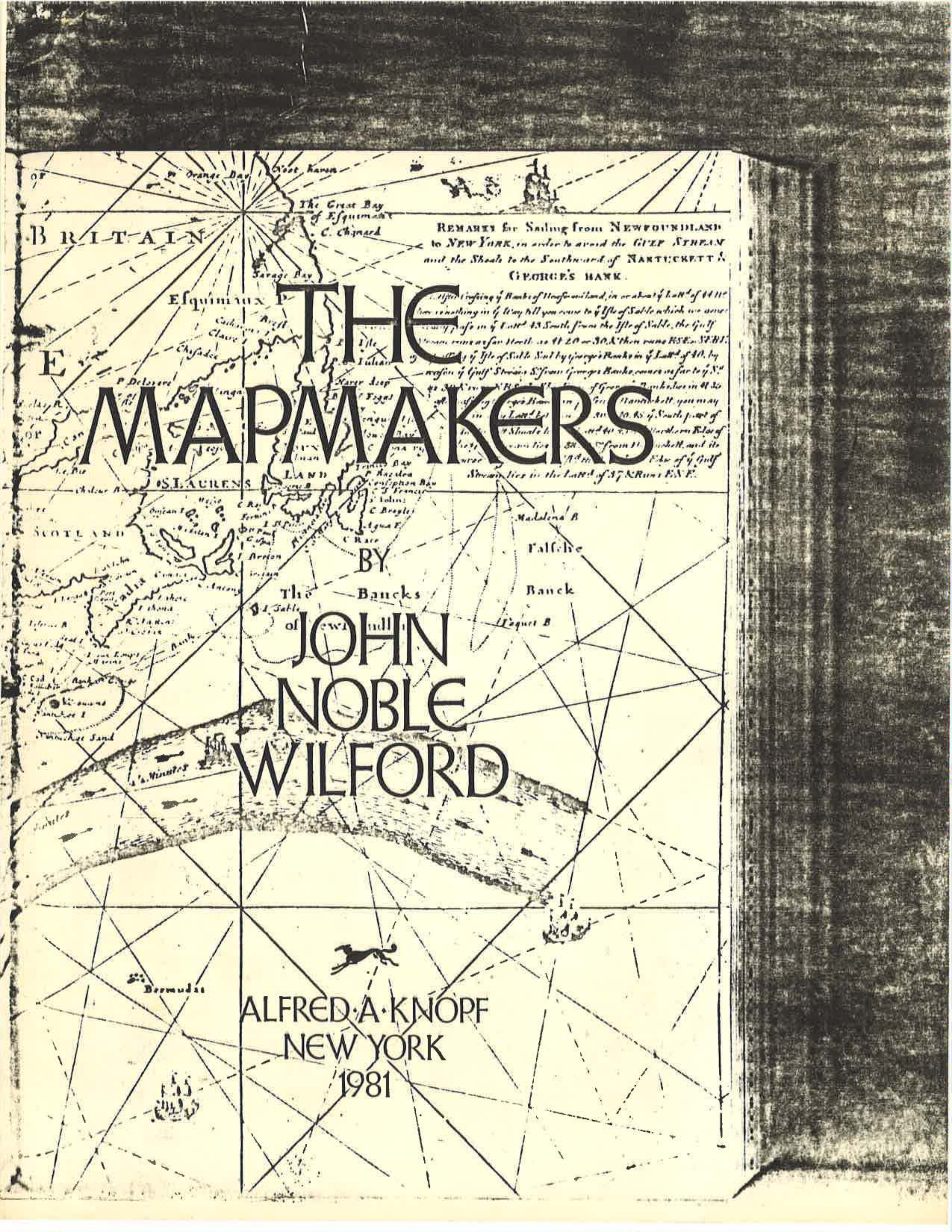

THE MAPMAKERS

BY

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DEEP HORIZONS

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Some still believe that it is possible to locate minerals and fluids with a divining rod —a forked stick which, if held in the right way by the right person, supposedly twists downward toward the concealed resource. The idea goes back at least to Biblical times, but is viewed with skepticism by nearly all scientists. Instead, the search for knowledge of the Earth's interior and for natural resources therein is now the pursuit of geologists and geophysicists, not dowsers, and subterranean mapping is one of their indispensable tools.

Geologic mapping, like other mapping, is a way of conveying complex information in a graphic form. This information involves the distribution of rocks and many kinds of geologic features—the sequence and thickness of rock formations and other subsurface structures—over the Earth's surface and to considerable depths below it. But, unlike topographers, who gather their information primarily by direct observation and measurement, geologists have to go about their mapping in much less straightforward ways.

Their methods are more subjective and interpretive. Rarely can geologists see their subject whole. Although the walls of the Grand Canyon, for example, are like a geologic cross-section map in full scale, in most places geologists cannot see the interior and must make educated inferences to arrive at such a map. Their inferences are based on the character of the topsoil, the distribution of ridges and valleys, and the occasional exposures of subsurface formations at widely scattered points, in cliffs, ledges, streambeds and in road cuts and other excavations. Only after the many bits of information are put together on a map, each in its proper position, does the geologic whole begin to emerge in recognizable form. In other words, while the topographer can usually see the panorama first and then reconstruct it in map form, the geologist never sees the whole until he has mapped the many parts.

New instruments and techniques are now taking subterranean surveying to greater depths, but the fundamentals of geologic mapping remain much the same as those practiced by William Smith, a geologist of the late eighteenth and early nineteenth centuries.

The first person to study geology by making a map appears to have been the French naturalist Jean Étienne Guettard, who prepared a mineralogical map to accompany a paper arguing that England and France were part of the same geologic region. The map was published in the proceedings of the Royal Academy of France for 1751. In the following years Guettard traveled extensively and managed to gather enough information to complete sixteen sheets of a proposed geologic map of France.

But most historians of geology credit William Smith with the conception and execution of the first geologic map in the modern form. His classic map, published in 1815, was entitled, *A Delineation of the Strata of England and Wales, with part of Scotland; exhibiting the Collieries and Mines, the Marshes and Fen Lands originally overflowed by the Sea, and the Varieties of Soil, according to the Variations in the Substrata; illustrated by the most descriptive names.*

The hand-colored map was the product of a quarter of a century of work by an extraordinarily keen and industrious observer. Born in 1769, Smith was the eldest son of an Oxfordshire mechanic, and became a surveyor's assistant at the age of eighteen. While holding the rod and dragging the chain, he observed the different kinds of soil and rock and wondered if there might be some order where there appeared to be only chaos. This was, and is, the instinct of a geologic mapper.

When his work took him down into coal mines, Smith took note of the way that certain rocks containing certain fossils and other distinctive material always lay in a definite order. He remarked that the strata lay one above another like "superimposed slices of bread and butter." He thought there must be some order to the structure of the Earth beneath his feet.

For several years Smith traveled about England laying out routes for canals, logging more than a thousand kilometers in a year and always making copious notes on the geology he encountered, particularly the patterns of strata. He observed the strata of rocks exposed on hillsides and in the cuts for the canals. He came to know rocks so well that by looking at the contours of a hill and the character of the countryside he could accurately predict the subsurface stratification. This earned him the nickname "Strata Smith."

The fossils that attracted Smith's attention led him to an important insight. Smith was the first to realize the significance of the fact that different strata had different fossils. This, he realized, provided a means of establishing the ages of the strata. And, once he had proved to his satisfaction that "the same species of fossils are found in the same strata, even at a wide distance," Smith knew that he had a way of extrapolating from isolated observations to produce maps of the substrata over extensive areas.

Smith's ideas about fossils and strata were not readily accepted. He was a self-taught geologist who worked for a living, and worked hard, at a time when science in Europe was still a gentleman's pursuit. But similar discoveries were being made in France, by Georges Cuvier, and so the doubts about Smith were eventually dispelled.

Between his many surveying and engineering jobs, and despite frequent diversions to collect and study fossils, Smith recorded his remarkable fund of geologic knowledge in the form of a map. Twenty colors were employed to depict different geologic formations. The lowest part of each separate formation was more deeply shaded than its upper reaches, a device which made the map more easily intelligible.

Prices of the Smith maps ranged from an equivalent of $25 to nearly $60, indicative of the considerable value placed on maps of the Earth's subsurface as early as 1815. Unfortunately, Smith had spent heavily on his great map and had made several bad investments in quarries and mines. In 1819 his debts caught up with him, and he was confined for ten weeks in the King's Bench Prison.

Not until 1831 were Smith's services to geology and geologic mapping publicly acknowledged. The Geological Society of London awarded him the first Wollaston Medal. A small pension made his remaining years more comfortable. He died in 1839 from influenza, which he contracted while on one final outing to collect fossils and observe strata.

Smith would probably fit right in on a typical modern geologic mapping trip, at least on one that continues the practice of charting the depths by conventional surficial observations.

The standard geologic maps show the distribution of geologic units at or near the surface of the earth. The map can be of loose materials such as river sediment, glacial debris, beach deposits, or sand dunes—surficial geology. Or it can be an attempt to show the distribution of consolidated igneous, metamorphic, or sedimentary rock units that underlie the topsoil—bedrock geology. How good the map is depends on the ability of the mapper to interpret what he sees at the surface. As Norman L. Hatch, Jr., one of the U.S. Geological Survey's more experienced surveyors, remarked: "Geology is an enormously interpretative thing, not like math where two and two are definitely four."

In 1965, Hatch and two other geologists undertook a mapping project in the Berkshires of western Massachusetts. Their task was to examine a rugged, sparsely populated 80-square-kilometer region and then prepare a map whose different colors would portray the kinds and ages of rocks that lie beneath the trees, grass, and topsoil. Their methods were those of conventional field geologists.

They discovered that an Amherst College professor had produced the last geologic map of the area in the 1880s. But he had worked with a poor topographic base map, and the current understanding of geology was inadequate, compared to modern standards. Hatch came across an 1831 publication whose author, with incredible aplomb, had entitled it *Final Report on the Geology of Massachusetts.*

The geologists also took advantage of available geophysical data on the region. Aeromagnetic surveys established the magnetic intensity of the underlying rocks, a clue to their composition. A gravity survey gave them the density of the rocks. A seismic survey would have been of doubtful value, since the region's subsurface strata are too folded and jumbled, not generally horizontal.

The survey took about seven man-months of field work. In drawing the map, the geologists had to assume that each rock type they saw represented a layer that was once continuous over the whole area. They also assumed that these layers occurred in the same order, from top to bottom, over the whole area. If the final geologic map was consistent with everything they knew about this and surrounding areas, and did not, for example, imply that one layer was older than another when fossils showed the opposite, the map would be inferred to be the best possible representation of the surface and near-surface distribution of rock formations.

At the bottom of the finished map Hatch prepared a cross-section of what the subsurface layering of the Berkshire region would look like if one dug a trench 600 meters deep along a line. The underground projection, Hatch said, was based on what he saw on the surface. In this case, the depth cross-section extended down to sea level; but it could go as deep as the geologists wished to go with the data they had in hand.

Even though the geologic map is interpretive, it has proved to be a useful method of recording and presenting data in compact and systematic form. Many kinds of scientists and engineers use such maps. Because certain types of rock or geologic structures are associated with certain kinds of mineral deposits, geologic maps can help find new places to explore for natural resources. Highway engineers use them to locate sources of construction materials and to predict foundation and excavation conditions. Hydrologists use them to locate underground water. And, because soil is commonly a product of the disintegration of the bedrock underneath, geologic maps are helpful to soil scientists in classifying soils for agriculture.

The increasing pressure to find more minerals and petroleum, along with normal human curiosity, has led to the development of sophisticated new techniques for probing deeper into the Earth's interior and mapping its unseen strata.

A direct method of subsurface exploration is known as well logging, the recording of various physical or chemical properties of the strata penetrated by a well. In a logging operation, measuring probes, or sondes, are lowered on cable into the drill hole. Insulated conductors in the cable pass power to the sonde and transmit signals to the surface. As the sonde is pulled up the hole, the measurements made are recorded, with depths noted, as a well log.

Some of the logging devices take advantage of the fact that different rocks have different electrical properties. Electrical currents are thus passed through the ground adjacent to the well, measuring for differences in the conductivity or resistivity of surrounding rocks; the presence of oil or gas contributes to a higher resistivity reading, since oil and gas are nonconductive. Gamma-ray probes are used to identify features by their emission of radioactive elements; clays and shales, for example, seem to contain more radioactive material than clean sands and limes. Another nuclear-type probe bombards the surrounding ground with neutrons and detects reflected radiations, which can reveal the presence of hydrogen in the form of either water or hydrocarbons. Other types of sondes are employed for determining the densities and angle and direction of strata penetrated by a borehole. Usually by identifying characteristic wiggles, breaks, or other features that persist on logs in different wells over an area, geologists can produce subsurface cross-section maps rich in detail.

But well logging can be slow and expensive. Much of the new emphasis in subsurface mapping involves geophysical methods of seeing what is down there without having to dig or drill. The three principal methods used by geophysicists in subterranean mapping are gravity, magnetic, and seismic surveys.

Gravity. By measuring slight variations of the Earth's gravitational attraction at given points, geophysicists can make some deductions about the nature and structure of subsurface geology. Variations in gravity arise from the topography of an area and the different densities of materials beneath the surface. The effect of topography—latitude, elevation, and nearby mountains—can be eliminated by compensating corrections. The corrected data are then plotted on a map, and the lines, called *isogals,* are drawn to connect points of equal gravitational attraction. Isogals are thus the contour lines of a gravity map.

With sensitive gravimeters it is possible to relate the changes in gravitational pull to changes in rock types in underlying structures. These provide clues to geophysicists. Thick, dense subsurface structures increase gravity, causing positive gravity anomalies; these may be associated with heavy ore deposits or structures containing petroleum. Lighter rock and salt domes diminish gravity, causing negative gravity anomalies; salt domes often act as traps for petroleum.

The effectiveness of the gravity technique in locating geological anomalies was first satisfactorily demonstrated in Texas in the 1930s. At the time the pendulum and the torsion balance were the favored measuring devices. The torsion balance acts on the principle that a suspended weight may be deflected by a large force of attraction and so may not hang absolutely vertically to the surface.

Geophysicists making gravity surveys now rely primarily on the gravimeter. It is a highly refined version of an ordinary spring scale, to which is attached a small object as a weight. As the meter is moved from place to place, changes in the weight of the object are caused by differences in the gravitational attraction. The gravimeter is designed to magnify the slightest weight change so that it can be detected and recorded.

But gravimeters are so sensitive to accelerations that they cannot be used aboard aircraft and are seldom used aboard ships. Consequently, magnetic and seismic surveys are more widely employed by geophysicists in mapping.

Magnetic. The magnet was used as early as 1640 to discover ore bodies in Sweden, and the dip needle, an adaptation of the compass, was used to locate similar deposits in Wisconsin as late as 1915. But subsurface mapping with the compass proved to be a slow and tedious task, for the instrument had to be firmly mounted and leveled at each measurement point to get an accurate reading. This drawback has been overcome with the development of the magnetometer.

An airborne version of the magnetometer was developed in the 1930s by the Gulf Research and Development Company and was used with moderate success in World War II as a submarine detector. Tests over known ore deposits proved so successful that as soon as the war was over aerial survey companies added magnetic surveying to their repertory.

A more modern type of magnetometer depends on an application of atomic physics. The sensing elements in the device are spinning hydrogen nuclei, or protons, which precess, or wobble, around lines of force in the Earth's magnetic field. The frequency of precession depends on the strength of the field, which can thus be measured.

Flight crews call the magnetometer "the maggie" or simply "the bird." In its early form, it weighed about thirty kilograms and was encased in a plastic container that looked like a small bomb—so much so, in fact, that authorities in a South American country once held a crew under house arrest for five days while they made sure that the bomb-shaped object cradled under the belly of the aircraft was indeed harmless.

For many years the survey planes had to follow the Earth's contours roller-coaster fashion, always about 150 meters above the ground. This made for a bumpy ride, and even veteran fliers often got airsick. In flight the bird was lowered by cable so that it trailed about 25 meters below, away from any magnetic interference from the plane itself. Once, flying a low-altitude survey over rugged terrain in Peru, a pilot came to a mountain that rose more steeply than he had estimated. The suspended bird clunked into the mountain and was demolished.

Now, however, the maggies have been improved so that aircraft can fly with the device attached to a wing or fuselage and maintain higher and smoother altitudes.

In one of the most ambitious applications of magnetic mapping, Canada's Department of Energy, Mines and Resources surveyed the whole of that country's vast Precambrian Shield, the repository of a wealth of mineral deposits. Some 7 million kilometers were flown by survey aircraft, and more than 7,000 contour maps have been published. Since the magnetometer measurements were recorded in digital form, rather than in the more classical way on a roll of chart paper, the mapmaking process could be carried out by computer, with automated plotting machines accurately drawing the magnetic contours.

The contour lines of a magnetic map are called isogams, a gamma being the standard unit of magnetic force. A gamma, for example, is about five-hundreths of the Earth's magnetic field in the vicinity of New York City. An isogam connects points of equal magnetic value. The contoured values may be either positive (magnetic "highs") or negative (magnetic "lows").

A strong magnetic high is a good indication of ore deposits, particularly iron. Only indirectly do magnetic surveys suggest subterranean structure. This occurs when geophysicists are able to use magnetic data to determine the location and disposition of the basement rocks, because they are igneous and contain iron, and hence, by inference, can determine the lay of the sedimentary rocks that might contain petroleum.

Seismic. When John Milne, an English geologist, went to Japan in 1875, an earthquake shook the land soon after his arrival and changed his career. In an effort to trace the sources of the frequent Japanese earthquakes, Milne borrowed the ideas of other scientists and produced the first seismograph, which is to the earth scientist what the telescope is to the astronomer—a tool for peering into inaccessible regions.

Milne used seismographs to make the first world-wide map of the zones of earthquake origin. Other scientists, using Milne's instruments and techniques, identified the sources and measured the velocities of seismic waves and, in so doing, developed an understanding of the Earth's deepest interior.

In 1909, for example, a Yugoslav physicist, Andrija Mohorovičić, noticed sharp changes in the velocity of seismic waves traveling deep through the Earth. This was how he discovered the discontinuity that forms the boundary between the Earth's crust and its mantle. Four years later, scientists were able to measure the radius of the Earth's core as being about 3,200 kilometers.

By then seismology had in a sense mapped the gross features of the Earth's interior: the crust, which is a thin surface skin (from about 6 1/2 kilometers thick under the oceans to about 50 kilometers under high mountains); the mantle, which extends from the crust about halfway toward the center; and the dense, partly molten core.

Economically, it was the crust that counted. If only seismic waves could be interpreted to detect more subtle layering in the Earth's crust, this might point the way to hidden resources. But the occurrence of earthquakes was too unpredictable to be of any real help in detailed subsurface mapping.

During World War I, a German scientist, Ludwig Mintrop, conceived the idea of creating artificial earthquakes to produce seismic waves. He induced shock waves in the ground as a possible means of locating enemy artillery emplacements. Though of little consequence in the war, the system was patented and applied in 1924 to search for possible oil-bearing rock formations in Texas. It was a success. From the differences in the return time of refracted seismic waves it was possible to locate shallow salt domes, the low velocities of the denser surrounding rocks contrasting sharply with the high velocities from the salt. This early seismic mapping method is known as refraction seismology, utilizing horizontally traveling seismic waves. It required large amounts of energy to generate the shock waves and resulted in an ability to map one or two levels of subsurface strata.

Today's routine method of seismic mapping utilizes the seismic reflection method. Sound waves are generated at the surface by small explosions, pneumatic devices, or vibrators. The sound penetrates deep into the crust. Velocity and density differences at the boundaries between different types of rock reflect part of the wave. Each reflecting boundary is called a horizon. The returning echoes are detected and timed by a sensitive listening device on the surface, a type of seismograph.

A miniaturized version of the seismograph, a rugged but sensitive device called a geophone, has been developed for easy handling in seismic surveys. The geophone consists of a magnetic circuit fastened firmly to a cylindrical case less than a centimeter in diameter and a coil suspended within the magnetic field. The case is coupled to the ground with a spike. As the surface shakes from the seismic waves, the magnetic structure moves with it but the coil stays still. The effect is that of a magnetic field moving past a conductor. This generates a current that is amplified and recorded as tracings on strips of paper or on magnetic tape.

The round-trip time of the signal is clocked to give an indication of the depth of the reflecting layer. From long experience geophysicists have learned the travel times of signals through topsoil, various kinds of rock, and deep sediments. The strength of the return signal is analyzed through computer processing to learn something of the nature of the reflecting layer; porous rock in which natural gas is trapped, for example, reflects a much stronger seismic echo than does rock filled with water. The result, after the survey has been repeated along a line, is a map showing a cross-section of the Earth's crust to depths of several thousand meters.

The sequence and shape of the various layers stand out in profile, like a sliced layer cake.

These profiles are seismic cross-sections used to construct seismic maps, which are now a routine part of the exploration for oil and gas.

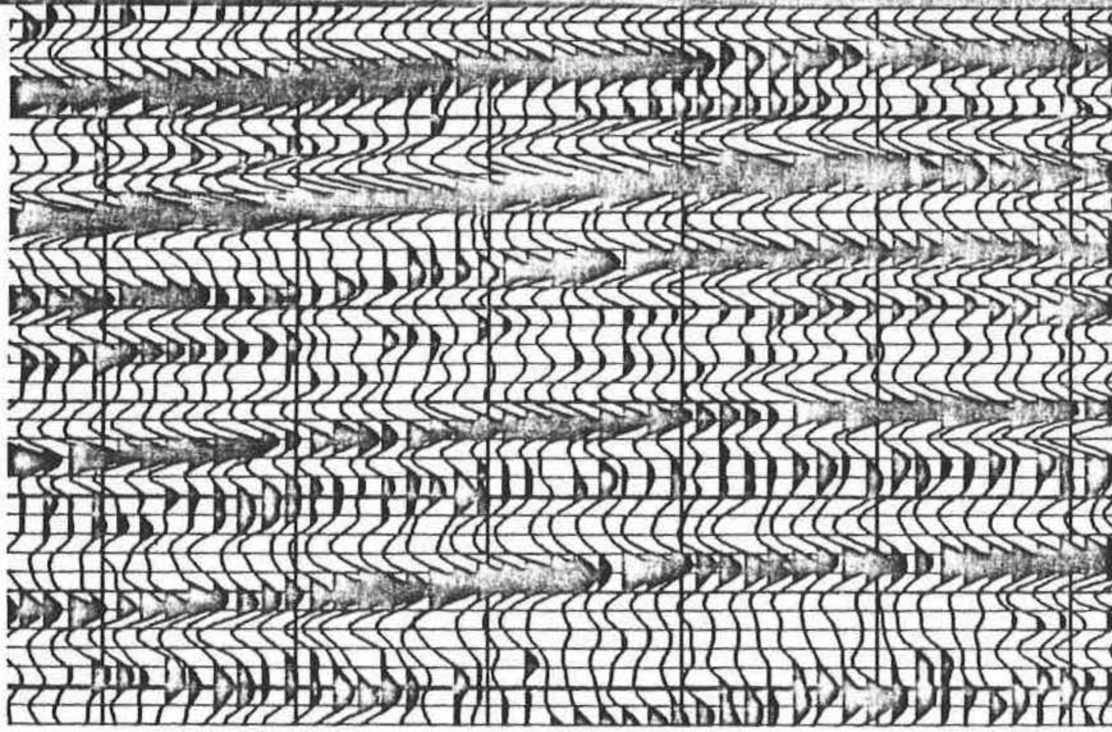
In the earlier days of seismic mapping, "seis" parties went around drilling holes to plant dynamite charges, which were detonated to create shock waves. Everywhere they drilled they made mounds of dirt that reminded people of the many little dirt piles dug up by a bug, the doodlebug. So seismic surveys became known, in the colorful language of exploration geophysics, as doodlebugging.

But today's doodlebuggers usually leave not a trace, with their faster, nonexplosive methods. A recent operation by Conoco, Inc., in Oklahoma is typical of seismic surveying.

Men known as jug hustlers, or jerbs, unwound long black cables over a straight line of more than 5 kilometers. Attached to the cables were clusters of geophones, often called jugs, about 6 clusters of 56 jugs each for every kilometer. Having so many geophones helped distinguish the real signals from random noise. Then five heavy trucks, the thumpers or vibrators, lined up nose to tail like a train of circus elephants. Each truck was equipped with a mechanism, called a Vibroseis, that presses a steel plate to the ground, vibrates it, and sends tremors of seismic waves deep below the surface.

Ahead of the caravan was the recording van, in which two men took turns directing the operation and monitoring the seismic signals. When the head jerb reported by radio that all the jugs were planted, and when each thumper driver called in ready, the observer in the recording van sent a radio signal that simultaneously activated each of the Vibroseis plates. The rear wheels of the trucks rose in the air as the steel vibrating plates shook the ground. The vibrations started fast, 40 cycles a second, and then slowed down, to 7 cycles. The sound waves were reflected off the substrata, in ways suggestive of different rock densities and porosities, and the reflected signals were picked up by the geophones and fed by cable to amplifiers inside the recording van. A computer inside the van converted the data from electronic impulses into numbers and summed up all the different sound reflections into traces on a seismic graph. After each sweep of vibrations, which lasted less than a minute, the trucks moved forward about one meter, waited for another radio signal, and repeated the vibrations. And so it went all day.

Surveyors had been there earlier with plane tables and levels to map elevations and lay out the grid for the seismic survey. During reconnaissance seismic mapping, the lines are many kilometers long and spaced several kilometers apart. For more detailed work, the lines are usually less than two kilometers apart and are crossed with still more lines so that small grids are developed.



SEISMIC CROSS-SECTION MAP REVEALING VARIATIONS IN STRUCTURE BELOW THE EARTH'S SURFACE

At the end of a survey the raw data, recorded on magnetic tape, are turned over to computer experts for special processing. Computers sort out the millions of seismic signals, measure the spurious noise, and come up with charts of how the Earth's rock layers would look if the crust could be sliced open. From these maps geophysicists can make shrewd guesses as to where oil or gas might have accumulated.

In particular, geophysicists examine the seismic maps for evidence of faults, salt domes, or anticlines, which are upward bulges of an underground rock layer. These structures can be identified and located by a careful analysis of the arrival times of reflected seismic signals.

Ignored in the processing for many years were variations in the strength of the reflected signals. This began to trouble Carl H. Savit, a scientist at Western Geophysical Company, which does seismic exploration under contract to the oil companies.

In 1960 Savit published a scientific paper suggesting that, in removing variations in signal strengths by filters and volume controls, geophysicists were discarding valuable information relating to the nature of the reflecting layers, data that might help distinguish between water, trapped natural gas, or oil.

By the late 1960s Savit had persuaded his company to introduce recording systems that would preserve all amplitude data and to install more computers. Other companies did likewise. They kept their techniques and results a secret, in the hope of maintaining an edge over competitors. In 1974 their secret methods became known to the public as the "bright spot" technique, after the stand-out pattern that appears on seismic charts where a rock layer is more likely to contain gas or oil.

While the unusual strength of a returning reflection is highly indicative of gas or oil, bright spot relies on other, confirming indicators. One is the ability to monitor the polarity of a reflection; the direction of movement (the polarity) of a gas-reservoir reflection is opposite to that from a water-filled sandstone. The other is the ability to make such fine interpretations of reflection signals as to detect a perfectly horizontal layer; since very few geologic surfaces are perfectly horizontal, such a surface must be an interface between two substances: either gas over water, gas over oil, or oil over water.

With more discriminating data to work with, geophysicists have begun to analyze seismic maps from a new and perhaps more rewarding angle, called stratigraphic analysis. The emphasis is on the composition of the rocks and sediments.

Charles Payton, manager of exploration research for Conoco, explained this new direction, saying: "In places like Oklahoma and Louisiana and Texas, if you are going to find any more oil and gas, you've got to look for either deeper structures or some different kind of trap than an anticline or a fault. That's where the business of stratigraphic traps comes in. There are many flat planes or layers beneath the surface. Almost every layer changes rock type from one place to another. Some of these may present natural barriers within layers. So we're trying to identify rocks in the layers and look for those barriers that could contain oil or gas."

Many oil companies are experimenting with shear-wave seismology. Sound waves directed vertically down in the ground, compressional or primary (P) waves, are the standard energy used in seismic mapping. Shear (S) waves, directed more horizontally through the ground, cause rocks to rub against each other sideways to the direction of the energy source. One of their most interesting properties is that they do not travel in fluids, which means that shear waves can be used to distinguish trapped fluids, possibly oil, from changes in rock densities.

In few areas of cartography are the economic rewards for innovation so swift and abundant. Bright spot led to important discoveries in the Gulf of Mexico, offshore in Nigeria and Indonesia, and in a few places in the continental United States. Stratigraphic analysis was responsible for new petroleum discoveries near Mobile, Alabama.

As petroleum exploration has moved more and more offshore, so has seismic mapping. The principles are no different than on land, only the equipment—ships instead of trucks; propane and compressed air guns instead of vibrating steel plates;

hydrophones instead of geophones; and navigation systems tied to signals from orbiting spacecraft.

The Baltimore Canyon, an offshore basin extending along the coast of Maryland to Long Island, was the focus of extensive geophysical surveying during the 1970s. Aeromagnetic surveys detected undulations in the canyon's bedrock suggesting the presence of vast and promising traps in which crude oil and natural gas might have collected. Then the seismic ships embarked to make more detailed surveys.

In the summer of 1975 the Shell Oil Company's *Phaedra,* a 55-meter ship with a crew of 30 and millions of dollars worth of electronic gear, was typical of the dozens of seismic ships plying the Atlantic waters and "sharpshooting" the Baltimore Canyon. She covered about 80 kilometers a day, following a precision-navigated crisscross of courses over the continental shelf off New Jersey.

Behind the *Phaedra* trailed two arrays of compressed-air guns. Once every 50 meters, on a signal from the ship's computer, the guns sent harmless, nonexplosive shock waves pulsing down through the water to the ocean floor. As the sound impulses reach the boundaries between various rock layers, they are reflected back to the surface and detected by hydrophones. An array of 2,900 hydrophones was strung out on a three-kilometer-long plastic-covered cable, which also trailed the ship. The hydrophones measure in milliseconds the time it takes for the air guns' sharp sound pulses to bounce upward.

In the *Phaedra*'s instrument room, the data from each shot were printed out as a pen and paper profile of the interior of the sea bottom. The sharpest echo might be from granite basement rock 600 meters beneath the sand and other rock strata. The echoes were simultaneously translated to digital form and stored on computer tape for further analysis back on land.

Working with measurements of the time taken by the shock waves to travel from the air guns to the reflecting layer and back to the hydrophones, computer processors sort and sift and study the data from every angle and produce maps of the strata several thousands of meters below the ocean floor. One of the maps produced from *Phaedra*'s mission revealed subsurface features 175 kilometers off the New Jersey coast that might hold as much crude oil as the rich East Texas field.

The technology of seismic reflection profiling developed by the petroleum industry is now being used to probe even deeper. In the early 1970s, it became apparent to a number of university scientists that seismic mapping techniques might, with slight modification, be applied to the geologic exploration of the hard rock "basement" of the continent. Whereas petroleum prospectors were satisfied mapping the depths of 10 to 15 kilometers, the scientists wanted to look at levels at least 40 to 50 kilometers down, and eventually all the way to the bottom of the lithosphere itself, which is presumed to be in most places about 100 kilometers deep. This includes not only the crust but a portion of the upper mantle of Earth.

Accordingly, in 1974, scientists organized the Consortium for Continental Reflection Profiling (COCORP) to conduct experiments in mapping the continental basement. The National Science Foundation provided the financial support.

The first experiment took place in March 1975 in Hardeman County, Texas, midway between Amarillo and Wichita Falls. "We selected the site primarily because of its good reflection properties," said Jack Oliver, a Cornell University geologist who was chairman of the consortium. "During exploration for oil in that vicinity, echoes were occasionally recorded for extended periods. These indicated that there were strong reflecting horizons at considerable depths. We designed our own profile experiment to record echoes for 15 seconds, compared with the industry practice of 6 seconds or less, so we would have a theoretical depth capability of 45 kilometers."

The Hardeman results were encouraging, dispelling any initial doubts as to the capability of seismic profiling techniques in hard rock (as opposed to the sediment basins probed in petroleum exploration) and at greater depths. The Vibroseis system of continuous seismic profiling was employed by the consortium scientists. They obtained data along three lines, for a total of 37 kilometers. The data disclosed the presence of a number of homogeneous, irregular-shaped bodies in the rock basement at depths of 12 to 33 kilometers. The scientists suggested that these were solidified igneous "plutons" that had intruded in molten form into the already formed rocks that make up most of the crystalline basement in that area. Strong reflections showed up at depths of 33, 37, and 43 kilometers, the deepest of which may have been a layer associated with the Mohorovičić discontinuity, the boundary between the crust and upper mantle.

The following December, after the Hardeman success, the consortium and its contractor for this phase of the work, the Petty-Ray Geophysical Company, turned their attention to a site of greater geologic interest: the Rio Grande Rift in central New Mexico. This is a long, wide trough that extends from Mexico to Colorado, its principal surface feature being the river by the same name. Like other rift systems, it is a region of instability—micro-earthquakes, numerous thermal springs, and a gradual swelling of the surface.

The Rio Grande experiment produced data from some 25 million individual reflection points. Deep reflections were recorded and mapped at depths of 36, 44, and 51 kilometers. At the extreme western edge of the profile, at depths below 21 kilometers, the scientists detected what may be a lava, or magma, chamber that could be responsible for the area's hot springs and uplifting terrain. The mapping of magma chambers is important because they are a potential source of geothermal energy, could evolve into full-fledged volcanoes with surface eruptions, and may be a major factor in concentrating minerals and other resources in zones immediately above them.

The work of mapping the continental basement has only begun. It will be many years before any mapmaker can sit down and draw with any certainty the contours of the bottom of the continental crust—the flip side, as it were, of a surface relief map of the United States. But someday this should be possible through an extension of seismic mapping techniques.

Even sooner, such techniques are expected to produce detailed subterranean maps, revealing for the first time the shapes and natures of continental underpinnings. These maps should be major interpretive tools of geology for decades to come. The most attractive single feature of the continuous seismic-reflection-profiling technique, according to the consortium scientists, based on their first experiments, is that it generates data in a form immediately recognizable to geologists.

"We think the big plus for our project is that it yields the highest resolution of any geophysical technique," Oliver explained. "There are other ways of getting information about the deep crust, like measurements of magnetic and gravitational anomalies, and studying the behavior of seismic waves from earthquakes and underground nuclear tests. But none of these other techniques yields information that *looks* like the geological things we see at the Earth's surface.

"Our game is to get detailed information on the deep rocks that has the resolution and structural detail of the shallow basement rocks and outcrops we know about. What seismic reflection profiling really does is extend the eyeball of the geologist from the surface to the subsurface, by providing the highest possible resolution of the fine structure of the deep crust."

This is only one example of an incredible new dimension of modern mapping. Cartographers are now able, with increasing confidence and precision, to map the unseen and thereby claim new worlds for human contemplation.

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