely settled areas of the globe, people have carved volcanic slopes into terraces for their fields. Down in the valleys the terraces rise in broad, low steps. Farther upward, where the slope becomes steeper, the terraces are only narrow ledges, but they provide some additional space on which to grow food.

Of the many volcanoes that lie in a double file along the island of Java, 32 are active in greater or

less degree. Sometimes a volcano pours mud down its slope. Worse still, a flow of hot lava may creep toward the villages, pushing before it blocks that have solidified.



Inhabitants of volcanic lands must face their dangers together. In Java the people have built mounds as refuge places. Earth and stone barriers have been laid out above some villages to turn aside flows of mud or lava. Alarm systems and signals warn of danger.

On the island of Hawaii, American army fliers have fought lava flows with bombs. But the most that bombing can do, if it accomplishes anything at all, is to break open a lava stream so that it spreads out and cools a little faster, which may help bring the flow to a stop before it overwhelms a village.

Sometimes a volcano erupts unexpectedly with enormous power. Before the year 1883, no one suspected that a volcano on the little uninhabited island of Krakatau, which lies in Sunda Strait between Java and Sumatra, would bring destruction to the shores of both islands and kill many thousands of people.

For over two hundred years, until the middle of

May, 1883, Krakatau had been quiet. Then the volcano stirred. Earth tremors were felt, but they were slight and frightened no one. For an hour, on Sunday morning, May 20, 1883, the people of Java and Sumatra heard thundering sounds like the rumble of distant artillery. Later, clouds of vapor and dust rolled into the sky over Krakatau. The dust drifted for miles over sea and land and fell like dirty snow. Nearer the volcano, spongy bits of stone—pumice—rained on the sea. Very light, it floated on the surface in drifts.

These signs caused no alarm. Excursion parties sailed to Krakatau from the city of Batavia, a hundred miles away, and climbed the volcano to see the show. They found there was an opening in the summit about thirty yards wide from which a column of steam roared upward.

Greater rumblings sounded during the summer, and clouds from the volcano spread darkness and dust for hundreds of miles around. The climax of activity came in August, during the night of the 26th and the morning of the 27th. Detonations punctuated the rumbling and increased in violence until the middle of the morning, when there were four mammoth explosions that made houses tremble a hundred miles away.

The sea surrounding Java and Sumatra was no protection against the exploding volcano. A great wave pushed out from Krakatau and rolled over the shores of Java and Sumatra, in some places piling up a wall of water 100 feet high. It pounded harbors and waterfronts. Boats, wharves and buildings were shattered and swept away. More than thirty-six thousand persons, caught in the flood and the wreckage, died.

The volcano became still. A party of scientists sailed to Krakatau and found that most of the island —about 12 square miles of it—was gone. It had foundered and sunk beneath the surface of the sea.

The scientists found it fairly easy to determine

the mechanism that had set off the great wave. When the island collapsed, a mass of sea water slumped down after it. The mass rebounded, gave a shove to the sea, and sent off the wave.

What made the island collapse? Part of the answer to that question was seen in the sky. The volcano blew a volume of fine dust as high as 34 miles.

Volcanic dust is made of tiny, crumbly particles. Often called ash because of its lightness and grayish color, it is really not ash at all, for it is not a product of burning. Examined under a microscope, the dust appears as shreds and splinters of glass mingled with tiny crystals. Chemically, it is similar to the lava and other solid matter thrown out in the same eruptions.

It has been estimated that about one and a half cubic miles of "ash" shot from Krakatau in 1883. All the ejected material together—ash, lava, and pumice—probably totaled four and a half cubic miles. Loss of this mass of material gutted and undermined the volcano until the weakened shell collapsed under its own weight.

Not all volcanoes explode. Some are quiet in their action, like Mauna Loa and the other volcanoes that form the island of Hawaii. This great volcanic mass rises 15,000 feet from the ocean floor to the surface of the sea, and another 14,000 feet above the surface. The base of the pile resting on

the ocean floor is about 74 miles across in one direction and 53 miles in the other. If we could stand on the bottom of the sea and look up at Mauna Loa, the volcano would be more imposing than the greatest mountain on earth.

Mauna Loa did not assume the classical shape of a cone, like Fuji in Japan. Gentle in slope, it has taken the form of a great shield. This shape results from the fluidity of Hawaiian lava. As a rule, Mauna Loa does not heave up rocky chunks and fragments. It spills out a lava which, when fresh, is so liquid that it flows almost like water. Quickly spreading down a slope, these lava flows do not build up cones but spread out widely, extending the shield on one side after another.

Several miles down the slope of Mauna Loa there is a crater—a bowl-shaped opening—called Kilauea. Lava often wells up into this crater and forms a lake. Streams of bubbles rise to the glowing surface of the lake and here and there spurt up in fountains. These bubbles are made of gases dissolved in the lava. As carbon dioxide gas is dissolved in soda water and bubbles out when the bottle is uncapped, so volcanic gases bubble out of lava.

What are these gases? You cannot stick a pipe into molten lava to draw off samples of gas. But scientists have done the next best thing. At Kilauea they have approached the lava lake as close as pos-

sible in order to get at some crack or vent where vapors rise fresh out of the lava. At such places they have piped off samples of the vapor to study it. In the vapor mixture they have found water, carbon dioxide, nitrogen, sulphur, and small quantities of other gases. By far the most plentiful gas is ordinary steam. It makes up from seventy to eighty percent of the gas volume, and often more.

What explosive destroyed Krakatau? Was it the mixture of steam and other gases? If so, what is the mechanism of such an explosion? The eruptions of another famous volcano will give a partial answer to these questions, and enable us to get a glimpse of conditions at a considerable depth beneath the surface.

II · A City Smothered

A TERRIBLE CHAPTER in the history of volcanoes is the tragedy of Saint Pierre, once the main city of the island of Martinique. This story will always be remembered, not only because a beautiful city was annihilated and the lives of 28,000 people snuffed out in one minute, but also because the source of the disaster was carefully studied and much was learned about volcanic forces.

Martinique belongs to the arc of islands called the Lesser Antilles, which separates the Caribbean

Sea from the Atlantic Ocean. Christopher Columbus landed on Martinique in 1502, and found the island inhabited by a small number of Carib people —the "Indians" of this region. Later, French settlers made the island a colony of France.

Martinique was colonized in the period of a growing world market for sugar. Like other West Indian islands it had the warm climate, abundant rainfall, and rich soil that made it suitable for the cultivation of sugar cane. But Martinique, like the other islands, lacked an all-important resource—people to work the land. The needed human beings were supplied by slave merchants. In Martinique as throughout the West Indies, captive Africans were sold to the planters. So hard was the life of these people that for over a century their number was continually reduced by a high death rate. In order to maintain the population the planters bought new slaves to replace the dead.

In 1794, during the great French Revolution, the National Convention proclaimed the end of slavery in all French territories. The very day after this act a British fleet occupied Martinique and helped preserve the old regime and slavery. At last, during the revolution of 1848, the people of Martinique won their freedom and citizenship.

By the end of the nineteenth century Martinique had a population of 189,500. The little island, more densely populated than France, supported 500

persons per square mile. Ranging in skin color from black to white but mostly of shades between, all inherited the French language and culture, and all felt a special patriotism for their beautiful island.

The city of Saint Pierre, before the year 1902, was the pride of Martinique and center of its commercial and social life. The city had no harbor, but there were always several ships anchored offshore in the roadstead, loading the main export of the island, rum. Cane, from which rum and sugar were made, grew behind Saint Pierre on plantations spread over the slopes and valleys of the north end of the island. In the city were most of the island's larger rum distilleries and factories.

The houses of Saint Pierre, strongly built of field stone and roofed with bright red tile, stood side by side on streets running parallel to the shore. The streets were laid out in steps on a slope that rose inland toward the ridge of green mountains in the interior.

In this lovely city 26,000 people lived, worked, and went to school. Youth from all over the island attended the Junior College of Saint Pierre. In the surrounding countryside people worked in the cane fields. Some families owned small farms, but even those who had only gardens were able to supply themselves with fruits and vegetables that grew abundantly in the rich soil.

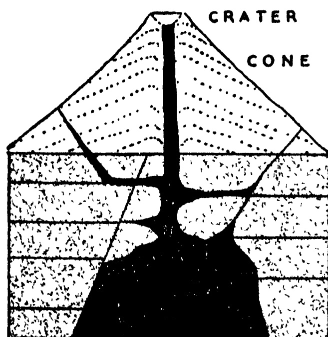
Amid their blessings, the people of Saint Pierre

had one misfortune—to live near the mountain they called Pelée, "Bald Mountain."

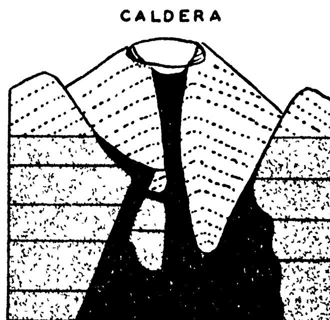
Before 1902 Pelée had no fame in the outside world. A pleasant green-clad summit about five miles to the north of Saint Pierre, it was only a few thousand feet high. Were it possible to view Pelée from the ocean floor, the mountain would seem more impressive, for it is the top of a structure rising 6,000 feet from the bottom of the sea to its surface.

Pelée, everybody knew, was an old volcano. In the year 1851 the mountain fumed a little and tossed up some ash in a harmless eruption. It seemed that Pelée was exhausted and breathing its last gasp.

Pelée had no regular cone shape. Long ago its cone had been wrecked by a collapse that left an irregular basin about half a mile across. This kind of



ANCIENT VOLCANO



AFTER COLLAPSE OF THE CONE

structure is known as a *caldera*, which is Spanish for cauldron. At one time water filled the caldera and formed a lake, but in the period of French settlement the basin was dry. It was therefore called the Dry Tarn.

Toward the end of April, 1902, the people of Saint Pierre saw a vapor column rise a thousand feet or so over the top of Pelée. Some light ash fell the next day on villages near the mountain. There was a little rumbling from Pelée and a slight earthquake tremor. The same events had happened half a century before, it was recalled, and nothing worse followed.

The stirring of Pelée greatly interested the teachers and students of Saint Pierre Junior College. They compared their volcano to the historic Vesuvius and read the ancient account of how Vesuvius destroyed the two lovely cities, Pompeii and Herculaneum.

Parties of sightseers, with students and teachers among them, climbed Pelée mountain. They found that the caldera was partly filled with water, which almost entirely covered the trees that grew in the basin, leaving only their tops above the surface. Not far from the center of the lake a little cone of cinders rose about thirty feet above the water. Billows of vapor and dust rolled from a crater-shaped opening in the cone. Jets of water spurted from the crater into the lake.

A landscape painter sat down on the brink of the Dry Tarn—dry no longer—and sketched the scene. Having no idea of the violent forces that were to kill him in Saint Pierre ten days later, he complained that by bad luck he did not see the volcano toss up any rocks.

During the nights of May 4th and 5th there were several powerful detonations. Afterward it was found that these explosions shook down the wall of the Dry Tarn on the southwest side, leaving a V-shaped breach. Through this gap the water of the Tarn rushed out, carrying along material from the cone and wreckage from the broken wall.

The thick mass poured down the valley of the River Blanche toward the delta, where there was a sugar refinery and also a number of houses. Before the people there could escape, the torrent spread over the delta and swept the buildings and 25 persons into the sea.

During the next two days and nights, flows of mud overwhelmed villages to the west of the mountain. Light gray dust fell everywhere. It weighed down the branches of the trees. At night an orange light illuminated the billows of vapor that fumed from the mountain. Glowing rocks were blasted into the air by explosions. Blocks and rubble hurtled down the slopes.

People of the north and west areas came to Saint Pierre for safety. A few residents began to

leave the city. The governor of Martinique came to Saint Pierre on May 7th to "keep order" and persuade the people to remain. He died with them the next day.

The type of eruption that destroyed Saint Pierre may have been seen in other parts of the world at other times, but it had never been studied and described. It was investigated and photographed by the geologist Lacroix, who was sent with a mission by the French government to study the exploding mountain. It is to Lacroix and his fellow scientists that we owe our knowledge of the forces that annihilated Saint Pierre and its people. After the tragedy of Saint Pierre, eruptions of this kind occurred many times.

The destroyer was a cloud that did not rise vertically from the volcano but rolled down its side, following the slope of the land. Such clouds, observed later, were seen to spurt from the V-shaped breach in the caldera wall and spill down the valley of the River Blanche. They left behind them a white track of dust on top of the older debris.

The stuff of such a "hot cloud," judging from its rapid fall down the mountain, was heavy. It must have been densely packed together, for as the vaporous material expanded it threw up a great dark wall of vapor and dust. A cloud sometimes rose to a height of several miles, and reached a volume of from 10 to 25 cubic miles.

Observers could not see the actual stuff from which these clouds emerged. When the material spurted from the mountain top it was already concealed beneath small lobes of vapor. At night the stuff was glowing hot as it jetted from the summit. Its temperature was estimated to be around 1,800 degrees.*

These hot jets moved with terrifying speed. Often a jet would cover a distance of four or five miles in as many minutes. In the most rapid part of its course it raced down the slope at two miles a minute.

On Thursday the 8th of May, a few minutes after eight in the morning, persons living a mile or so east of Saint Pierre, as they looked toward the mountain, saw only a plume of vapor rising straight in the still air. Then, all at once, a jet spurted from the summit. The sound of the explosion that set it off did not reach the observers until later. They declared afterward that the jet shot through the air as if aimed directly at Saint Pierre. Indeed it may have gone above ground at the beginning of its course, for it leaped over ravines and other obstacles that on later occasions turned aside a cloud.

In about a minute and a half the cloud rolled to Saint Pierre and covered the city. Persons just outside the zone of destruction felt a blast of wind

*All temperatures mentioned are given in the Fahrenheit scale.

pressing away from the cloud. This was caused by expansion of the surrounding air as it became heated. A moment later a returning wind swept inward toward Saint Pierre. It was strong enough to knock down persons on the edge of the zone of destruction. This was air that moved along the ground to take the place of the hot, thin, low-pressure air rising over the city.

The outward wind saved the lives of a few persons aboard ships at anchor in the roadstead. The blast threw these fortunate ones into the sea before the cloud itself reached them. They were burned, but only about the head and on parts of the body above water. Most of the ships were overturned and sunk. With the cloud came darkness and a light fall of pumice, then rain muddied with ash.

The two rushes of wind, outgoing and returning, tumbled the walls of houses and brought the tile roofs down on the heads of the occupants. Flames from lamps and stoves set the wreckage ablaze. Fires were fanned by the returning wind, which made a blast furnace of the city.

Among the relics dug up later from the dust was a sheet of notepaper. A student had written on it, in a clear hand, remarks about the eruption of Vesuvius in the year 79. If only the teachers and students of the Junior College had heeded the warning in the ancient tragedy of Pompeii!

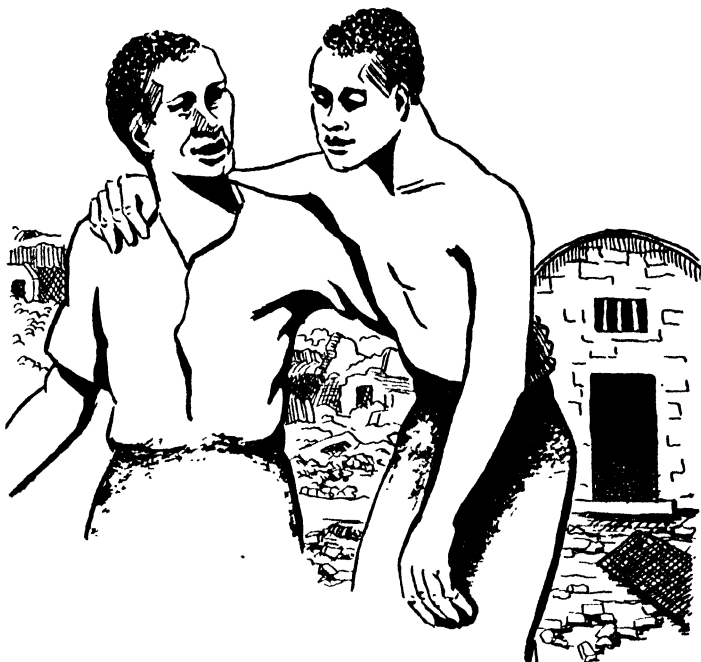
During the week following the city's destruction,

refugees from the surrounding areas were gathered and cared for. A shoemaker in Saint Pierre had somehow lived through the disaster. It seemed that no other soul in the city had survived. But on Sunday, four days afterward, a searching party of three men heard cries coming from the dungeon of the city prison. The prison itself was destroyed, but the dungeon, a stone building of low vaulted structure, had withstood the blasts. The searchers broke open the massive wooden door and liberated a prisoner, Louis Cyparis.

Plantation worker and occasionally seaman, Louis Cyparis had quarreled with a companion at a party and injured him. For this he was sentenced to a month in jail. He had nearly finished his time when he was allowed out of jail by day to do some work in the city. Hearing of a dance in a neighboring village he went there and danced all night. He returned to jail the next day to complete his term. In order to punish him for going away without permission the warden locked him up in the dungeon. It was to this punishment that Louis Cyparis owed his life.

In telling his story he said that before breakfast time on Thursday morning he suddenly heard people call for help and cry that they were burning. Then there was silence. "A vapor rushed in through the little window over my door," said Louis Cyparis.

"It burned so much that I jumped about everywhere, to the right and to the left and into the air, trying to get away from it."



For four days, from Thursday to Sunday, the prisoner waited, hungry and in pain, and wondered if he would ever again see the world outside his dungeon.

Louis Cyparis had burns on his back and on various parts of his body, but the fabric of his clothing was not harmed at all. Many of the victims' bodies were found to be severely burned though their clothing was uninjured. In sections of the city that fires did not reach, wooden doors and tree trunks were not even singed. The vapors of the cloud that reached Saint Pierre, though they suffocated people and scorched their flesh, apparently were not able to ignite fabric or wood.

Louis Cyparis said the hot vapor lasted only an instant, but for that moment he almost ceased to breathe. There was no smoke and no special odor. The survivors from the ships and persons on the edge of the zone of destruction all agreed on that. Some of the injured seamen who had experience with steam burns compared the vapors of the cloud to steam.

If the hot cloud was made of steam and other gases only, how did it get to Saint Pierre, five miles from the summit of Pelée? Water vapor would have expanded upward, in the manner of the plume of steam that often rose from the summit. Plain steam could not have rolled down the mountain, keeping together for some miles in a compact mass.

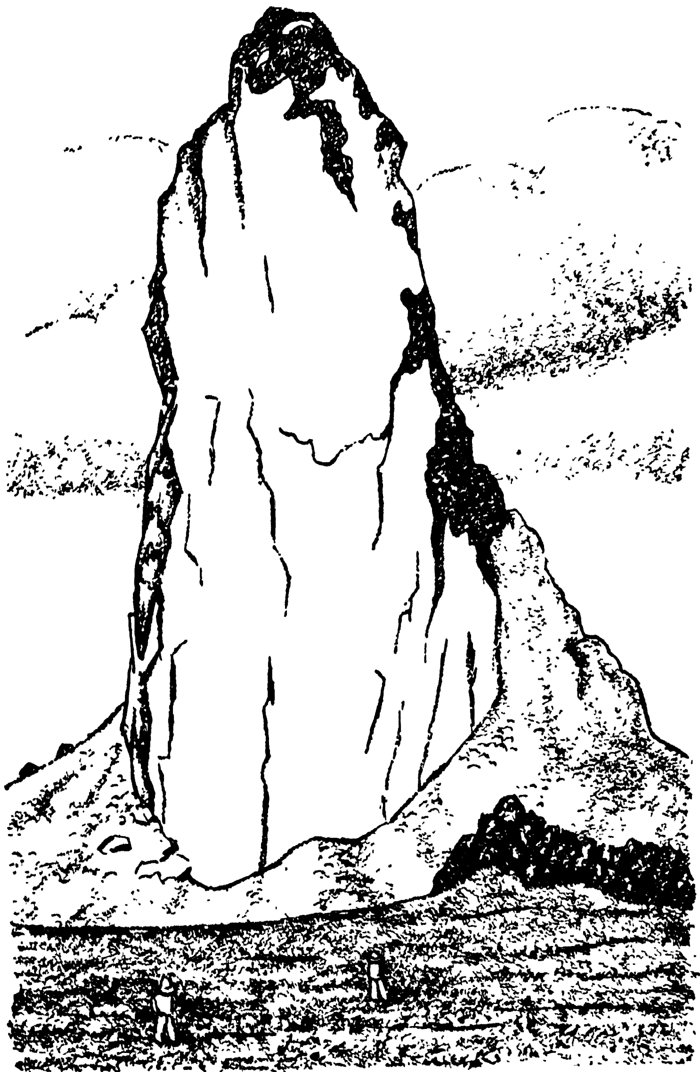
The jet acted, not as a gas but as a heavy liquid, and that is what it was—lava. This lava was highly charged with gases. The stuff frothed up quickly and violently like overcharged soda water. A portion of the gases blasted downward and, rebound-

ing from the ground, held up the mixture and shoved it boiling down the mountainside.

Why couldn't Pelée have shot its gases and solid fragments straight up from the crater, as from a mortar aimed vertically? In the first place, Pelée had no open crater. The volcano expelled most of its lava in solid form, and the chunks immediately blocked the passage from which they had come. The chunks and fragments formed a cone under which gases accumulated until their pressure was great enough to blow a new passage through the cover. Often a gas and lava mixture erupted from the side of the heap rather than the top. This evidently happened in the case of the jet that sent the hot cloud to Saint Pierre on May 8th.

The stiffness of the lava erupted by Pelée was shown by a remarkable structure that punched through the mountain top six months after the ruin of Saint Pierre. This structure, made of solid rock, rose in the form of a spire 1,000 feet tall, like a great tombstone for the city. The monument first appeared on November 4, 1902, and rose at a rate of about forty feet a day for three weeks. Then explosions tumbled the spire, and blocks from it rolled out of the V-shaped breach and hurtled down the mountain.

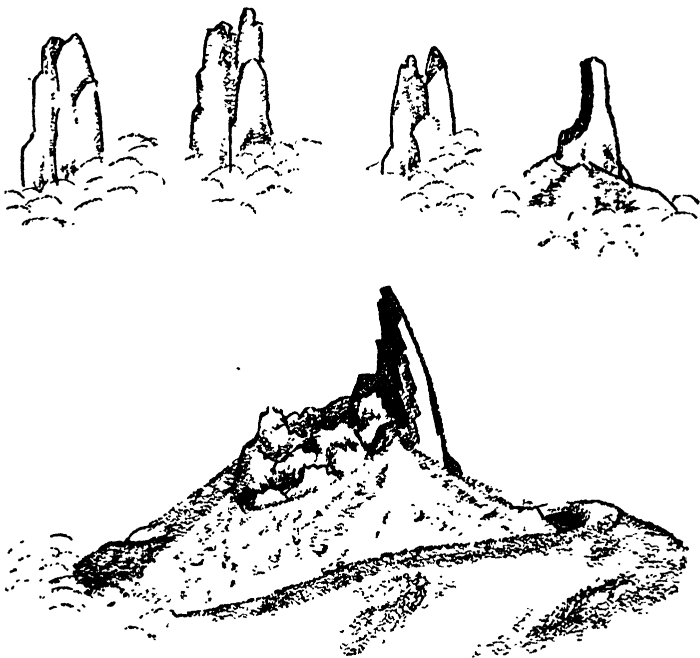
There followed a new upbuilding of the spire and a new collapse. The cycle of growth and ruin repeated itself several times. Had there been no crumbling and all the rock remained standing, the



The spire of Pelée Mountain

spire would have reached a crowning height of a mile and a quarter.

The spire was a sort of indicator of pressure beneath the volcano. After each big collapse, the stump of the spire rose faster for a while, because its weight was less and the volcano could push it up more easily. But as the spire grew tall again, its rate



Stages of the growth and collapse of the spire

of growth decreased, because the weight began to equal the volcano's pressure.

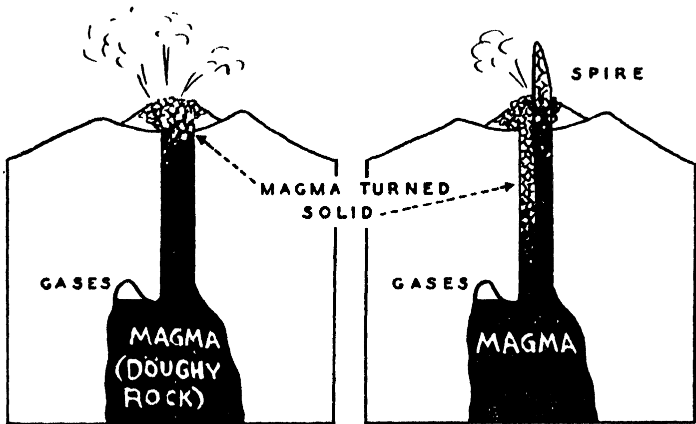
Lacroix and other geologists risked their lives to study the growth of the cone and spire. They climbed to the very edge of the caldera. Crouching there amid a swirl of fumes and pelted with mud

and pumice, they peered over the brink. They could see that only a trench remained between the caldera wall and the base of the cone, which rose steeply where the Dry Tarn had been. The cone was a tumbled mass of blocks and rubble. It had no crater. When the vapors cleared away sufficiently, the observers could see, towering above them on one side of the cone, the great rock spire.

Trails of light sometimes glowed around the base of the spire and then died out. The spire itself was streaked with light when explosions or shrinkage cracked off a skin of rock and revealed that the interior still was red hot.

How was this remarkable spire created? Let us picture the interior of the mountain. Beneath the visible base of the spire, the rock that formed it was hot enough to be like dough—it could be forced to flow. This doughy rock came from a mass of the same stuff lying deeper beneath the mountain. Pressure inside the material forced some of it through cracks and weak spots in the solid rock of the mountain. The stuff squeezed its way upward, re-opening a blocked passage through which earlier eruptions had poured. This passage became a sort of pipe leading up from the depths. Doughy lava oozed through it. The lava may be compared to toothpaste squeezed from a tube. The toothpaste is shaped by the neck of the tube. In a similar way the lava was shaped by the pipe of the volcano. As

the lava oozed out of the pipe, it turned solid and formed a spire.



We can see why Pelée was so explosive. Its lava came out solid or so nearly solid that it repeatedly clogged the upper section of the pipe. This clogging held in the accumulating gases until they built up pressure enough to blast through the cone at some weak point.

Why was Pelée's lava stiff rather than fluid like that of the Hawaiian volcanoes? In the first place, the temperature of the lava when erupted was only about 2,000 degrees—too low for the lava to be very fluid. A second factor was the chemical make-

up of the lava. It was a mixture that does not become very fluid at melting temperatures.

The relative stiffness or fluidity of a material is called its viscosity. We say molasses or honey is viscous, and we may be thinking merely that it flows more slowly than water. But this is not enough for the physicist. He measures the viscosity of a material very exactly by the resistance it offers to a force. The force may be the weight of the material itself—in other words, gravity. In any case, the force necessary to make a material flow a certain amount in a given time is the measure of its viscosity.

Among the factors affecting the viscosity of lava is the amount of dissolved gases. A high gas content tends to make a lava more fluid; a low gas content tends to make it more viscous. At Pelée there were gases enough, but they could not make the lava fluid because the chemical composition and temperature were too much in favor of high viscosity.

Difference in the viscosity of lavas largely explains why volcanoes differ in their behavior. They can be grouped in a series, with quiet shield volcanoes like Mauna Loa and Kilauea at one end and violently explosive volcanoes like Krakatau and Pelée at the other. Between the extremes are volcanoes that have fluid and explosive eruptions in turn. Vesuvius is one of these volcanoes of mixed

behavior. Sometimes Vesuvius pours out a fluid lava, and sometimes it plugs up and blows its top. The disaster that overwhelmed Pompeii and Herculaneum was probably similar to the smothering of Saint Pierre.

III · Floods of Rock

We have considered some of the effects of volcanic eruptions. Still we are bound to wonder what forces start a volcano operating in the first place. Where does the energy of volcanoes come from?

Fifty years ago scientists assumed that the earth's interior, 30 miles or so from the surface, was liquid. Wherever the molten material could force its way through some crack or weakness, it produced a volcano. The liquid condition of the interior was explained by the theory that this planet in its youth

was a hot liquid mass. Gradually the surface cooled enough to become solid, and a crust of rock was formed. The crust acted as an insulator. Heat escaped through it so slowly that the interior remained molten.

This idea of an all-liquid interior has been disproved by study of earthquakes — a matter we shall go into in a later chapter. It is true, however, that temperatures increase from the surface downward. In volcanic areas the increase may be so rapid that at a depth of only a few hundred feet the temperature is several hundred degrees. Elsewhere the increase is much slower. In South African gold mines the temperature rises less than two degrees every 300 feet. The deepest borings for oil go down about four miles. Past that depth we have no direct knowledge of temperatures. Yet we can safely say that the earth is increasingly warmer beneath the limit of borings. The only way heat can pass through a solid like the earth's crust is by conduction. And heat is conducted from the warmer part of a body to the cooler—for example, from the spoon in the teacup to the spoon handle. In the earth, the direction of heat flow is from the warmer depths, and therefore temperatures must be increasingly higher at deeper levels.

Readings taken from a large number of mines and bore holes show that the average increase of temperature downward is about one degree for

every 60 feet. If the increase continues at this rate, the temperature at a depth of 30 miles will be about 2,700 degrees, which is hot enough to melt rocks at the earth's surface.

Does this bit of mathematics mean that rock is liquid below 30 miles? Not at all. Rock, like most substances, expands when it turns liquid. In order to expand it needs some extra room. But is it possible for rock at a great depth to make extra room for itself? Not unless it can shove against the pressure caused by the whole mass of rock lying above it. At a depth of 30 miles the pressure would amount to about 202,500 pounds pushing against each square inch of rock from every direction—top, bottom, and sides. Such pressure, equal in all directions, is called confining pressure.

At the surface of the continents, the only confining pressure is that caused by the atmosphere's weight—15 pounds to the square inch. Against this small pressure rock at a temperature of 2,700 degrees has enough heat energy to expand and liquefy. But if pressure is increased the rock will need more heat energy in order to expand. At a depth of 30 miles, where the pressure is 202,500 pounds per square inch, rock can be hotter than its surface melting point and yet remain solid. The high confining pressure cramps the rock together and keeps it solid.

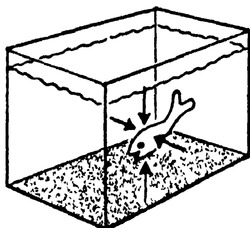
How, then, does some deep rock manage to

liquefy and reach the earth's surface as lava? How can a volcano come into existence and keep operating?

Let us get at these questions by asking another one: what happens to rock when forces acting upon it are not equal from all sides? Suppose we take a piece of common rock—granite, limestone, anything. Using ordinary hand tools we can exert quite a bit of force on the rock. Suppose we press the chunk in a machinist's vise. Force is thereby exerted upon the chunk from two opposite sides. The force is transmitted right through the rock from one side to the other and back again. Such a force working inside a material is called a stress. There are stresses acting through the rock in other directions also, but they are not equal to the main stress. This shoves the rock material and deforms it slightly. The deformation is a small temporary change of shape, from which the rock will recover if the stress is removed. We call such a change of shape a strain. The rock will take just so much stress and strain. Then it reaches the limit of its strength, and it breaks.

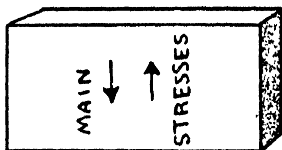
We have been talking about the behavior of rock at the earth's surface, where confining pressure—that of the atmosphere—is only 15 pounds to the square inch. But the physicist tries to understand how rock behaves at considerable depths, where the confining pressures are high. He therefore uses a press that will create confining pressures up to

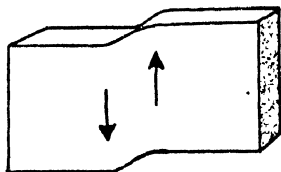
STRESS, STRAIN, AND STRENGTH



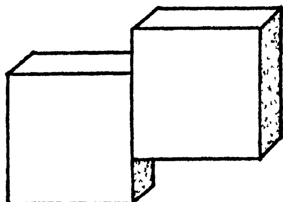
A STRESS IS A MECHANICAL FORCE ACTING WITHIN A BODY. IN A LIQUID, STRESSES SHOVE WITH EQUAL FORCE FROM ALL DIRECTIONS. THIS EQUALITY OF STRESSES IS CALLED CONFINING PRESSURE.

IN A SOLID, STRESSES ACTING IN CERTAIN DIRECTIONS MAY BE MUCH GREATER THAN STRESSES ACTING IN OTHER DIRECTIONS.





UNEQUAL STRESSES DEFORM A SOLID. ITS CHANGE OF SHAPE IS CALLED STRAIN.

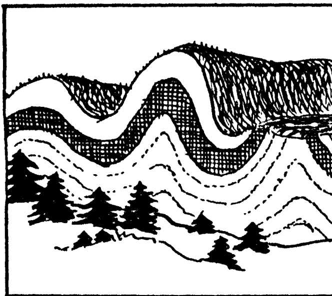


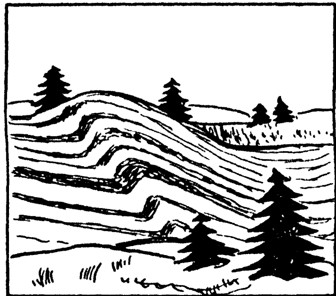
BEYOND A CERTAIN POINT, A SOLID BODY CAN STRAIN NO FURTHER. THIS POINT IS CALLED ITS STRENGTH. THE STRENGTH OF A SOLID IS MEASURED BY THE AMOUNT OF STRESS REQUIRED TO BREAK IT OR TO MAKE IT FLOW.

millions of pounds per square inch. He immerses a piece of rock in liquid in the steel cylinder of the press. The purpose of using liquid is to have it transmit pressure upon the rock equally from all directions.

The physicist finds that high confining pressure does not fracture the rock, but holds it together. The rock will change shape permanently if, while under pressure, it is bent or otherwise subjected to a force that creates stress differences within it. Somehow, the crystal bits of which the rock is made divide along planes and slip past each other without coming apart.

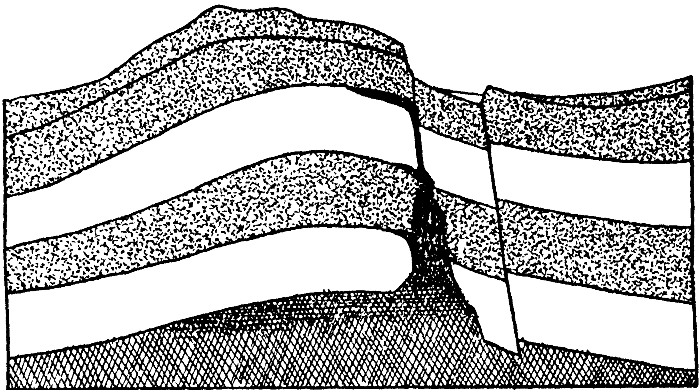
This sort of rearrangement, continuing for a long time, amounts to a slow "flowing" in the solid state. In many places we find rocks that have gone through such changes. Thick layers are found bent but unbroken. The materials in them have been spread out in ribbons, bands, or sheets. These ar-





rangements, which developed while the rock was in solid form, result from internal "sheet-flowing."

At a depth of 30 miles, where rock is hot but solid, some material nevertheless moves toward the surface and produces volcanoes. How? It cannot rise against gravity unless there is a force greater than gravity pushing it up. Under confining pressure the upward push at a given level is the same as the downward push. It can become greater if the downward push is somehow relieved by a weakness in the overlying crust—a warping or buckling, for example. In a place where such a weakness exists, the downward push diminishes and makes the upward push relatively greater. It becomes a stress acting to force the rock upward.



Magma rising along paths of weakness in the earth's crust

Under stress the rock yields plastically. It begins to flow upward, very slowly.

After a period of time measured perhaps in millions of years, tongues of plastic rock force their way through weaknesses in the crust. Somewhere along its upward course the ooze of hot rock reaches a point where pressure is not great enough to prevent it from expanding. So it begins to expand—that is, to turn liquid. Some of the minerals that melt first speed up the process by dissolving others. Some of the wall rock surrounding the flow also dissolves and melts. Continuous expansion helps the liquefying rock to force its way upward.

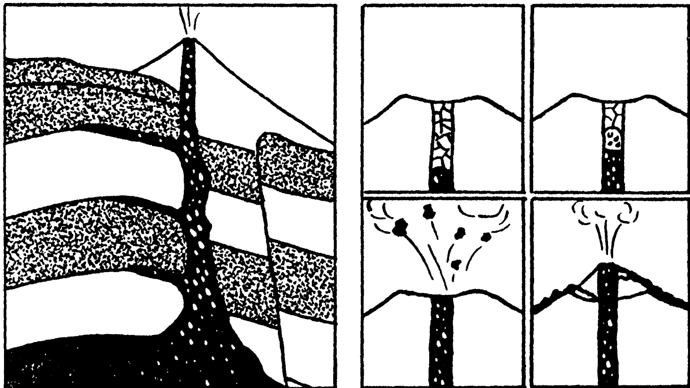
Thus a tongue of liquefying rock develops not far beneath the surface—probably at a depth of a dozen miles. It is in a state called a magma, after a Greek word meaning dough. Magma differs from lava in a very important respect. Lava is liquid rock at the surface, after the gases have mostly bubbled off and left the liquid quiet and inactive. Magma, on the other hand, is liquid rock under pressure sufficient to keep the gases in. If the magma opens passages to the surface, the gases may boil off gradually. The magma becomes lava, which wells up and spreads placidly over the surface, as at Hawaii.

The story is different when a magma tongue is blocked by overlying structures. The magma may partially relieve its pressure by pushing and melting

its way horizontally between rock layers. But the path of least resistance generally is upward, so the magma tongue continues to rise.

As the magma reaches levels of lower pressure, some of the dissolved gases are able to boil out. They force their way to the surface through small vents. These may be in an old volcano or in entirely new ground.

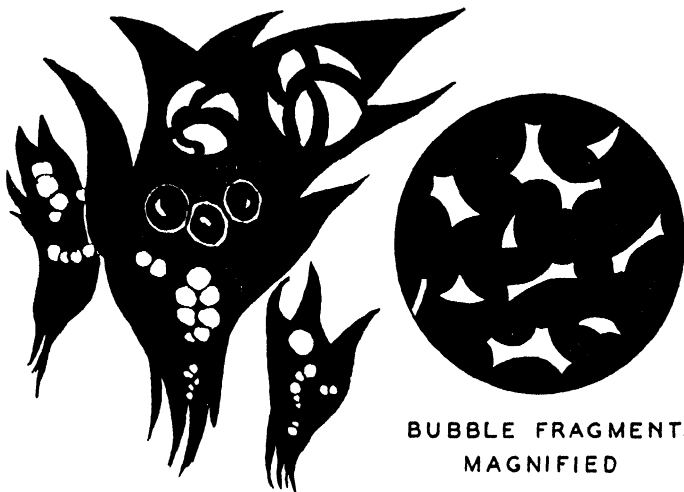
The escape of gases from upper portions of the magma further relieves pressure on the mass beneath. More of it is able to expand, liquefy, and flow upward, bringing larger supplies of gases. At



STAGES IN A VOLCANO'S LIFE. After the first period of eruption, the cone collapses and the neck is chocked with a lava plug. Later, renewed activity of the magma melts and blasts away the plug

Pelée mountain, the lava and gases melted and exploded their way through an old volcanic pipe. It had been plugged with lava from a previous eruption and with debris from the collapsed cone. When the plug was sufficiently melted away and weakened, the gases beneath it blasted through to the surface.

An explosion quickly releases pressure on the gas-charged magma. The effect is like the uncapping of an overcharged bottle of soda water. A portion of the magma flashes into foam. The froth is blasted up amidst a vapor cloud. The bubbles have a lava film around them. This turns solid



BUBBLE FRAGMENTS, MAGNIFIED

quickly while the gases in the bubbles are still expanding. The film bursts, and its fragments become the stuff known as ash.

A volcano is a steam engine needing water and heat to drive it. We cannot understand volcanic action unless we know the source of both the water and the heat.

How does water vapor get into a magma? Our first thought is that the water may be ordinary surface water or ground water that seeps down and meets the rising magma. In the case of an island volcano or an undersea volcano, a great supply of water lies above the magma. But beneath the water is rock. Some kinds of surface rock are put together loosely enough so that water can seep through pores and saturate it. But there are only thin films of such porous rock at the earth's surface. A magma cannot come into contact with much of it.

Suppose a magma does touch some waterlogged rock. We can imagine what would happen. The water-bearing rock would heat up and its water would turn to steam. This would create gas pressure in the rock. But would the pressure be enough to force steam from the rock into the magma? The magma itself has a gas pressure so high that it forces vapors of its own into the rock.

Whatever the contribution of steam from surface rocks, it becomes a factor only toward the end of the magma's path. Steam from the upper rocks

may heat a spring and make a geyser, but we doubt that it supplies a very large percentage of the gas pressure needed to keep a volcano erupting.

Most volcanic water vapor probably is carried within the magma itself. We know that magma under pressure can hold a good deal of water vapor in solution. Even lava cooling at the surface still contains water vapor and other gases. They bubble out and form cavities in the lava like the holes in Swiss cheese.

Lava with cavities made by gas bubbles

As lava solidifies, its chemical compounds combine to make minerals. Each mineral gathers into its own special crystal shape. Before the crystals form, some water exists in the lava in disguise. In-

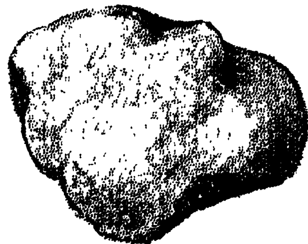
deed we can scarcely call it water, for it is just atoms of the two elements that make up water—hydrogen and oxygen. The atoms are attached to a number of chemical compounds. As the lava crystallizes, all the atoms or groups of atoms in these compounds are juggled around and re-combined to form minerals. In the process, some of the hydrogen and oxygen atoms are left over. The orphan atoms join and form water vapor. Since there is less and less liquid left in the crystallizing lava, the added water vapor cannot remain in solution, so it bubbles off with other escaping vapors.

Under special circumstances melted rock can solidify in another way. It can become glass. This happens when a melt cools so fast that the chemicals

A ROCK MELT TURNS TO GLASS BY QUICK-FREEZING.

OBSIDIAN

PUMICE



PUMICE SOLIDIFIES UNDER LOW PRESSURE; OBSIDIAN, UNDER HIGH.

do not have a chance to combine into minerals. Pumice, for example, cools very quickly, forming a natural glass with no crystals or very few. Ordinary manufactured glass is made from chemicals that will crystallize if they cool slowly enough.

When a rock melt forms glass, all atoms of oxygen and hydrogen stay attached to the compounds of which the melt is composed. Since these compounds remain about the same in the glass as they were in the melt, physicists consider glass a sort of liquid in disguise—a state between a true liquid and a crystalline solid.

Now we come to the big question, the source of volcanic energy. How is the heat of magmas produced? Formerly it was assumed that the earth's internal heat remained from an earlier stage when our planet was a globe of hot material escaped from the sun. But then Marie Curie and her associates discovered a continuing source of heat in the earth—radioactivity. Atoms of uranium and a few other elements break up and form atoms of different elements, and in the process liberate heat energy.

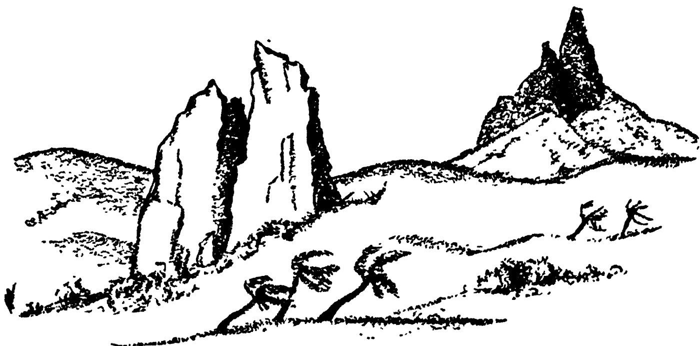
Radioactive elements are found in lavas, and therefore exist in the magmas from which lavas come. These elements as they decay contribute heat to the magmas. Since new heat is thus being generated in the earth at all times, we can no longer say the interior is cooling off. Perhaps it is becoming

hotter. Many scientists are inclined to think it is.

A final question on volcanoes: what makes a volcano stop erupting? Why should it plug up and lie quiet for a period, or even become extinct?

During a period of eruption a volcano builds up its cone or shield. As this becomes mountain-high the volcanic pipe is lengthened. Magma then has to rise that much higher—perhaps an additional mile or more—to reach the surface. The column of magma weighs down on the mass beneath. Under increasing pressure the deep magma stiffens and begins to solidify. The eruption stops and the lava in the top of the pipe cools and hardens into a plug.

The plugging of a volcanic pipe may mean just a bottling of pressure for future explosions. But in time volcanoes do become extinct. Their relics are found in all regions of the world. Volcanic plugs in



Volcanic plugs on the island of Nuka Hiva

many places remain standing alone where the looser material of the cones has crumbled away.

It is believed that all volcanoes, after a similar life history, come to an end. How, exactly, does this happen? A certain amount of heat leaves the magma with each eruption. If the magma loses more heat in eruptions than it gains from radioactivity, the loss will cause the volcano to quiet down. In addition to heat, a volcano needs the driving force of gases. When the gas supply as well as the heat diminishes, the magma becomes viscous and sluggish; it lacks the explosive force necessary to blast through obstacles. Depletion of both heat and gases from the magma brings the volcano to its final rest.

Earthquakes

IV · *Our Planet Quivers*

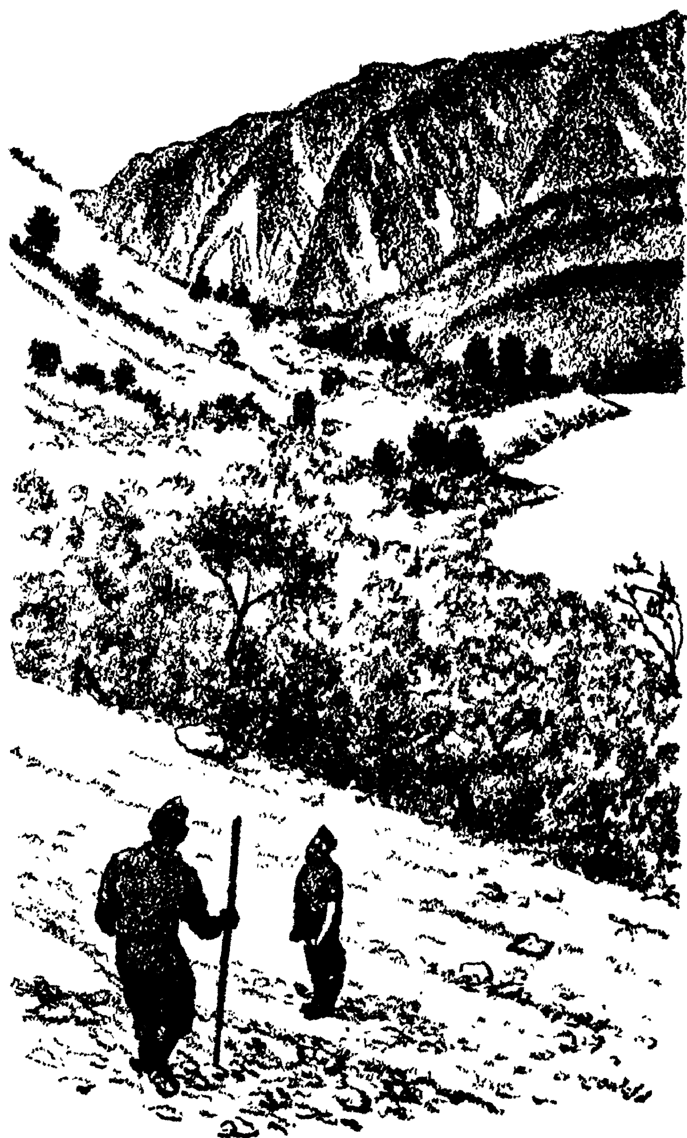
EARTHQUAKES happen every day and every hour. There are a million or more a year, if we count small tremors as well as great. About a dozen of the million, in an average year, are strong quakes, and two are mighty catastrophes.

What is an earthquake? A person who has been through a quake tries to tell what it was like. Even a slight quake is something uncanny. We expect the earth to remain still and firm at all times. When it shudders beneath our feet we are dismayed. There seems to be no security anywhere.

The main threat of earthquakes is their ability to shake down structures, whether natural or man-made. In a mountainous region, overhanging cliffs may collapse and material on a slope may break loose and cause an avalanche.

On August 15, 1950, an earthquake jolted the Himalayas in the region where the borders of Assam, Tibet, and Burma meet. The main tremors came early in the evening. In the villages, people were thrown to the ground by sudden strong shocks. There was a roaring caused by rockslides, and it seemed the mountains were falling into the gorges. Some villages were swept away. In the high mountains, slopes were stripped of soil and vegetation, and there remained only faces of bare granite. In the valleys, dams broke and floods washed away the fields. In other places landslides made new dams behind which water rose and flooded the valleys. For several days and nights there were renewed shocks. Through all the disturbance the people guarded their flocks and tended their fields. Setting about the work of repair, they mended houses, they rebuilt dams, they opened passages in the landfalls that blocked the streams.

During the great earthquake that shook Kansu and other parts of northwest China on December 16, 1920, there was great loss of life and destruction even though the region was not thickly settled.



Disaster here resulted from the nature of the soil. This is a fine, close-packed deposit called loess, which slides easily when wet. The people lived in cave-like dwellings on the slopes and banks of loess. The earthquake set whole hillsides moving, and families were buried alive in their homes.

Poorly built stone and masonry structures are in especial danger. On November 1, 1755, an earthquake shook the city of Lisbon at the worst possible time. It came on All Saints' Day at the hour when people were crowded into the churches for services. Suddenly the ground heaved, walls and columns swayed, and the great structures collapsed. After a few minutes of terrible shaking most of the city lay in ruins and 60,000 of its inhabitants were crushed beneath the wreckage.

The way in which the crust of the earth moves during a quake was very little understood until recently. But during the last 75 years scientists have used various methods to get at the facts, and have gained considerable knowledge. Much was learned from studying the effects of the San Francisco earthquake of April 18, 1906. This quake left dramatic evidence of some of the things that had happened to the crust.

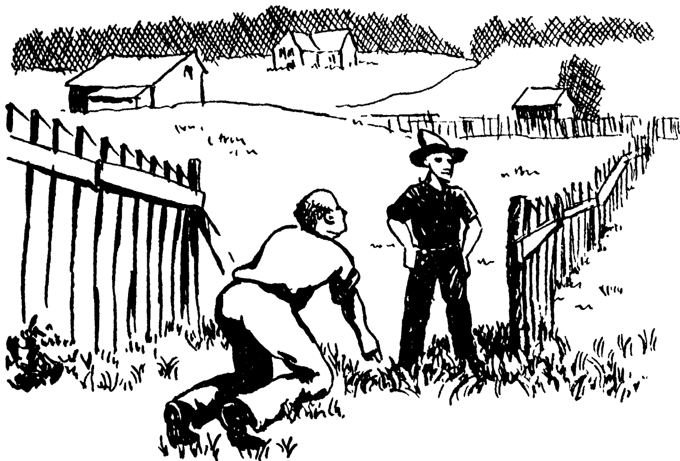
There is a long crack in the surface rock of California—really a system of cracks—known as the San Andreas Rift. It crosses the state from the

southeast to the northwest and passes under the Pacific Ocean above San Francisco. The Rift has existed for a very long time, as can be seen from breaks in the mountains and valleys along its course. Every now and then forces working in the crust cause the rock masses along the Rift to slip past each other.

During the 1906 earthquake the surface on the west side of the Rift slipped toward the north, and that on the east side slipped toward the south. The extent of the crustal slipping was shown by the way in which fences and roads were broken where they

crossed the Rift. Very commonly they were carried out of line by 12 or 15 feet. The greatest amount of displacement was 21 feet.

More often the main direction of rock slipping is not horizontal but vertical, or vertical and horizontal combined. Whatever the direction of slipping, the crack along which the rock moves is known as a "fault." During an earthquake that shook the Rann of Cutch, India, on June 16, 1819, a cliff 30 feet high was created by vertical movement along a fault plane. On one side of the fault the surface sank 10 feet, while on the other side it rose 20 feet. During the Alaskan earthquakes of September, 1899, a vertical uplift raised the shore along Yakutat Bay as much as 47½ feet.



How much of the earth's crust moves during an earthquake? From surveys made before and after the San Francisco earthquake it was determined that slipping took place along 275 miles of the San Andreas Rift, and the areas of displaced surface extended four or five miles from the Rift on each side. In Japanese earthquakes a number of great blocks are involved, each separated from other blocks by fault planes along its sides. A block moves as a unit. After the terrible earthquake of September 1, 1923, it was found that blocks of 10 miles on a side rose or fell as much as seven feet. Often the vertical movement was unequal, so that it tilted a block in one direction instead of raising or lowering it evenly.

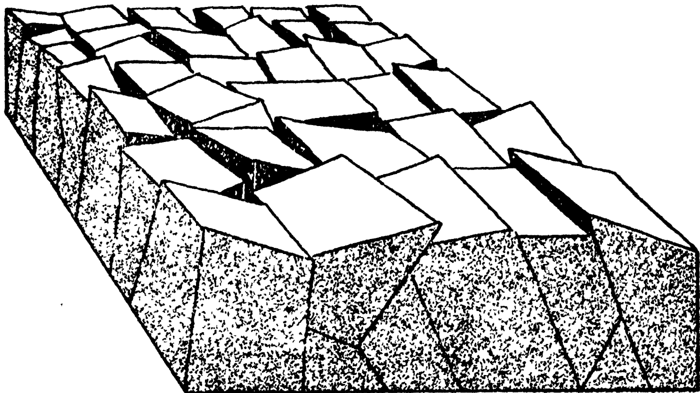


DIAGRAM OF BLOCK FAULTING IN JAPAN

Since three-quarters of the earth's surface is covered by the oceans, it is not surprising that more earthquakes occur under the ocean than on the continents. Undersea earthquakes doubtless are caused by the same sort of crustal movements as on land. Sometimes an undersea earthquake produces a great "tidal wave." This kind of disturbance really has no connection with the tides, so scientists have adopted a more suitable term for it, the Japanese word *tsunami.*

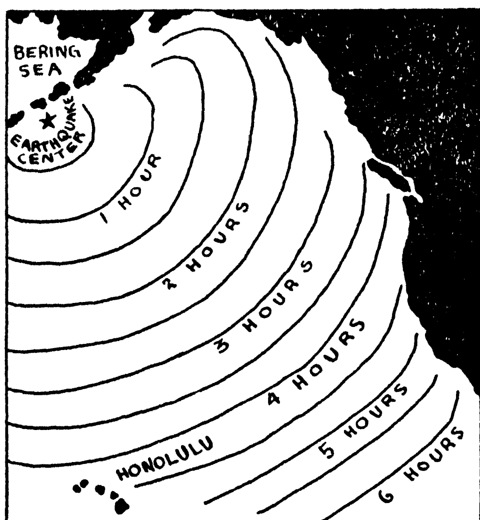
A tsunami announces itself by a withdrawal of water from the shore. Then the sea returns in the form of a massive wave, which may be uplifted to a height of 50 or even 100 feet. After the Lisbon earthquake of 1755 the water withdrew from the harbor and a few minutes later a tsunami rolled in, shattering the wharves and sweeping away people who had fled to them for safety.

A recent tsunami was traced for thousands of miles of its course. It was launched on April 1, 1946, by a disturbance under the Pacific off the Aleutian Islands. Most earthquakes that produce tsunamis originate in deep trenches in the ocean floor. This one occurred in the Aleutian Trench, a long furrow which has been sinking and becoming deeper during the last several million years. The disturbance of April 1, 1946, apparently was caused by an episode in this long-term sinking. A block of the crust dropped, and an enormous mass of water

slumped down with it. The sunken water rebounded, giving a shove to the water above it. The shove, or wave, passed upward from level to level. The mass quivered many times, and each time sent off a wave. When a wave reached the surface it pushed out on all sides. It was not high. Tsunamis are not even noticed from vessels on the open sea, for their crests are only a foot or two high. But the waves are long. The distance from one crest to the next may be from 100 to 400 miles. Thus the volume of water quivering in a tsunami wave is enormous. When a portion of such a mass of water piles up against a shore, it produces a mountainous wave.

The waves of the Aleutian tsunami were about 100 miles long from crest to crest, yet they moved with such great speed that the crests passed a given point within 12 minutes of each other. The tsunami arrived at Honolulu 4 hours and 34 minutes after its launching. Since the distance it covered in that time was 2,240 miles, it traveled at an average speed of 497 miles an hour. The rising of the first wave off Hawaii drew water away from the shore. People noticed they could no longer hear the sound of the surf. They looked and saw that the water had withdrawn far from the beach. It was a warning to those who knew the ways of the tsunami. They fled, and a few minutes later a towering wave roared in and swept over the shore. The water withdrew again to form the bulge of another wave

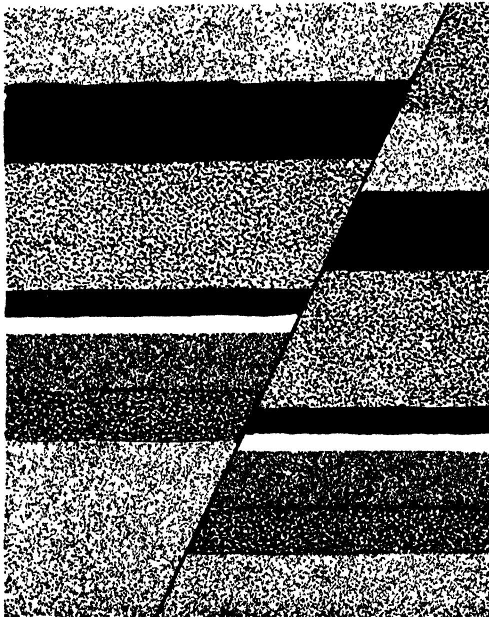
whose crest was approaching, and so it went and came several times in rushing rhythm. The tsunami was measured on tide gauges at many points along the American and Asian shores of the Pacific. It traveled the 8,066 miles from its source to Valparaiso, Chile, at an average speed of 445 miles an hour.



ADVANCE OF THE TSUNAMI
OF APRIL 1 1946

Earthquakes of the past have left clear traces. For example, we may notice a cliff face with neatly

bedded horizontal layers of rock, and across all the layers runs a vertical crack. The layers, we find, do not continue straight across the crack. They are out of line by a good many feet. This "offset" is proof positive that the formation was broken and the separated masses of rock moved in different directions along the fracture plane. The movement must

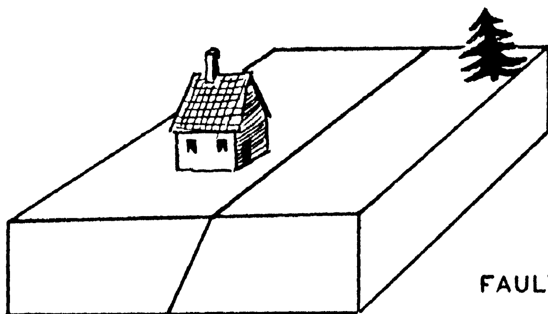


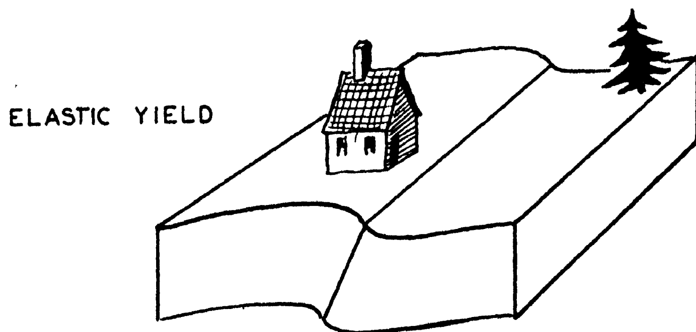
A FAULT PLANE. The rock on the two sides has slipped in opposite directions

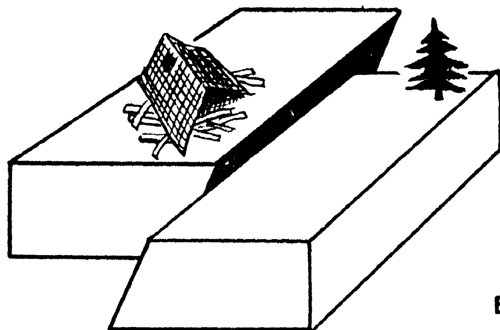
have caused a severe earthquake at the time it took place. Perhaps there were several movements at different times, and several earthquakes.

When we consider that thousands of cubic miles of rock may move during an earthquake, we wonder what sort of energy can perform such mammoth work. The movement is so sudden and violent that it seems some vast explosion must accomplish it. But we do not know of any explosive force capable of producing a major earthquake. Volcanic explosions cause tremors that may be strong near the volcano but fade away before they travel far. When an atom bomb was detonated in New Mexico, vibrations from the explosion could barely be detected by instruments a few hundred miles away at Pasadena.

Earthquakes are sudden and violent because rock has a way of storing up energy and releasing it all at once. Assume that some force working over a long period sets up stresses in the crust. Neighboring masses of rock are shoved in opposite directions, whether vertically, horizontally, or at some intermediate angle. As the masses move, their bordering portions pull out of shape. This distortion, or strain, may be relieved somewhat by plastic yield—that is, by flowing. But if the flowing is not sufficient to relieve all of the strain, the rock stretches. The stretching is an elastic yield. Through it the rock accumulates energy somewhat in the manner


FAULT PLANE


ELASTIC YIELD

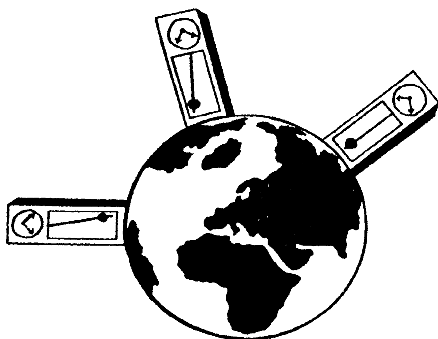

AFTER THE
EARTHQUAKE

of a bent spring. If the rock breaks, it will use its stored energy to jump back to its old shape.

The earth's crust is very strong. It may strain out of shape, but it does not fracture until the stress becomes tremendous. When the breaking point is reached at last, some relatively small force, like a change of tides, may become the straw that breaks the camel's back. The great Japanese earthquake of 1923 happened during a storm when the pressure of the atmosphere over Japan was unusually low. This drop in barometric pressure, Japanese scientists believe, may have been the "trigger" force that set off the earthquake.

An earthquake shock itself is a quick release of energy that was previously stored in the crust. The rock has been wrenched and pulled. It has stretched, but it can yield no further. The stresses tugging at the rock have become equal to its strength. The rock breaks. It quivers like a broken steel spring. The trembling is very fast, and therefore violent. It may act as a trigger force setting off other breaks in a wide region. Shock follows upon shock. The region may be shaken repeatedly for hours or for days. Finally, when many strains have been relieved, and the rock masses of the crust have readjusted themselves, a measure of quiet returns to the restless earth.

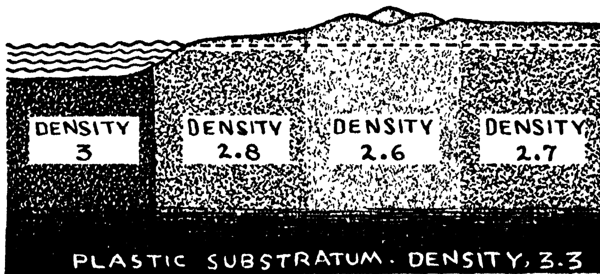
V · *Blocks That Rise or Sink*



STORED ELASTIC ENERGY causes rocks to rebound. Stresses store the energy, but what force creates the stresses in the first place?

Let us start at this problem by considering an idea very important in the theory of the earth's structure. According to this idea, certain blocks of the crust become lighter and others heavier, as a result of some activity like the transfer of material by flowing water and ice. Deep down, the blocks "float" in plastic material. A lighter block can rise

higher in this substratum, and a heavier block can sink lower. Thus areas of the crust tend to approach equilibrium with each other. Their condition of balance, or the tendency to approach it, is called isostasy—"equal standing."



ACCORDING TO THE THEORY OF ISOSTASY, THE EARTH'S CRUST FLOATS ON A PLASTIC SUBSTRATUM. COLUMNS OF EQUAL AREA HAVE EQUAL MASS. TALLER COLUMNS ARE MADE OF LIGHTER MATERIAL; SHORTER COLUMNS, OF HEAVIER MATERIAL.

Where two neighboring blocks of the crust are slowly moving, one up and the other down, they pull at each other along their common face. At a certain depth, where pressure is great enough, the material of the blocks is more or less plastic. Therefore the rock along the common face of the blocks can draw out like taffy. At this level, in other words, the pull between the blocks is relieved by plastic

yield. But at upper levels, where pressures are lower, the rock is much less plastic. It is not able to flow sufficiently to relieve the strain. As flow (plastic yield) becomes less and less, the rock gives way by stretching (elastic yield) and thus stores energy for earthquakes.

It need not surprise us that a material can be plastic and elastic at the same time. Ordinary pitch (hardened tar) behaves partly as a viscous liquid and partly as an elastic solid. If we place a coin on the surface of pitch and leave it for a long while, the coin will eventually sink into the pitch. If a chunk of pitch stands by itself, not in a container, the force of its own weight in time will cause it to flow and spread out flat. In other words, the pitch behaves as a liquid. Yet if we take a piece of pitch and bend it forcefully, it will break, and the broken halves will quiver. In other words, the pitch behaves as an elastic solid.

Since rock in the earth becomes more and more plastic under increasing pressure, we may imagine that at a depth of a hundred miles or so it will flow readily and therefore will not stretch enough to store energy for earthquakes. This is not always the case, however. Scientific instruments record some earthquakes that originate at levels down to 435 miles. This is evidence that, in spite of plastic flowing at such a depth, rock can stretch, break, and rebound.

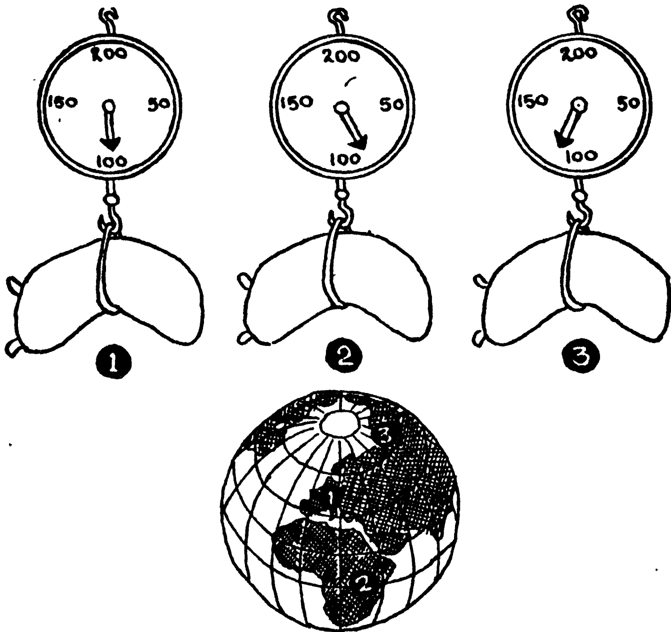
It may seem a fanciful idea that great stresses can originate from weight differences in the earth's crust. Yet this explanation is supported by a great number of facts. Let us consider some of them.

When we speak of portions of the crust being lighter or heavier than others, what do we mean? What is weight? When we weigh a sack of beans on a spring scale it pulls downward. This pull is an example of the force that attracts all bodies toward the earth's center. In weighing an object we really measure the force of attraction between the object and the earth.

The attractive force, gravitation, operates between all bodies. The tides remind us of this, for the force that lifts the ocean surface is a pull between the moon and the earth. If two metal balls are suspended near each other they draw together. Their attraction can be seen, and its force can be measured.

In the great movements of materials on the earth, gravitation is the principal force at work. It sets rivers and glaciers in motion, causing both to flow down-slope. We can thank gravitation for the fact that our planet does not get out of shape. The ocean keeps a level surface because all parts of it flatten out to be as near the center of the earth as possible.

Reliable a force as it is, gravity nevertheless varies in strength at different places on the earth's



HOW GRAVITY AFFECTS WEIGHT. A sack of beans weighing 100 pounds in Paris will weigh less than 100 pounds at the equator and more than 100 pounds in far northern and far southern latitudes

surface. Let us consider how differences in gravity affect the working of that commonplace instrument, the spring scale. Suppose we take a mass that has a given weight at sea level—say a 100-pound sack of beans—and weigh it at various locations around the earth. If the weight of the sack of beans is 100

pounds in France it will be somewhat less than 100 pounds at the equator. There are two reasons for this. One is the spinning of the earth on its axis. This motion generates the kind of force that causes mud to fly from a rotating wheel. It is called centrifugal force. The earth's rotation, speediest at the equator, produces too little centrifugal force to make the sack of beans fly off, but the force is great enough to make the beans weigh a little less at the equator than in higher latitudes.

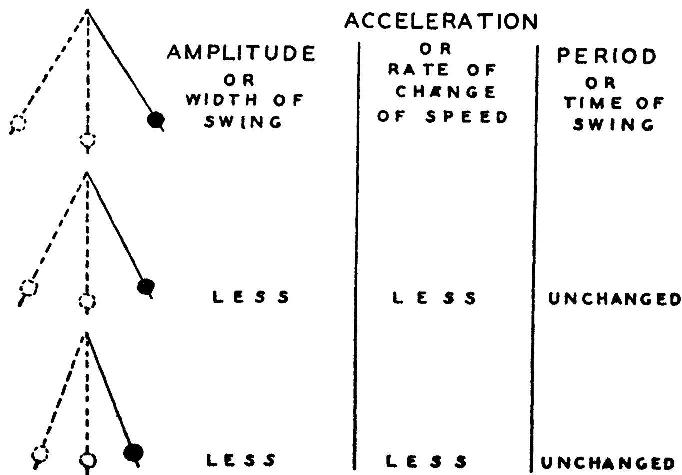
The second factor is the bulge of the earth at the equator—itself produced by the centrifugal force of rotation. Because of the bulge, the surface at the equator is farther from the center of the earth than is the surface at other latitudes. With increasing distance from the center of the earth the force of gravitation becomes less. At the equator, therefore, the earth's pull on the sack of beans—the weight of the beans—decreases further.

Around the poles, the situation is reversed. Centrifugal force decreases as we go away from the equator. The lessening of centrifugal force around the poles permits the earth's surface to draw a little closer toward the center of the earth. Therefore the pull of gravity is greater. And since centrifugal force is less and gravity greater, the sack of beans weighs more than 100 pounds.

The spring scale is too crude a tool to give us exact measurements of gravity. For this purpose the

scientist uses a much better instrument, the pendulum. The pendulum is simply a weight suspended on a line so that it can swing freely. The time it takes to make a full swing is constant, while the width of the swing becomes less and the speed becomes slower. Two forces work to keep the pendulum swinging so regularly. One force is its tendency to keep moving—its inertia. The other is gravity, which always pulls the pendulum back toward the earth. The pendulum does come to a stop at last, because of friction, but only after a great number of swings, each taking the same period of time.

The pendulum of the geodesist—"earth sur-



veyor"—has refinements to make it more accurate, but in principle it is like the pendulum that regulates a grandfather clock. Suppose we take a pendulum clock to the places where we tried out the spring scale. Say the clock is regulated to keep perfect time in Paris. At the equator, where gravity pulls on the pendulum with a little less force, the swing is not completed so soon, and the clock "loses time." But at points between the equator and the poles, where gravity pulls harder at the pendulum, the swing has a shorter period and the clock "gains time."

The gravity pendulum, like the clock pendulum, swings with different periods in different latitudes. The geodesist must keep this in mind when he sets about "weighing" blocks of the crust. Let us say the geodesist takes his pendulum to a height in the Andes Mountains, starts it swinging, and notes the period of the swing. The mass of the mountain, we know, must add some pull to the force of gravity. If this were the only change it would make the period of the pendulum shorter. Our pendulum clock would gain time and our sack of beans would weigh more. But the actual effects, we find, are opposite. The clock slows down, the beans weigh less, the pendulum period is longer.

Why is this? Is it because the pendulum, the clock, and the sack of beans are farther from the center of the earth than they would be at sea level,

ıd the pull of gravity on them therefore is less? ıis is a factor, of course. It is clear that the geo- ›sist must do a bit of mathematical work before › can arrive at any safe conclusion about the eight of the crust under the mountain. So he akes two corrections: one for the mass of the ountain, and the other for the height above sea vel, which is added distance from the center of e earth. After these corrections the geodesist has a ıe value of gravity under the mountain. It is less, › finds, than values of gravity in neighboring eas, and less than expected in that latitude. This ıding indicates that the rock beneath the moun- in is lighter than the rock beneath neighboring eas.

It is known that the Andes Mountains are rising. ıe reason for the uplift, we may reasonably think, that they are lighter, and pressure from the astic substratum raises them above the surround- g areas.

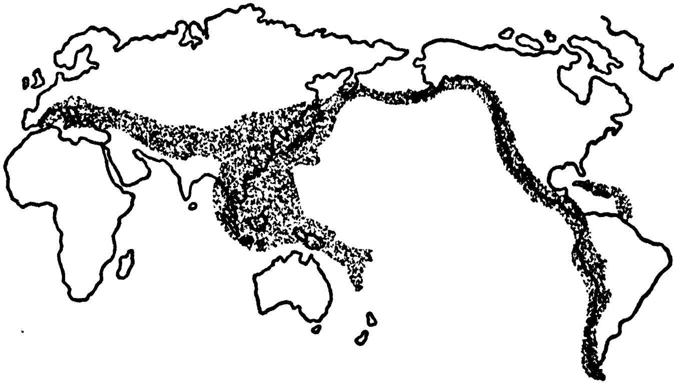
In some regions, the force of gravity is greater an it should be theoretically in those latitudes. ıis is true especially of ocean areas. Measuring avity under the oceans at one time seemed im- ›ssible. A method was found, however, by the utch geodesist Vening-Meinesz. He worked in a bmarine at levels deep enough to be out of the ay of surface wave movements. Once he had ob- ined a measurement he corrected it for special

conditions. One of these was the depth of the submarine beneath the surface, meaning the closer approach of the pendulum toward the center of the earth. This factor would tend to increase the pull of gravity. The other condition was the fact that the water between the pendulum and the ocean floor was lighter—less dense—than an equal thickness of solid crust on land. This factor would tend to decrease the pull of gravity.

Once these and some other corrections are made the geodesist finds that, in the majority of ocean areas he investigates, the pull of gravity is greater than it should be theoretically. This must mean that the rock beneath the ocean floor is generally heavier than the rock of the continents. And if the crust under the oceans is heavier, this fact can help explain why the ocean-covered regions have sunk and formed basins.

If we examine a world map showing the distribution of earthquakes we can see there is a close connection between quakes and vertical movements in the crust. A certain number of quakes occur in all parts of the world, but the majority are concentrated in a few long belts. The greatest belt encircles the Pacific Ocean. It parallels the American and Asian shores, and runs through the regions of Japan and Indonesia. Eighty percent or more of all recorded earthquake activity has originated within this great zone. Another belt extends east

and west, through the Mediterranean Sea and the Himalaya Mountains.

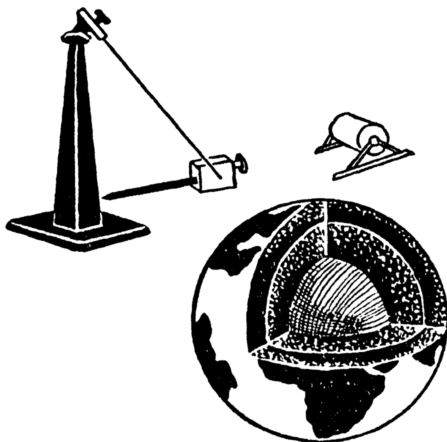


The earthquake and volcano belts of the earth

Each of these great belts lies along ranges of rising mountains, among them the Himalayas, the Alps, the Andes, the California Coast Ranges, and the Aleutians. Around the Pacific zone, the mountain chains are paralleled in a number of places by deep trenches where the ocean floor has been sinking in recent geologic time. Among these trenches are the Atacama Deep off the coast of Chile, the Japan Trench, the Aleutian Trench, and the Java Trough.

The rise of the mountains and the sinking of the deeps around the Pacific generate great stresses and strains in the crust. The strains are partly re-

VII · Structure of the Interior



SEISMIC WAVES change their speed according to the physical properties of the rocks through which they pass. The changes in speed therefore give clues about conditions along the path of the waves.

What causes change of wave speed? Rocks and other materials differ in the degree to which they resist deformation by waves. If a rock is very resistant—very elastic—it springs back from its deformed condition quickly, and as a result the wave goes through the rock very fast. If a rock is less

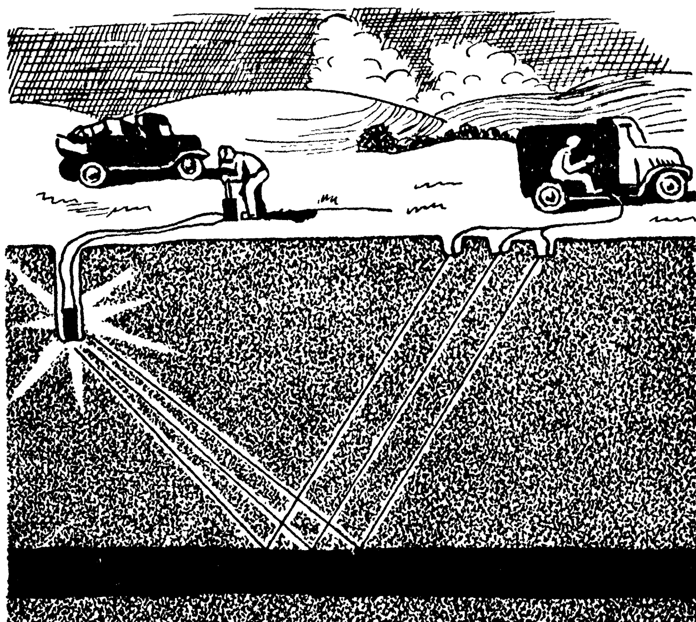
resistant it springs back more slowly and the speed of the wave is less.

The speed with which a rock recoils from compression waves—P-waves—depends on its resistance to compression. This property can be measured in the laboratory. The physicist finds that under high pressures, even a diamond, which is very resistant, can be compressed to a slight but measurable degree.

The speed with which a rock recoils from the sidewise shaking of S-waves depends on its rigidity. This property also can be measured.

Laboratory determinations of elasticity make it possible to compute the speed at which earthquake waves will travel through typical rocks of the earth. There are practical ways to check the accuracy of some computations. For example, dynamite can be exploded so as to send waves through a known kind of surface rock. The measured speed of such waves is reasonably close to the speed computed from the elastic properties of the rock.

Since physicists know the speeds at which waves pass through various materials, they can use the speed of earthquake waves to tell what kinds of rock they pass through. In this way it is possible to learn something about parts of the earth that we cannot reach for direct study—the floor of the Pacific Ocean, for example. Waves that pass through rock at the bottom of the Pacific are found

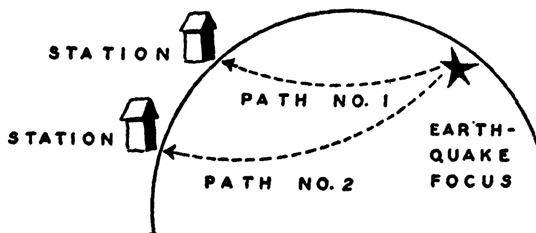


SEISMIC PROSPECTING. Locating a bed of shale by artificial earthquake waves reflected from it

to have speeds characteristic of basalt. This is a dark, fine-grained rock, denser and heavier than most continental rocks. Earthquake waves thus confirm the evidence obtained by measuring gravity, which also indicates that the Pacific is floored by a material denser and heavier than average continental rock.

Since P-waves and S-waves go through the

earth, their speeds can suggest the kinds of material and the physical conditions that exist at different levels. But how is it possible to know wave speeds at different levels? The method is simple in principle. Since the earth is spherical, waves that come to a station from near points take a shallower path than those from distant points. In other words, path number 1 on our diagram is shallower than path number 2. By comparing the average speeds of waves following deep paths and waves following shallow paths, we find that those following deeper paths go faster.



About the same increase of wave speed with depth is found in all parts of the world. This shows that physical properties of the interior at a given depth must be about the same everywhere.

The speed of seismic waves is affected by two conditions that change with depth—density and pressure. Let us consider density first. The density

of a material is its weight per unit of volume. A cubic centimeter of water weighs one gram, and the density of water therefore is one gram per cubic centimeter. In order to have a scale of density, all materials are compared with water. Thus a material twice as dense as water is said to have a density of two. The surface rocks of the earth have an average density of three. Beneath the surface, pressure squeezes a greater weight of material into the same volume—in other words, increases its density. Deep-lying rock therefore has greater density than the same kind of rock at the surface.

Increase of density tends to decrease elasticity, so that wave speeds would become less with depth if density were the only factor involved. But increasing pressure tends to make rock more elastic. This effect overbalances the effect of increasing density. The net result is greater elasticity and greater wave speeds at increasing depths.

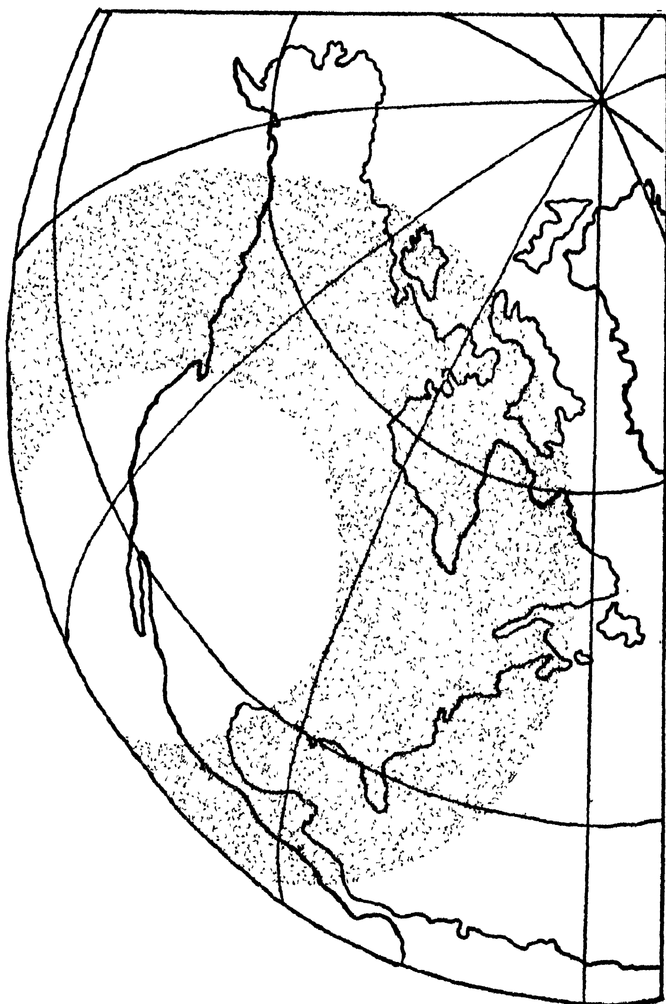
Through studying a mass of data seismologists have found that at certain levels the changes of wave speed (and direction) are rather sudden. The level at which a change occurs abruptly is known as a discontinuity. It is interpreted as meaning that the wave passes from a material with one set of physical properties into a material with another set of properties. Whatever the nature of the rocks, their elasticity increases with depth.

At a certain very deep level, however, waves no

longer increase their speed. They actually slow down. We know it because of this fact: when waves transmitted through the center of the earth are timed, it is found their average speed is less than that of waves on other routes not deep enough to traverse the center. Why this slow-down? Decreasing pressure is not the answer, of course, for pressure cannot decrease with greater depth. There is only one kind of change that can explain the slow-down at a very deep level. This is a great increase of density.

The earth has a dense core, we conclude, but we want to know more about it. In the first place, how large is this core? The size is estimated from a certain strange phenomenon. In certain places the P- and S-waves of the mightiest earthquakes become so feeble that they barely register on seismographs, or fail to be picked up at all. The places where the waves fade or disappear, it is found, lie in a broad belt always located in the same position with respect to the center of the quake. This "shadow zone" extends over the area between 102 degrees and 143 degrees from the quake center.

In the example illustrated on our map, the center of a powerful quake is at a point near Perth in southwest Australia. Waves from the shock go straight to Los Angeles, on the opposite side of the earth, where they are clearly recorded. But at a distance of about 2,000 miles from Los Angeles in

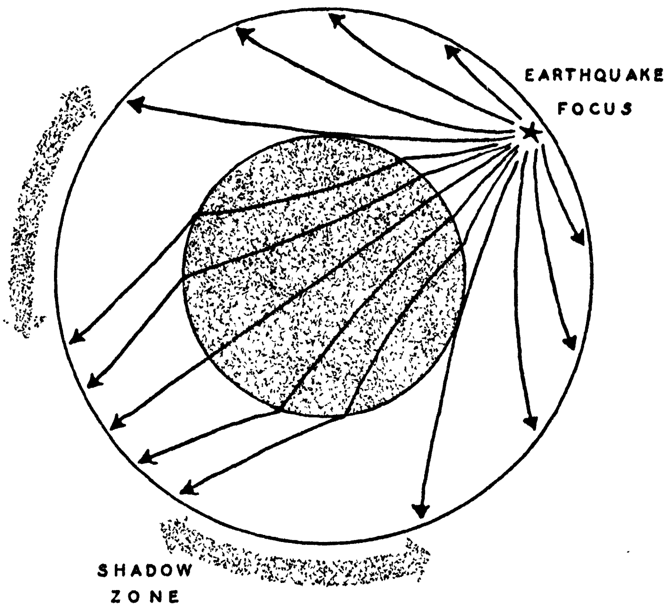


EARTHQUAKE SHADOW ZONE. The circular belt where P- and S-waves from an earthquake in southwest Australia fade out

any direction the waves fade out or disappear. This is the beginning of the shadow zone. It includes the cities of Washington and New York, where the quake is practically unnoticed. The outer edge of the shadow zone crosses Alaska and South America. At points beyond it, in South America and Europe, the waves are picked up clearly.

The mystery of the missing waves can be explained if portions of the wave front struck something that turned them away from the zone of shadow and toward Los Angeles. It is known from experimental studies that seismic waves turn and slow down when they pass from a less dense material to a more dense material. In this respect seismic waves behave somewhat in the manner of light waves. When rays of sunlight pass through a reading glass lens they bend inward toward each other. In the case of seismic waves, the core acts as a sort of lens. Our diagram shows how it affects earthquake waves passing through it. Sections of a wave front entering the core are turned (refracted) away from the zone of shadow and toward the Los Angeles area, opposite the center of the quake. The position of the shadow zone indicates the size of the core. Its radius is more than half the radius of the earth.

From the speed of waves that pass through the core, it is estimated that the average density of the core is about 11. Evidence from astronomy supports



this finding. When we divide the known weight (mass) of the earth by its volume, we find that its density as a whole is 5.5. Since the density of surface rock is less than 3, there must be some very dense portion of the earth that makes up the planet's average density of 5.5. Most of the extra density, we conclude, is in the core.

What material is the core made of? If we could remove the pressure of the whole mass of rock weighing down on the core, the density of the core, by computation, would be 8. This is the density

of solid iron at the earth's surface. That the material of the core really is iron is suggested by the iron meteorites that sometimes crash into the earth. Meteorites are supposed to be fragments of a shattered planet. If that planet had an iron portion, why not ours?

Is the material of the core liquid or solid? In theory, earthquake waves should give an answer to this question too. Let us consider the nature of the waves and see how they should behave in a liquid. In the first place, a liquid must have elasticity in order to transmit waves. Is a liquid elastic? It is, of course, in the sense that it resists compression and after being compressed jumps back to its old volume. Hydrostatic presses, jacks, and brakes work on the principle of liquid resistance to compression. Since a liquid resists compression, a wave that vibrates by compression and rarefaction will be transmitted through it. Sound waves are an example. Being compression waves they easily travel through water and other liquids. The compression (P-) waves of earthquakes pass through the earth's core, but this is no test of the core's physical state, since P-waves will pass through it in any case, whether it is solid or liquid.

Maybe S-waves will give us the answer. How do they behave in liquids? Do liquids have rigidity, the kind of elasticity that S-waves depend on for their transmission? We know from common experience

that liquids have no rigidity at all. Shake or pour them out of shape and they certainly do not jump back. Therefore S-waves cannot pass through a liquid.

If it is proved that S-waves do not pass through the earth's core, this will be evidence that the core is liquid. So far, no waves coming through the core have been recognized as S-waves, but such S-waves would be very difficult to identify in any case. Seismologists therefore cannot be certain that no S-waves pass through the core, and the question of the physical state of the core is left hanging. Though we cannot yet determine whether the core is liquid or solid, efforts to answer the question are not wasted. Earth physicists have learned a number of things about the earth's interior structure and properties, and in time they doubtless will solve the question of the physical state of the core.

Mountains

VIII · Folding of the Earth's Crust

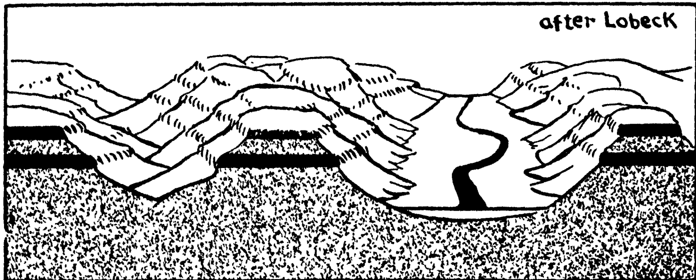
DURING MUCH OF the earth's history the continents were relatively low, with shallow inland seas and extensive marshes. The widespread seas helped to distribute both rainfall and heat, thus moderating climates everywhere, even in the Arctic and Antarctic. Forests grew in Greenland and in Antarctica.

During shorter periods the continents were uplifted and chains of mountains rose on their surface. The inland seas drained and evaporated. Climates

became cooler and drier because of the height of the land and the vanishing of the seas. Deserts developed in some regions. Ice accumulated in the mountains. Ice sheets spread over half of Europe and North America, and covered the Antarctic continent.

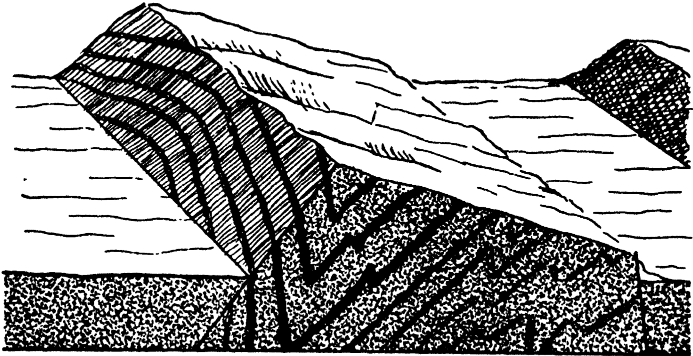
We live in an age of great mountain-building activity, which has helped produce deserts, glaciers, and extremes of cold and heat. These conditions limit the kinds of plants and animals that can exist in affected regions, and thus influence the whole development of life on the earth, including human life.

How are mountains created? What combination of forces can remold the strong crust of the earth as though it were putty? A few mountains are volcanoes, but all the earth's volcanoes together are insignificant compared to great systems like the

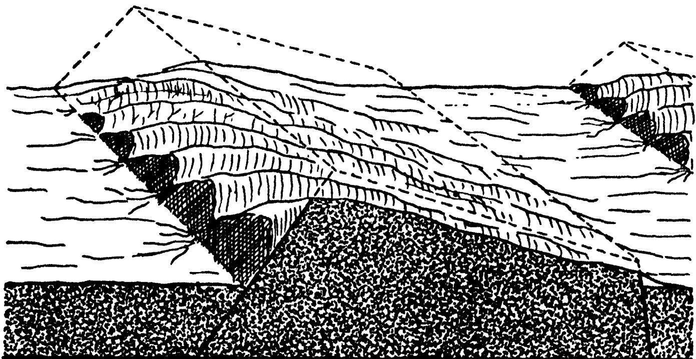


A plateau cut by streams

Andes and the Himalayas. Some mountains, among them the Catskills in New York State, are merely remnants of a flat upland that rivers have cut into valleys and ridges. Mountains of another kind, like the Basin Ranges of Nevada, have been created by vertical movements of blocks of the crust. Blocks



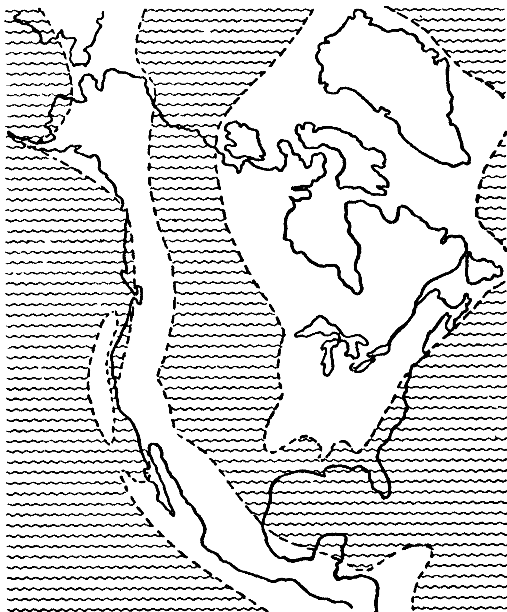
BLOCK MOUNTAINS FORMING



BLOCK MOUNTAINS ERODED

along one side of a fault system rise while blocks on the other side sink, and in time the rising blocks become mountain-high.

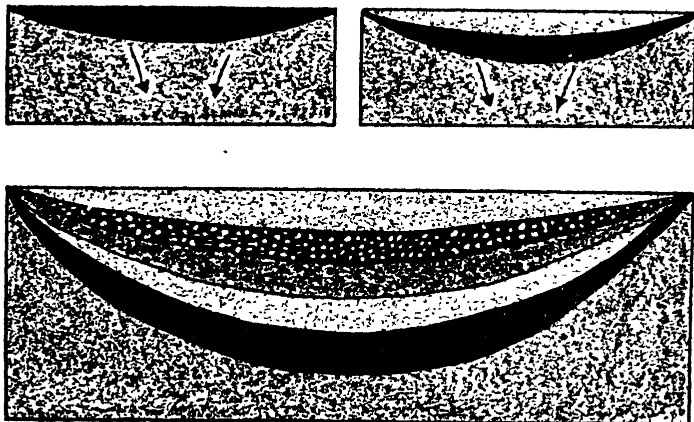
The vast mountain chains that span the continents—the Himalayas, the Andes, the Appalachians, the Alps—have a more complicated history, which geologists try to unravel by studying their structure. An important fact, observed a hundred



NORTH AMERICA ABOUT 80 MILLION YEARS AGO. Shallow seas covered the belt where the Rocky Mountains and Coast Ranges stand today

years ago by the American geologist James Hall in connection with the Appalachians, is that the layers of rock making up these mountains are unusually thick. The same layers—whole series of them—can be identified in areas neighboring the mountains, but there they are much thinner.

The layers originally were sediments. That is, they were made of sand, lime, and other substances deposited by water and wind, but mainly by water. This means that the area now occupied by the mountains was once a great depression in the earth's crust—a "geosyncline"—to which rivers carried their burden of sediment. Much of the material in the layers is characteristic of shallow-

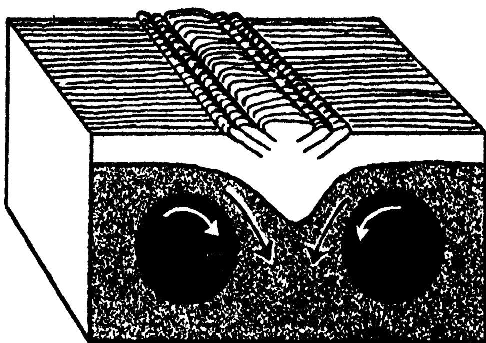


A SINKING GEOSYNCLINE. Sediments are deposited in layers

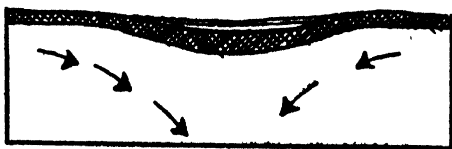
water deposits, indicating that the geosyncline at times was covered by a shallow sea. Some series of layers are as much as several miles thick, yet shallow-water deposits occur at intervals all through them. The only possible explanation seems to be that the floor of the sea continually sank while the deposits were accumulating. Deposition and sinking balanced each other closely enough so that the depth of the water varied only within a narrow range.

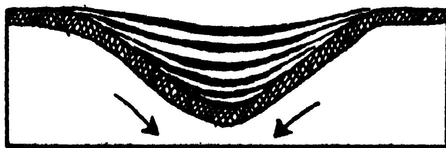
We cannot say that the load of sediments originally caused the geosyncline to sink. The sediments would not have accumulated there in the first place unless there was a basin where they could be deposited. This basin existed before the sediments, and probably must be attributed to events occurring inside the earth. Geophysicists—earth physicists—have suggested that very slow currents may be set up in the plastic interior by differences in temperature. The currents, it is thought, may pull downward and cause a downward warping of the crust, or may push upward and cause an upward warping.

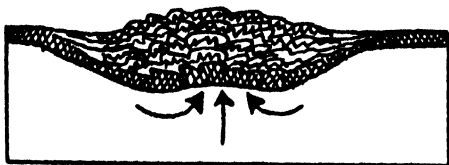
Though we have no direct knowledge of temperature conditions deep inside the earth, we do seem to be on the right track in thinking that geosynclines are produced mainly by interior forces. Supporting this view is evidence from a surprising source—the bottom of the Pacific Ocean. The geodesist Vening-Meinesz, in measuring gravity in



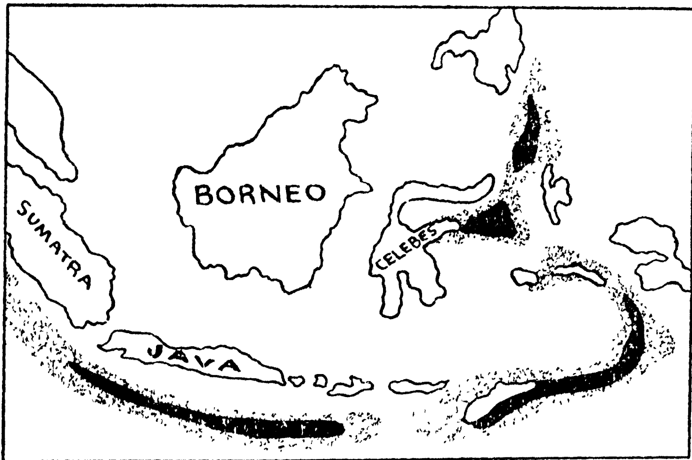
MODEL IN WHICH ROTATING DRUMS SET UP CURRENTS IN GLYCERIN. THE CURRENTS PULL THE CRUST INTO FOLDS.







HOW CURRENTS IN PLASTIC ROCK MOVING AS SLOWLY AS AN INCH A YEAR MAY FORM A GEOSYNCLINE AND FOLDS.

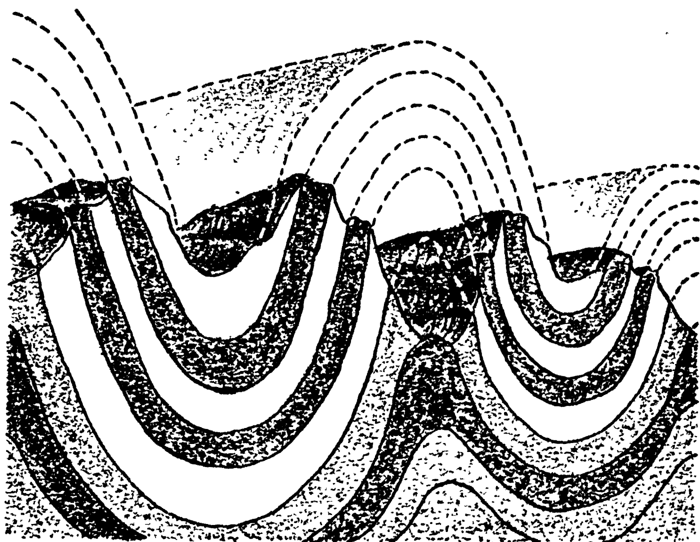


BELTS OF LOW GRAVITY. The belt to the south of Java parallels the Java Trough

the south Pacific, found that the long narrow deep known as the Java Trough lies in a belt of low gravity surrounded by a region of high gravity. This is taken to mean that the Trough and the whole low gravity belt is floored by rocks of less density than the rocks underlying the rest of the region. But if the Trough is lighter, why does it sink? Should it not rise? If isostasy were able to operate uphampered, the Trough doubtless would rise. The fact that it does not do so shows there is some interior force at work dragging it down. The Java Trough seems to be a typical geosyncline. Mighty forces are at

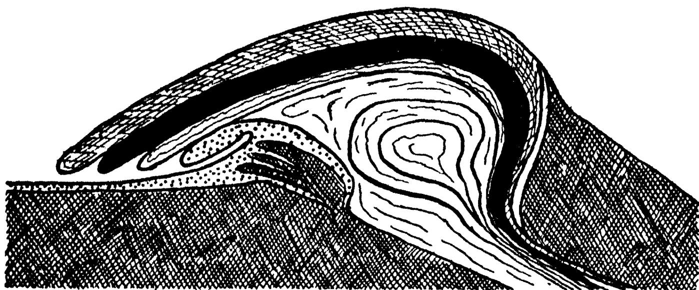
work there, and we wonder if some day—say 50 million years from now—they will produce a mountain system at the bottom of the ocean.

As for today's mountains, we recognize that the geosynclines in which they had their beginnings were floored by thick sediments. These necessarily were laid down in horizontal beds, though we find them in a very different position today. At many places the layers are steeply inclined, vertical, or even upside down. At some time after their deposition, obviously, the layers were bent into complex forms. The structures nowhere remain complete, for weathering and erosion have taken a



great bulk of material from their tops. What we find are stumps and edges of the layers coming to the surface at various angles. On comparing the exposed edges of layers, the geologist may find that a whole series occurs several times, in an order showing that the layers came together in great folds.

There are folds in the Alps that overturned and pushed out horizontally for a distance of 30 or 40 miles. In some cases layers were piled on top of each other like the folds of a towel as it comes from a mangle. Such a structure, if piled on the surface,



would make an enormously high mountain. But the original folding took place at some depth beneath the surface. This is proved by the fact that the rock could bend and flow plastically. At the surface there was probably no sign of the events going on below.

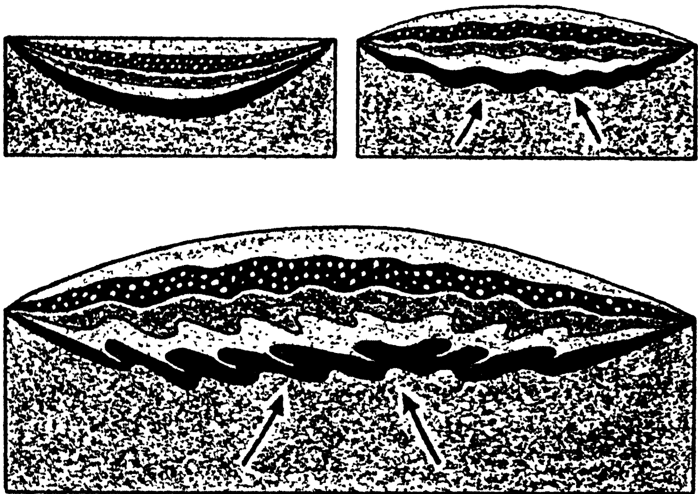
Whatever the varieties and complications of folding, it all achieved one general effect—to narrow the area of the layers. They are crumpled together in a manner we can understand by pressing a table cloth inward from two sides. Folds in the middle tend to overturn so that their forward edges move toward the sides of the area.

What mechanism compressed the great fold systems that we find today in the Alps, the Andes, the Appalachians, and the Himalayas? At one time it was thought the folding resulted from a general shrinkage of the earth. According to this theory the earth has been contracting as it cools off, and the surface continually re-fits itself to the shrunken interior by wrinkling and folding.

The discovery of radioactivity has discredited the theory of a cooling and contracting earth. The constant generation of radioactive heat, and the extreme slowness with which heat is conducted to the surface, make it seem unlikely that the earth is cooling at all, or has cooled since the time when today's mountain folds were forming. And since the earth probably has not been cooling and getting smaller, we cannot attribute fold systems to a general contraction of the crust.

How then can we explain the very evident contraction that occurred in the geosyncline? The chain of causes goes back to the original sinking. As the layers curved downward, they had to stretch and

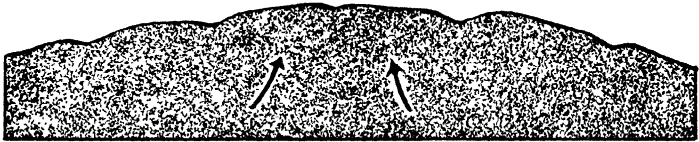
increase their area. Time passed—several million years—and new forces came into play. These forces, which we shall discuss in a minute, started a rising movement. Could the sedimentary layers, which were bent downward, flatten out again as they buckled upward? In order to do so they would have had to push back the margins of the geosyncline. But this was prevented because the rock at both sides of the geosyncline was denser and stronger than the sedimentary layers. Therefore the sedimentary layers, as they buckled upward, folded

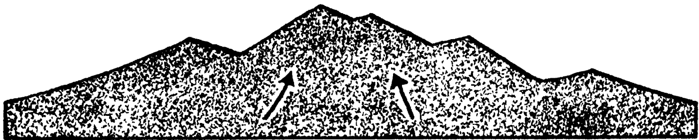


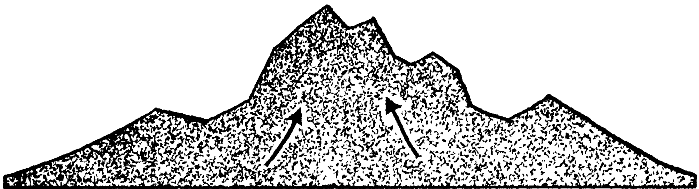
A RISING GEOSYNCLINE. As the sediment layers buckle upward, they reduce their area by folding

and slid over each other. This was the only way they could narrow their area.

The sediments accumulated to a great thickness. Being lighter than rock at the sides of the geosyncline, they tended to rise in the plastic substratum. A tug-of-war developed between the rising tendency of the sediments and the downward pull in







HOW SOME MOUNTAINS GROW. Erosion lightens a plateau, enabling the central part to rise while the general level of the plateau is lowered

the interior. Perhaps the "buoyancy" of the sediments helped to bring the crustal sinking to a stop. In any case the sinking paused or ceased, and the sedimentary mass began to rise, shortening its area and folding as it did so. The shallow sea drained and evaporated. Rock that had been at sea bottom became high land.

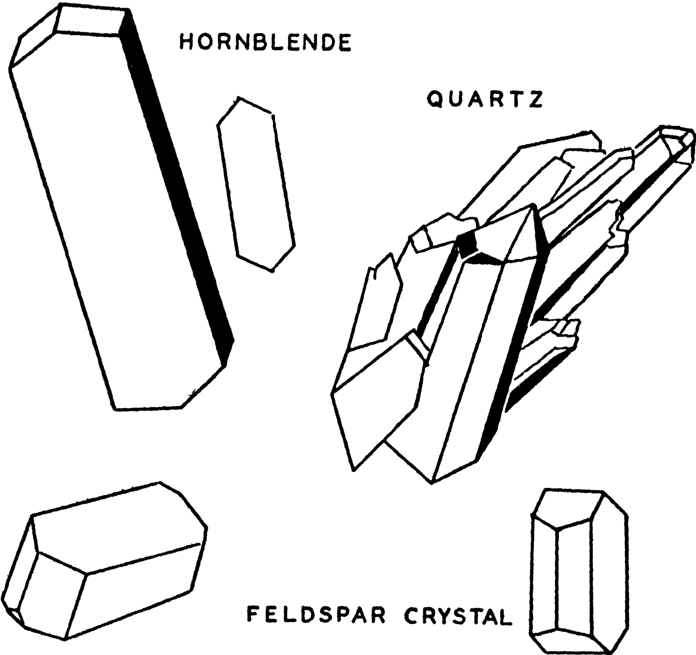
Other forces now contributed toward modeling the uplifted land. Weather and water attacked the rock surfaces. Some of their materials were dissolved and others fragmented, and rivers carried away both. Weathering and erosion in time so reduced the high region that it became lighter and rose further. The gradient—slope—of rivers increased. They became swifter and cut deeper valleys into the rocks. The remaining high land was carved into ridges and peaks. To this day the mountain forms continue to wear down, yet do not disappear. Erosion, by lightening the area, allows it to rise. Since uplift compensates for erosion, the mountains remain high and the rivers keep their sharp gradient and go on sculpturing ridges and peaks.

IX · *Rocks Remade*

ROCK, THE BUILDING MATERIAL of mountains, has a history of its own. The same movements that shape rock into mountains also change its internal structure.

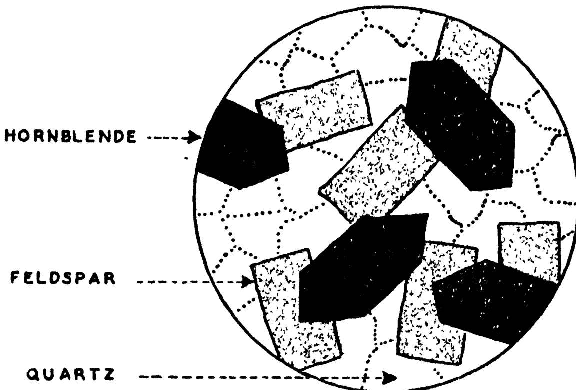
In order to understand these happenings let us distinguish two kinds of rock structure—crystalline and clastic. "Clastic" means composed of fragments. Unconnected bits such as grains of sand may be pressed together with some cementing material, and the product is sandstone, a clastic rock.

Crystalline rock, on the other hand, is formed by a process of internal growth. When magma or lava turns from a glassy liquid to rock, the change is not a simple "freezing" that takes place all at once, but a whole series of connected events. As the melt cools it reaches a temperature at which one of its chemical substances—or several—turns solid. The atoms making up this substance join in a definite kind of linkage—a lattice, it is called—and in this way form a crystal of characteristic shape. Other



substances remain liquid until the melt reaches a temperature at which they in turn crystallize. While crystallization is going on the melt resembles slush —it is a mixture of solid particles in a liquid.

If a crystal is able to grow without hindrance it may become as large as your fist or even larger, like the big crystals of quartz that are sometimes found. But crystals meet obstacles that limit their growth. They bump against crystals of other minerals formed earlier or forming at the same time. The earlier crystals are able to grow large and perfect in form because they have ample space in which to develop. But minerals that crystallize later must squeeze into



ORDER OF CRYSTALLIZATION. Granite cross section (schematic) showing that the minerals crystallized in this order: hornblende, feldspar, quartz

the space left to them. Therefore they tend to be smaller and less perfect in form. An experienced student of rocks can examine a specimen, note the size and arrangement of crystals, and from this evidence determine which minerals crystallized earlier and which later.

Rocks that crystallize from a magma or lava are called igneous, from the Latin *ignis,* "fire" —a reference to the heat of the mixture. But crystalline rocks are also made by another process. Any rock, if subjected for a long enough time to high pressures and movement, will be transformed in structure. If the rock was already crystalline, its arrangement will be changed. If it was a clastic rock like sandstone, the minerals of the fragments will be forged into crystals.

Transformed or "metamorphic" rocks in some cases have structures that reveal their history. Crystals of the various minerals may be grouped, each with its own kind, in streaks, bands, or thin sheets. Pressure alone will not bring like crystals together. Such arrangements require, in addition, internal movement. This is a plastic movement in the solid state. It is caused by the bending, folding, and "taffy-pulling" of the mass of rock. As sheets of the material slide against other sheets, crystals are able to collect, each with its own kind, and lock together.

Banded, streaked, and sheet-arranged rocks are

common in folded mountains. They predominate wherever layers have been bent and tortured out of their original horizontal position. They clearly result from the internal taffy-pulling that accompanies folding.

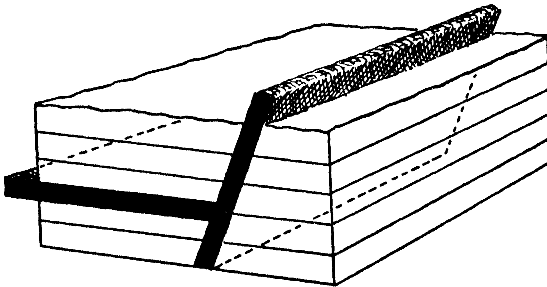
A sedimentary rock (*left*) and a crystalline rock with minerals arranged in bands

Rock history is not always so well demonstrated. Granite, familiar as a building stone for several thousand years, confronts us with a puzzle. The core of many folded mountains is granite, yet most granite has none of the flow structures caused by folding. Does this mean granite did not originate like the folded layers, by transformation of sedimentary rocks?

We all know the appearance of dressed and polished granite. It is made of coarse, interlocking crystals, most of them white, pinkish, or light gray, with a peppering of black. The waxy white crystals are quartz, the pink and gray are feldspars, and

the black are hornblende and mica. A similar assortment of minerals composes the flow-structured rocks neighboring the granite.

At one time granite was considered to be a transformed rock related to the metamorphic rocks with which it is associated. Later it was found in veins running through these metamorphic rocks. Such evidence led geologists fifty years ago to think that granite arrived in the mountain folds as a liquid. It is an igneous rock, they decided, and the matter rested there for half a century.



Veins of rock that oozed into place as a liquid

The granite problem really was not solved, just dropped. If granite is in fact an igneous rock, it becomes very difficult to explain its presence among the flow-structured metamorphic rocks. These rocks ordinarily show no sign of having been shoved aside

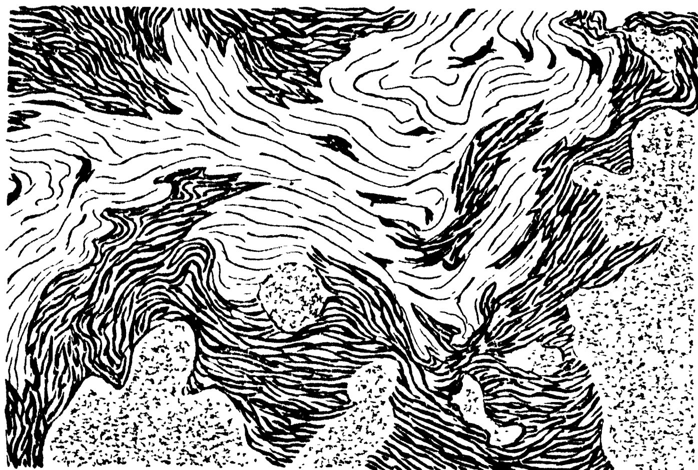
by the granite, yet how could granite push its way among them without disturbing them? From the position of the granite and the other rocks it appears as if the granite had been able to carve out the space it occupies. Granite masses sometimes extend over an area of thousands of square miles. If the granite arrived as a magma, how did it displace the metamorphic rocks that were there before it, and what has happened to those rocks? In an attempt to answer this question it has been suggested that the rising magma might have "stoped"—that is, wedged off—chunks of overlying rock, which sank deep into the magma, out of sight and out of our reach. A convenient way to get rid of thousands of cubic miles of rock!

Even if we grant, for argument's sake, that a magma might carve its way into rock structures, there is still a further difficulty to explain. Though many kinds of rock come from volcanic magmas, granite has never been found among them. Why not? Why is there not at least some granite among the known lavas of the world?

The transformation theory easily disposes of this question. The flow-structured rocks associated with granite are similar to granite in composition. If granite arises from the transformation of these rocks, it derives its chemical make-up from them, and there is no need to explain why granite differs from lavas. The other question—how granite dis-

placed local rocks—is, of course, simply answered. The rocks turned to granite.

But did they? Is there any evidence pointing to the transformation of other rocks into granite? Such evidence has been found in abundance in many parts of the world. Conditions in southern Finland are particularly instructive. There, granite and flow-structured rocks lie side by side in great confusion. In some places granite nearly surrounds the metamorphic rocks, and elsewhere the positions are re-



Rock relations in southern Finland (after Saksela)

versed. Often the two kinds of rock interlock in small-scale mixtures, with little tongues and wedges of each pressing about each other like the pieces of a Chinese block puzzle.

Granite and the flow-structured rocks grade into each other. Where granite lies near the flow-structured rocks it is sometimes streaked and banded somewhat like them, showing that it too underwent an internal sheet-flowing. Among the metamorphic rocks, on the other hand, the streaking, banding, and sheet arrangements tend to fade out where the rocks approach granite. These gradations convincingly indicate that the metamorphic rocks turned into granite, and that granite is, in such instances at least, the end product of the same process of transformation that produced the flow-structured rocks.

By what mechanism does this final change—this "granitization"—take place? A number of proposals have been made, and geologists are hotly debating them at the present time. Some think that, under conditions of high temperature and pressure, liquids and gases percolate through the rocks, bring in new materials in solution and take away others, and in this way eventually change the rock to granite. Other geologists believe that the transformation can proceed without liquids or gases taking any part in it. Groups of atoms (ions), it is thought, migrate along crystal faces or even through the crys-

tals. Elements are shifted around and substituted for each other over a long time, and the process eventually creates the mineral structure of granite.

What, in the light of these discussions, can we reasonably conclude about the origin of granite?

Granite in some small formations—veins, for example—apparently got there in a liquid or half-liquid state. It seems impossible, however, that gigantic bodies like the cores of mountain chains could have arrived from the depths as magmas. Much more probably they resulted from transformation in the solid state of the flow-structured rocks among which they lie.

X · *Footholds for Life*

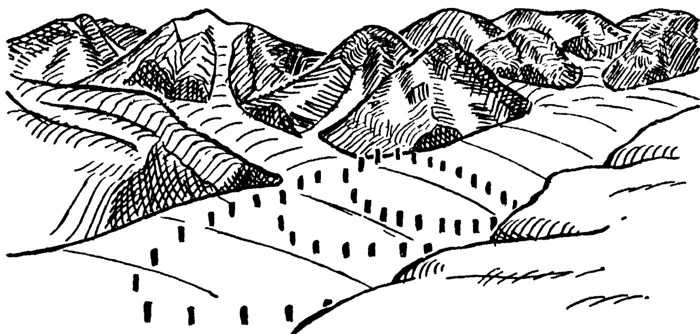
EVEN DURING their building, mountains are slowly worn down by air, water, and ice. The work of destruction begins at the summits. There as elsewhere, some exposed minerals are broken up by oxidation. Soluble products are washed out of crack planes. Water seeping into crevices freezes and, in expanding to ice, splits off films and chunks of rock.

Above a certain height, the "snow line," it is cold enough for snow to remain throughout the year. New snowfalls accumulate in layers which,

piled one upon another, press down on the deeper, older snow. Pressure and movement, working together, compact the snow into crystals of solid ice. The mass becomes a glacier—a stream of ice that moves down-slope.

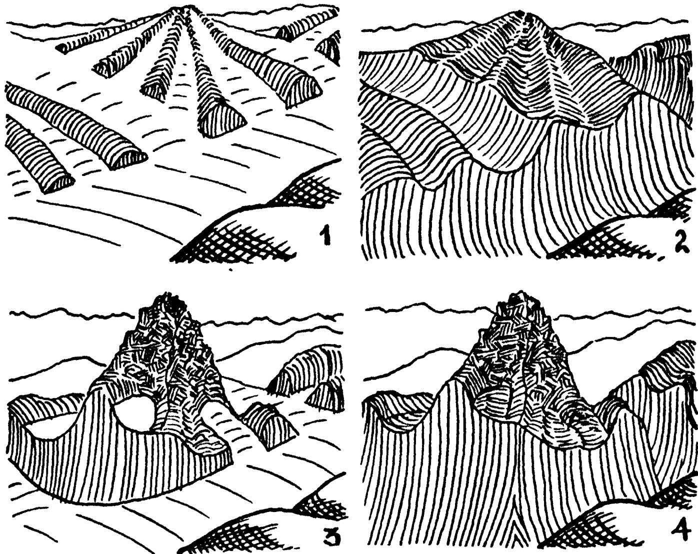
We may compare ice flow to rock flow. Ice is, in fact, a crystalline rock. It flows in the same manner as other rocks, through rearrangement of crystals, which spread themselves out and recrystallize in sheet formation.

Stresses are produced in a glacier by the weight of the ice itself—in other words, by gravity. The glacier is thicker in the middle than along the sides. Because there is more weight along the central axis, gravity pulls harder there, and the center flows faster than side portions. This can be seen by placing a line of stakes across a glacier. In a few months or years the line will curve pronouncedly down-slope.



As it flows, a glacier receives contributions of rock that fall from the peaks and ridges above. The glacier itself pries off loosened bits from the valley beds and walls. Rock fragments from all sources, some of them large boulders, become embedded in the moving ice. Like the teeth of a giant carpenter's rasp, they scrape the valley floor and sides, file them down smooth, and carry the filings along to help work upon the lower valley.

Several glaciers biting at a ridge eat through it



How glaciers carve a Matterhorn peak

in places, thus dividing the ridge into separate peaks. At its head, near the mountain summit, a glacier gouges out a hollow—a "cirque." When several glaciers have carved hollows on all sides of a mountain, they leave it standing alone, a sheer, tall peak, heroically sculptured like the Matterhorn in the Alps.

A glacier constantly transports its burden of fragments. A dark ribbon extends along each edge, made of debris fallen from the upper slopes. Where two glaciers merge into one, the ribbons along their joined edges combine to make a band running down the middle of the ice stream.

What is the destination of a glacier's cargo? Climate determines how far a glacier can push down to the lowlands. In the Arctic and the Antarctic, glaciers go on unchecked until they flow into the ocean. In temperate and tropical regions a glacier has to contend with melting temperatures in the lowlands. If ice moves down faster than it melts, the foot of the glacier advances. If movement and melting exactly balance each other, the foot halts. If melting goes on faster than new ice is supplied, the glacier retreats.

A melting glacier gradually releases its load of debris, which in time forms heaps—"moraines." The ribbons along the edges become "lateral moraines." Material deposited at the foot makes a larger "terminal moraine." If the front of the glacier remains

Glacier
Mount Robson
British Columbia

practically stationary at one place for a long time, while the upper ice keeps moving forward to melt there, the terminal moraine builds up to form a great barrier across the valley.

Mountain glaciers have left many traces of their advances and retreats. It is possible, by studying glacial relics, to review the changes in climate that have succeeded each other for the last several hundred thousand years.

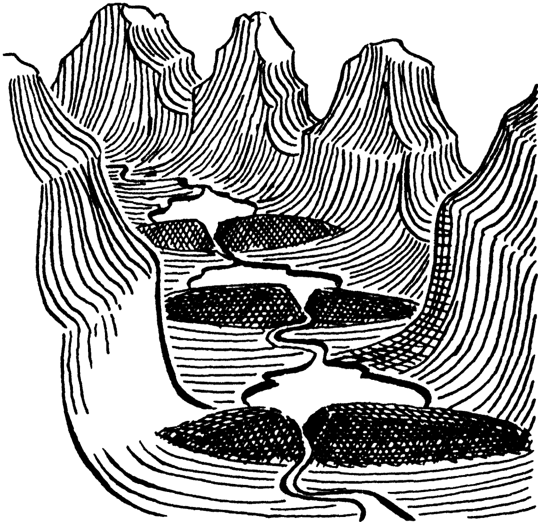
Ice is the main sculptor of the higher parts of the Andes. It carves out valleys of a typical shape, different from that of river-made valleys. A river cuts a narrow, V-shaped channel. The channel can be small and yet drain the mountains, because water flows swiftly, and in a short time a great deal of water passes through the channel. But a glacier, since it flows much more slowly, needs a wider, deeper channel to drain the ice from the mountains. The ice fills the valley from wall to wall, scours the whole floor, and gives the valley the shape of a U.

In the lower valleys, where the glaciers retreated long ago, streams have cut and leveled the moraines so thoroughly that they have become almost unrecognizable. Farther up, the relics of the glaciers have been less disturbed. Here we can easily trace a glacier's retreat by the moraines it left behind. Each moraine marks a resting place

where the foot of the glacier paused. The moraine testifies to a long period of stability in both snowfall and temperatures.

Most Andean glaciers paused together, in response to the same climatic conditions. During the pause, each continued scouring its upper valley. When there was another period of rapid melting, the glacier retreated and uncovered the sculpturing it had done above the moraine.

Today many Andean valleys rise in a series of great steps, which originated in the following way. As the remnant of a glacier continued to melt high in its valley, it sent down a steady stream. The



Glacial trough with a chain of lakes behind moraine dams

water was held back by the moraines, which acted as dams. Lakes formed behind them, one above another. Water flowing into each lake brought a load of sand and silt. This was spread over the lake floor and made it level. Meanwhile the stream was cutting passages through the moraines. When the passages were deep enough, they drained the lakes. The dry lake bottoms, rising one above another, became the steps of a giant staircase.

If we stand in the high Andes or fly over them, the peaks and ridges seem a forbidding wasteland. But as we look down between the ramparts of rock we see the valley steps, and they are green.

Long before Europeans set foot in South America, the Quechuas and other peoples discovered these valleys and transformed them into footholds for human life. The steps were well suited for cultivation. They were flat; they were covered with good soil; they were watered by steady streams that could be divided into irrigation channels. Settling on the valley steps, the people worked together to lay out their fields and to irrigate them. By cooperative labor the cultivators flourished and in time created a civilization.

In Java, the Indonesian people learned to till the slopes of volcanoes. In the Andes, the Quechuas cultivated glacier-cut valleys. The two peoples are different in speech and customs, but they are alike

in the human co-operativeness that enables them to master the riches of their mountains.

Because the earth has mountains, glaciers can exist; because it has geosynclines, seas can gather. All the surface features of this world depend, directly or indirectly, on the mighty forces at work within. They continually change the rocky crust on which we dwell. Sometimes the spasms of change destroy men and other living things, but in the long run they balance the surface and keep it habitable.

Mankind cannot control either the interior forces or their surface effects, but at least we understand to some extent the processes of volcanism and earthquakes, and this knowledge enables us to avoid or lessen their dangers. The explorations of the earth physicist, indirect as they are, give us a glimpse of the world beneath our feet. As his work goes on, we certainly shall gain a fuller understanding of the forces that change our restless earth.

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