The World's Deepest Well

Now at 12,000 meters, a research well at Kola in the Soviet Arctic has revealed the cause of a seismic discontinuity and has pioneered drilling techniques for the deep exploration of the earth's crust

by Ye. A. Kozlovsky

Since 1970, on the barren rock of the Kola Peninsula 250 kilometers north of the Arctic Circle in the Murmansk region of the Soviet Union, a drilling derrick as tall as a 27-story building has been driving a well into the Baltic continental shield. The drill bit, grinding through crystalline rock for more than half of its journey, has now carried the bottom of the well to below 12,000 meters. The Kola "superdeep" well is the world's deepest. It is deeper by far than the 1,500- to 7,000-meter wells usually driven to prospect for or to extract oil, coal, iron, the nonferrous metals, diamonds and other treasures of the earth.

The first treasure sought by the Kola well is understanding of the deep structure of the continental crust and the forces that have shaped it through four billion years of geologic history. Present understanding derives in large part from the sample of the earth's crust, about 15,000 meters of its average 30,000-meter depth, that is exposed here and there at the surface. The velocity of seismic waves, increasing with the depth of burial but varying with the constitution of the rock, and the readings of instruments flown by aircraft and earth satellites that sense the gravitational and electromagnetic fields of the earth all tell a great deal more about what is hidden below. There is no substitute, however, for direct observation of what is deep in the earth and what is going on down there now.

The Kola well has traversed 1.4 billion years of earth history through the Proterozoic era into Archean rock 2.5 to 2.7 billion years old. It has exposed half a dozen cycles of crust building that brought new igneous rock into the crust from the molten mantle below, then broke it down by weathering and glaciation, sorted it and redistributed it in sedimentary strata, and then reconsolidated it to crystalline rock again in the metamorphism induced by the heat and pressure of the next intrusion of igneous rock. The rock samples, brought to the surface with difficulty that has increased with depth, establish a general thermal model of the evolution of the crust through the period when the main features of the earth's continental shields were laid down. The record makes it possible to determine the composition of the primitive crust at Kola, at least; that proves to have been granodiorite, an igneous rock somewhat poorer in quartz than granite is.

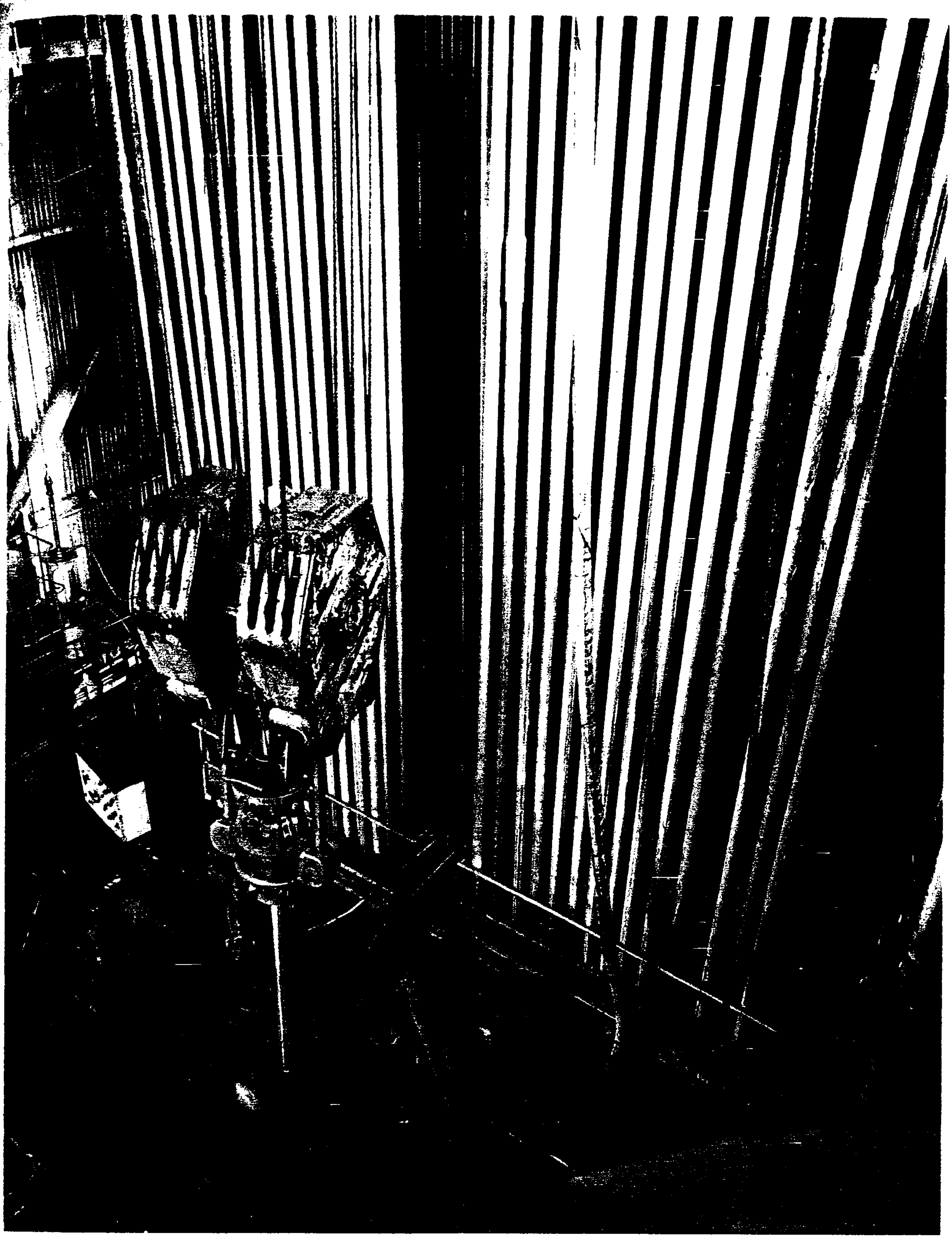
A major objective of the Kola well was to penetrate through the upper crustal layer of granite into the underlying basement rock of basaltic composition. Basalts are less often found at the surface, and the presumed basaltic basement is nowhere exposed on the continents. The boundary is thought to be marked by an abrupt increase in the velocity of seismic waves that has been observed around the world at midcrustal depths. At the Kola Peninsula the shift in velocity occurs at 9,000 meters. The Kola well was the first to cross that boundary. It did not, however, find basalt below it.

Instead the well had come to the bottom of an anomalous zone of disaggregated metamorphic rock it had first penetrated at 4,500 meters. As it worked its way through this zone the well encountered surprising, copious flows of hot, highly mineralized water. Such water—"water of crystallization"—comes from minerals making up crystalline rock; it is released as the constituents undergo dissociation and reassociation in the kneading and baking of metamorphism. Metamorphic water plays a major role in the genesis of ores. Ordinarily it finds its way out of the metamorphic formation and deposits its mineral burden higher in the crust. At Kola the water was trapped at the site of its liberation by layers of overlying impervious igneous rock two kilometers thick. To squeeze the water back into the rock would require pressure that is found only deeper in the crust or in the upper mantle. Since the tensile strength of the rock is a fraction of this hydraulic pressure, its dehydration was accompanied by microfracturing. This phenomenon of the hydraulic disaggregation of metamorphic rock, never before observed, may have a significant place in the structure of continents.

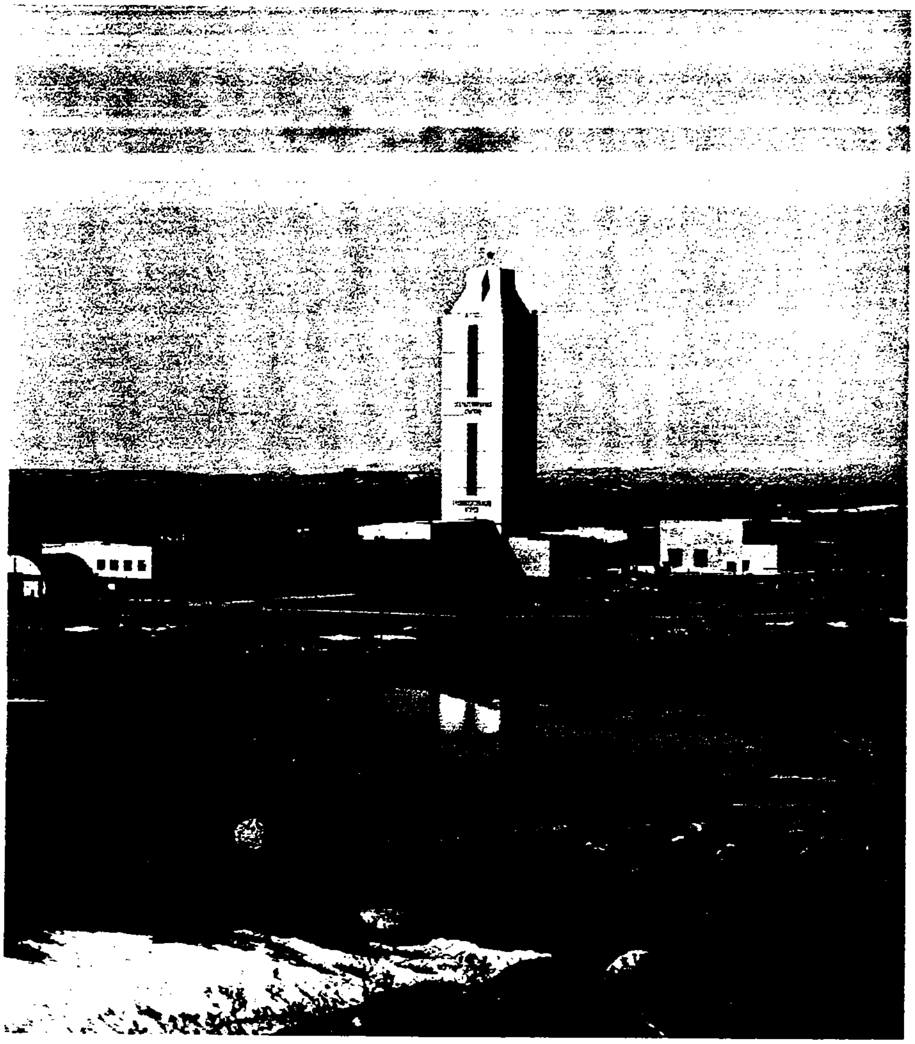
In the flows of mineralized water encountered in the zone of disaggregation and in thin, sharply defined formations below, and in the evidence of mineral deposits that was revealed at other levels, the Kola well demonstrates that man has barely scratched the surface in his search for minerals. Immense resources lie at depths awaiting the technology to reach them.

The descent of the well also released flows of gas at all levels. Among the gases identified are helium, hydrogen, nitrogen, methane and other hydrocarbons, and carbon dioxide. The light elements in these gases came, of course, from the crystal structure of the rock by the same metamorphic processes that freed the water. That there were two sources for the carbon dioxide is suggested, however, by its carbon-isotope composition. The presence of fossil microorganisms in the Proterozoic rocks, hundreds of millions of years old, indicates that the second source of the carbon dioxide was biogenic.

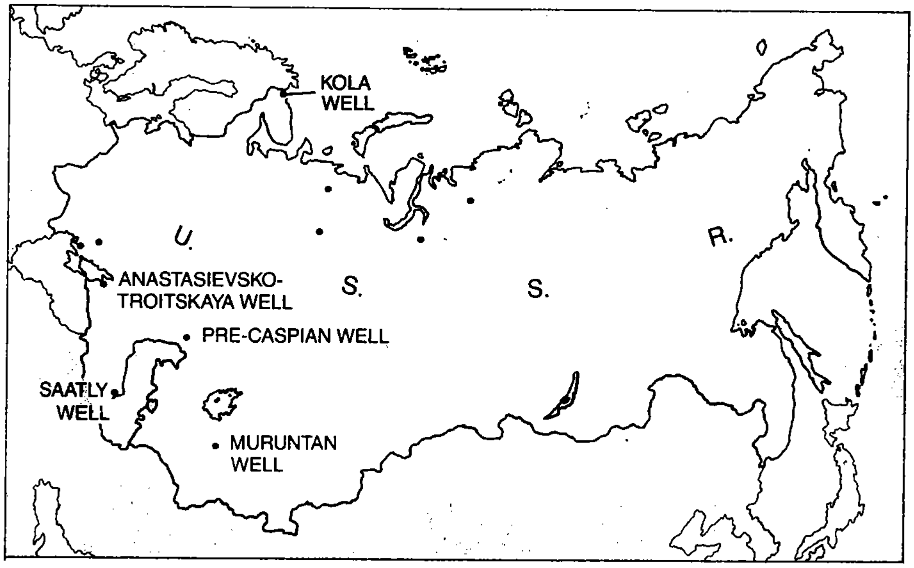
The drilling of the Kola well inaugurated a long-term program of systematic drilling of the deep structure of the earth's crust in the territory of the U.S.S.R. that will continue into the next century. Under the auspices of the Interdepartmental Council for the Study of the Earth's Interior and Superdeep Drilling, geologists and mining engineers undertook in 1962 to develop the technology for the drilling and study of deep wells. In 1970 drilling began at Kola and at Saatly in the Baku oil and gas district on the Caspian Sea, where the well has penetrated to 8,500 meters. A deep seismic survey of the Soviet territory has meanwhile helped to establish the sites of the other deep and su-



WELLHEAD AT KOLA is flanked by sections of aluminum-alloy drill pipe. The photograph was made within the drilling derrick that rises above the wellhead and supports the drill string; the structure is 86 meters high, with a capacity of 400 metric tons. The power unit for the drill, situated at the bottom of the well, is a turbine driven by the high-pressure flow of drilling mud pumped from the surface.



DERRICK HOUSING stands 30 stories above the tundra at the Kola site, 250 kilometers north of the Arctic Circle. The enclosure keeps the wellhead above freezing for year-round drilling.



DRILLING SITES selected for a comprehensive study of the earth's crust dot the U.S.S.R. With technology developed in the drilling of the 12,000-meter well at Kola and the Saatly well on the Caspian Sea, which has reached a depth of 8,500 meters, three more wells will be drilled to depths of more than 7,000 meters at the labeled sites. At the same time wells of lesser depth will be bored at other locations (*unlabeled dots*). The wells all lie at the intersections of recent seismic profiles and will add to an understanding of the genesis of ore and hydrocarbon deposits.

perdeep wells that are now to be drilled.

A better understanding of the deep structure of the crust will yield methods for predicting the occurrence of and prospecting for mineral deposits and oil and gas fields at depths far below those exploited today. As the Kola well has shown, mineral resources may be found at great depth. An essential objective of the research enterprise, therefore, is to develop technology for penetrating the earth's interior to depths of 10,000 to 15,000 meters.

On the global scale the earth's crust is thin enough: a mere 35 kilometers in a radius of 6,000 kilometers. Seismic and other indirect evidence seems to confirm the hypothesis, put forward in 1926 by the British geophysicist Harold Jeffreys, of a three-layered—sedimentary, granitic and basaltic—continental crust. The correlation of the density of rock samples measured in the laboratory with the velocity of seismic waves observed in the field gives a density of 1.8 to 2.5 grams per cubic centimeter and a velocity of about five kilometers per second for sedimentary rock. Density and velocity rise to 2.5 to 2.75 grams per cubic centimeter and five to six kilometers per second in granitic rock. At the so-called Conrad discontinuity the velocity of seismic waves rises to six to seven kilometers per second; this has been taken to mark the transition to the basaltic layer with a density of 2.75 to three grams per cubic centimeter. The granitic layer, composed of the lighter elements oxygen, silicon and aluminum, was laid down in the Archean era and is widely developed on the surface of the continents. While the continental crust may thicken to 70 or 75 kilometers under mountain ranges, the oceanic crust has a depth of only five to 10 kilometers; it is commonly thought to be composed of the basaltic layer overlain by deposits of sediment.

Below the continental and oceanic crust the Mohorovičić discontinuity in the velocity of seismic waves locates, it is supposed, the top of the mantle. The velocity rises abruptly to 7.8 kilometers per second and increases in jumps to 13.6 kilometers per second down through the upper (35 to 300 kilometers), the middle (300 to 950 kilometers) and the lower mantle (950 to 2,900 kilometers). The density of the mantle rock ranges correspondingly from 3.3 to 5.9 grams per cubic centimeter. From the direct evidence of volcanic rock as well as from indirect evidence supplied by meteorites and geophysical and astronomical data, the mantle is thought to be composed of magnesium and iron silicates down to a depth of 1,100 kilometers. At lower levels sulfides and oxides of iron, copper, zinc, lead, mercury, antimony and bismuth, as well as selenium, tellurium, gold, silver and other heavier metals, predominate. Temperatures in the upper mantle range apparently from 1,000 to 1,500 degrees Celsius, and the pressure at those depths reaches 100,000 atmospheres.

To test and extend the picture of the earth's crust put together from indirect evidence, geologists have yearned to sink wells to the Conrad and the Mohorovičić discontinuity beyond. The Kola Peninsula was chosen for the present enterprise because the Baltic shield there is representative of the ancient granitic continental plates of India, North America, southern Africa, western Australia, Antarctica and Greenland. The well site also lies in the Pechenga copper- and nickel-ore mining region, and it was hoped that a well there would throw light on the genesis of those ores. The region, exposed to glaciation and weathering for hundreds of millions of years, has lost 5,000 to 15,000 meters of the upper portion of the granitic layer by erosion. Thus the 12,000-meter geologic section of the Kola well corresponds to an "average" continental layer at depths of between 8,000 and 20,000 meters below the surface.

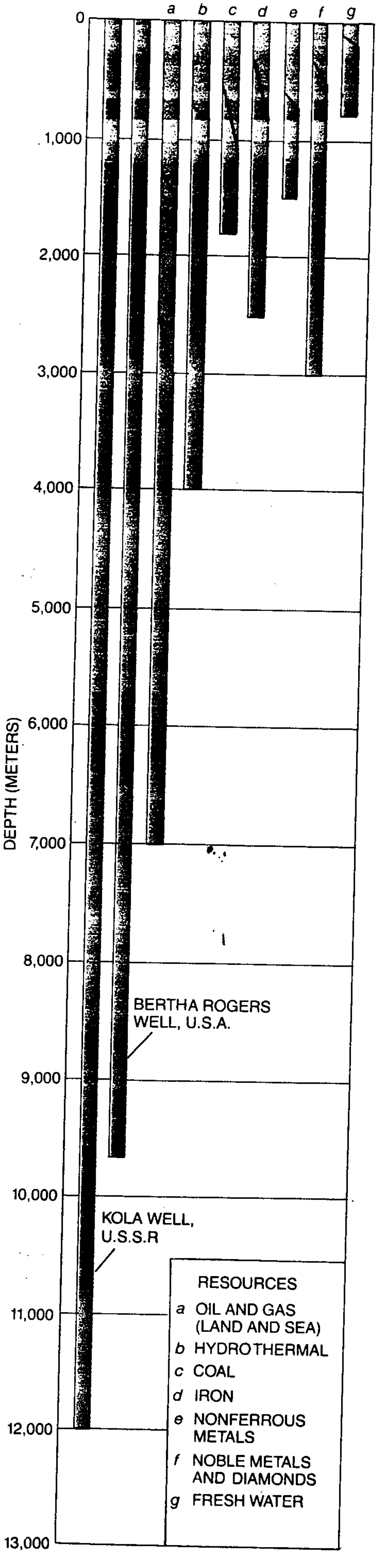
The sinking of the Kola well has induced significant innovations in drilling technology. Below 10,000 meters conventional rotary drilling, which turns the bit at the bottom by rotating the entire drill string, encounters disabling difficulties. The 800- to 900-metric-ton weight of the steel-pipe string sets up enormous stresses at the surface and amplifies the forces resisting rotation of the string. In the Kola well a bottom-hole turbine, driven by the flow of the drilling mud, turns the bit. Rotation of the string is eliminated entirely or is reduced to a few turns per minute, summoned to back up the turning of the bit by the turbine.

The drilling mud in an ordinary well is pumped down the inside of the drill string to cool the grinding bit and entrain the cuttings; it returns to the surface by way of the annular space between the drill string and the wall of the well and in the process helps to maintain the integrity of the wall. In the Kola well the mud is pumped to the turbine at a pressure of 250 atmospheres. A reducing gear under the turbine in the string lowers the rotation of the bit three or four times below that of drills in conventional wells to an optimal 80 to 150 revolutions per minute and correspondingly increases its rotation moment. A hydraulic feedback line in the pumping system, transmitting pressure surges in the drilling mud at 1,500 meters per second, controls the rotation of the turbine and the string and thereby the speed and moment of the drill bit. Noise filters of original design ensure reliability of control at a depth of 12 kilometers.

The drill string, made of a high-strength aluminum alloy, weighs only 400 or 500 metric tons. This is a great advantage, since the replacement of worn-out bits or the recovery of core samples requires that the entire string be pulled to the surface and lowered to the bottom again hundreds of times. To accomplish the penetration of the Kola well to 11,000 meters, the total length of drill pipe run through the well mouth in the course of such round trips exceeded 25 million meters. Apart from reduction of the burden on the derrick, the lighter weight of the string decreases the wear on the string itself and on the casing and wall of the well brought about by friction in all this travel. That wear can be considerable, for drilling never proceeds perfectly vertically. The Kola well drifted from the vertical by an average of five degrees down its passage to a maximum of 17 degrees at 10,000 to 10,500 meters; at that point the drill bit was 840 meters to one side of the wellhead [*see illustration at right on next page*].

The design of the Kola well itself had to respond to unpredictable changes in conditions as the drill bit worked its way down. While the first two kilometers of the well were cased [*see illustration at left on next page*], it became evident that greater freedom of movement and decision making would be necessary farther down. The result was the strategy of "open-hole advanced drilling." Below 2,000 meters the entire well has been drilled without casing.

Every piece of rock extracted from the deep earth has its value. As the Kola well deepened it became increasingly difficult to bring cores to the surface. Ordinarily cylindrical core samples 60 to 80 millimeters in diameter enter the drill tube as the bit erodes the ring of rock at the bottom; the core remains there in the barrel until the drill string is hauled to the surface. At sufficient depth, however, the rock "bursts" from the release of internal forces when the drill bit relieves the compression of the overlying rock strata that sets up those forces. If ordinary sampling equipment were used at such depths, pieces of the core would block the entrance to the core barrel, and 90 to 95 percent of the core would be ground into the drilling mud. A new core-sampling tool that diverts some of the mud stream into the core barrel catches the pieces of the burst core and carries them



WELLS AND MINESHAFTS vary in depth according to the resource sought. The bar graphs compare the median (*gray*) and maximum (*color*) depths to which shafts of each type have been sunk with the depth of the Kola well and the Bertha Rogers well in Oklahoma. That borehole, the world's second-deepest, was a gas well; drilling stopped at 9,674 meters when bit struck molten sulfur.

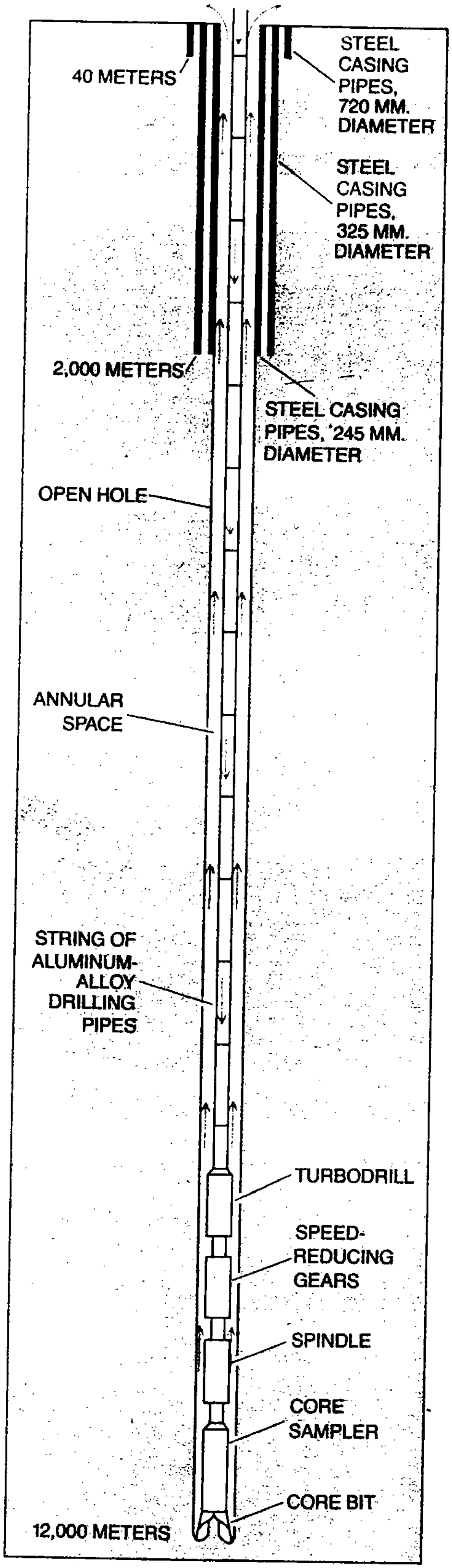
into a special chamber, clearing the entrance for new samples.

The technology now demonstrated at the Kola well opens the possibility of drilling to between 15 and 17 kilometers. New problems must, however, be anticipated. Ordinary aluminum alloys lose their strength at temperatures of between 110 and 150 degrees C. We have succeeded in developing alloys to withstand temperatures of between 230 and 250 degrees. Powder metallurgy promises aluminum alloys with temperature stability at the 270 to 300 degrees that must be anticipated as the well goes deeper. Titanium-alloy drill pipes may be made to withstand the 400-degree temperature that occurs at even greater depths.

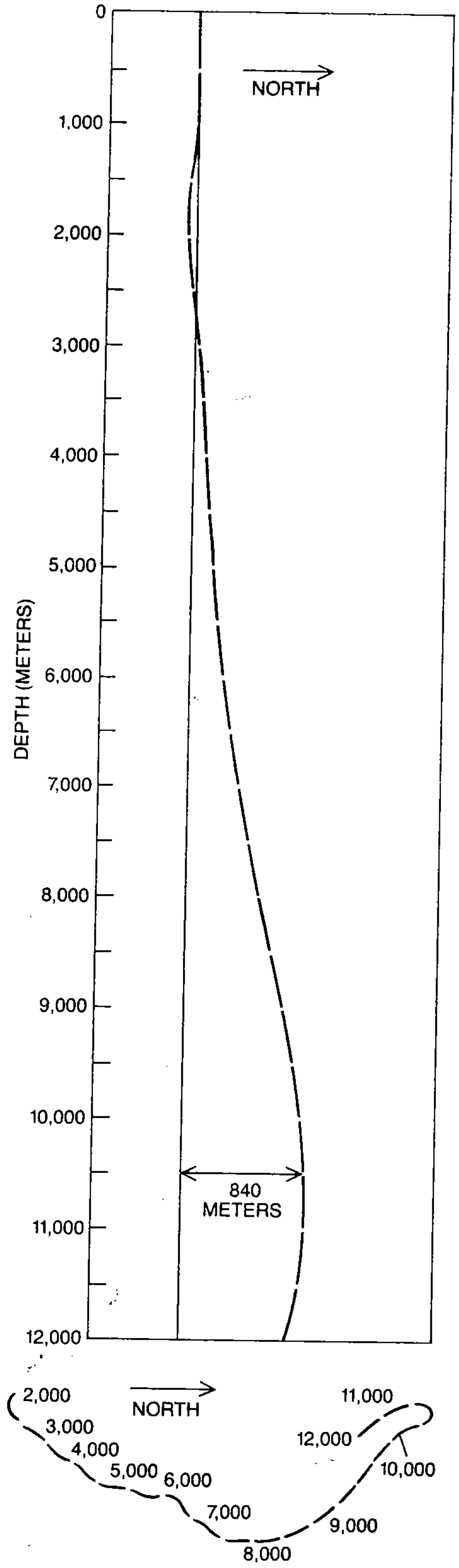
Along with high temperatures, technology for deep drilling must anticipate pressures reaching 3,000 atmospheres, corrosive chemical effects from highly mineralized trapped water, loss of stability in the rock mass around the borehole and deviation of the hole from the vertical. Retrieval of core samples to the surface becomes increasingly tricky. To solve this problem it is necessary to design a means to core and to transport rock samples in sealed containers that will preserve conditions prevailing at the hole bottom, including the saturation of the rock there with gas and water. A pressure chamber is now being developed in the laboratory to simulate the conditions that prevail at depths of 15 to 20 kilometers, that is, temperatures of 300 to 400 degrees C. and pressures of 2,000 to 3,000 atmospheres.

The earth history penetrated by the Kola well must, of course, be read from the bottom up. In the Archean complex, between 12,000 and 6,842 meters, the first stage saw the accumulation of thick sedimentary strata from the weathering of the primal granites, the weathering being punctuated by intrusive flows of plutonic granite. That these granites were rich in iron and titanium is evidenced in the concentration of magnetite and ilmenite ores, which reaches 40 to 50 percent of the rock at 8,711 meters. In the second stage the rocks underwent folding, metamorphism and ultrametamorphism at temperatures of 750 to 900 degrees C. and pressures of 5,000 to 11,000 atmospheres.

Geologists are able to reconstruct history in this way because rocks are highly sensitive recorders of temperature and pressure. From the same starting material supplied by the mantle, metamorphic rocks develop a variety of distinguishing characteristics, "facies," which may include variation in elemental composition, depending on the pressure and temperature at their formation. In general, metamorphism results in the production of denser rock with less bound water from more hydrous rock.



SCHEMATIC OF THE WELL shows the progressive narrowing of the hole. To a depth of 40 meters the hole was drilled with a bit nearly a meter across and walled with pipe 720 millimeters in diameter. Drilling proceeded with a 214-millimeter bit. The first 2,000 meters of the hole was eventually widened and cased with 325-millimeter pipe to control collapses. At greater depths the hole is uncased but is shored up by the pressure of the drilling mud, which flows down the pipe and back to the surface in the space around the pipe.



BOREHOLE TRAJECTORY, mapped in profile (*top*) and as horizontal wander in relation to the wellhead (*bottom*), departs from the vertical by a maximum of 840 meters, at a depth of 10,500 meters. Some drill-hole wander is inevitable, but it increases friction as the drill string is lowered into a borehole or removed for the recovery of core samples or the replacement of worn-out bits. Sensors incorporating gyroscopes and plumb bobs were used to measure the inclination of the hole and steer the bit in an attempt to reduce wander.

Elements not incorporated in the new crystal phases go into solution with the newly freed water.

Radiocarbon dating places the culmination of the Archean metamorphism in the Kola Peninsula at 2.7 to 2.8 billion years ago. It was followed by deep erosion by water and accumulation of sediments of the weathering crust in isolated depressions. In some regions of the world, notably South Africa, immense deposits of metal-bearing conglomerates are associated with such sedimentary deposits.

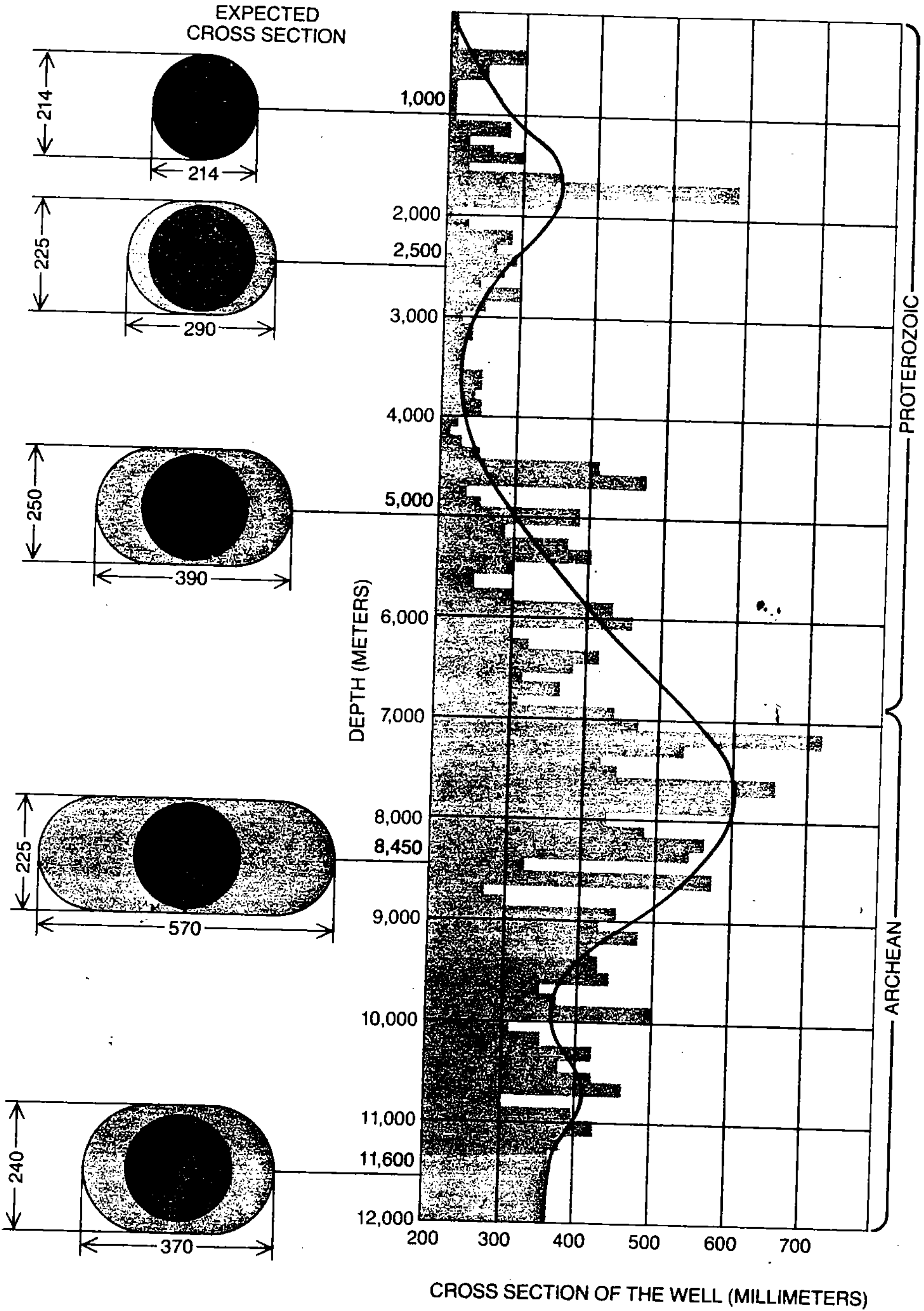
The Proterozoic complex, from 6,842 meters to the surface, began to build up on the Archean basement 1.1 billion years ago. The rock records four major phases in the buildup of the continental crust during this period. During the first phase, sedimentary volcanic material was deposited on the Archean floor. The gravelly strata show abrupt changes in thickness, indicating they were deposited by streams in ancient valleys. The first of two cycles of plutonism brought intrusion of granitic rock, devoid of metallic elements, that overlaid the previously formed rocks and brought them under alteration through low-temperature metamorphism. In the second cycle the mantle contributed rock rich in metallic elements. These ore-bearing intrusions laid down the copper-nickel sulfide deposits that outcrop in the Pechenga region. The Kola well found such deposits at intervals down to a depth of 1,500 to 1,800 meters. The fourth phase of the Proterozoic era brought on the anomalous episode of "closed" metamorphism that resulted in the hydraulic disaggregation of the metamorphic rock first observed in the Kola well through the zone 4,500 meters thick that crosses into the Archean basement.

Core samples show the content of chemically bound water remaining constant, at 4 percent of the rock, to 4,500 meters from the surface. There, quite abruptly, the water content of the rock decreases to 2.1 percent. It is there that the zone of disaggregation begins, with microfracturing of the rock increasing its porosity by three or four times over that observed in the rock above and correspondingly reducing he density of the rock mass from 3.1 grams per cubic centimeter to 2.9. The freed water trapped in the interstices of he fractured rock, calculations show, orced the initial total volume of rock and water to increase by 1.7 percent. The enormous hydraulic pressure thus xerted caused the microfracturing that must initially have increased the porosiy of the rock to 10 times that of the verlying strata.

The lower boundary of this zone, at ,000 meters, is marked by an increase n the velocity of the seismic waves. This roved, of course, not to be the presumed Conrad discontinuity from granitic to basaltic rock. The increase in elastic-wave velocity simply marks the bottom of the zone of disaggregation with the return to rock of normal density and the cessation of the inflow of thermal water into the well.

The value of a firsthand look at the interior of the earth is amply demonstrated by this discovery. Hydraulic disaggregation of metamorphic rock may explain the geologic nature of boundaries marked by changes of elastic-wave velocity and reflection of such waves observed around the world in the upper part (down to 15 or 20 kilometers) of the earth's crust. Moreover, this phenomenon must substantially change notions about water circulation in the continental crust and the nature of the subsurface hydrosphere.

The high mineral content of the fissure waters and the flow of gases in the well show that active gas-water processes proceed in crystalline rock at great depths. The prospects for the discovery of new ore deposits at those depths are raised correspondingly. In the zone of

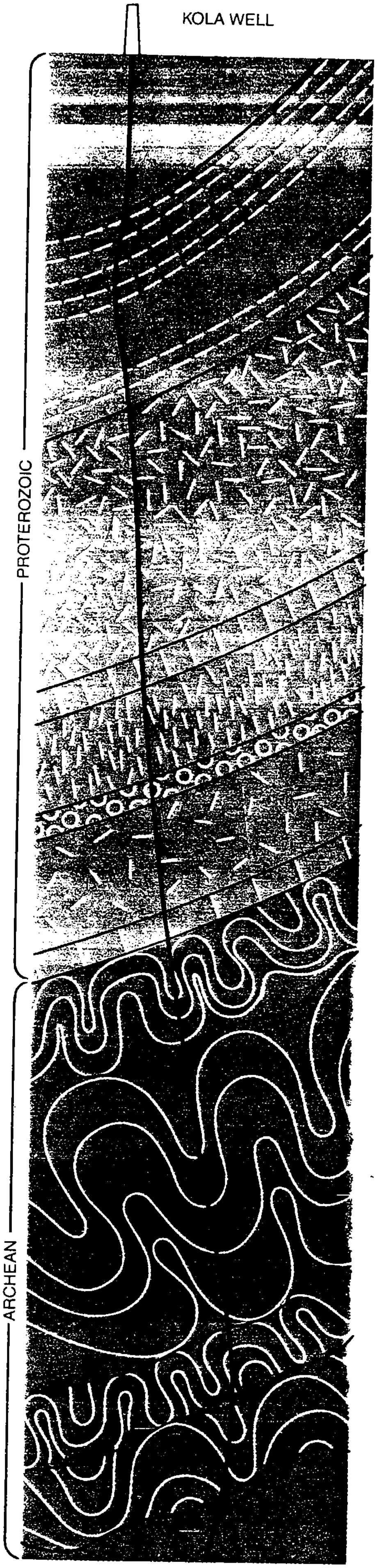


CROSS SECTION OF THE BOREHOLE changes with depth, although bit diameter was constant. The bar graph (*right*) shows caliper measurements of the hole across its greatest diameter at each depth; the curve charts the trend. The generally elliptical shape of the hole represents the resolution of unequal horizontal compressive forces in the rock; the hole's short axis corresponds to the direction of the greatest force. The rock spalled and burst along the axis of lesser force, widening the hole and yielding fragments that were swept to the surface in the drilling mud. The magnitude of the effect varied with changes in rock pressure and character.

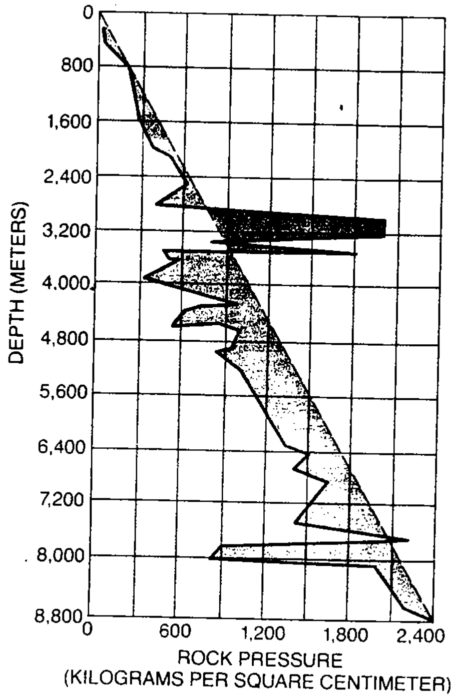
disconsolidation in the Kola well the rock fragments are cemented by sulfides of copper, nickel, iron, zinc and cobalt. The relatively low temperature of formation of these sulfides and the isotopic composition of the sulfur, which resembles that of meteorites, suggest these sulfides were generated by the mantle. Favorable conditions for the formation of hydrothermal ore deposits thus prevail through an extensive vertical range in the continental crust.

Direct measurement of temperatures in the well compels revision of ideas about the distribution and flow of heat in the earth's interior. It has been supposed that in a tectonically stable region such as the Baltic shield the temperature would increase only slowly with depth, rising to 50 degrees C. at 7,000 meters and perhaps 100 degrees at 10,000 meters. In fact the measured temperature gradient fit the expected one-degree increase every 100 meters down only to 3,000 meters. From there temperature began to rise by 2.5 degrees every 100 meters. At 10,000 meters it reached 180 degrees. Hundreds of cubic meters of cold drilling mud pumped into the well returned to the surface heated to 45 degrees. Since the radioactivity of the rocks traversed by the well can make only insignificant contribution to this heat flow, it must plainly come from the mantle below.

The success of the Kola well has instilled new confidence in plans for the systematic deep and superdeep drilling of the earth's crust encompassed by the borders of the U.S.S.R. [*see bottom illustration on page 100*]. Sites for the wells have been chosen at the crossing points of a network of interlinked seismic profiles, including the contributions from an extensive program of deep seismic soundings that has been carried out over the past decade.



GEOLOGIC STRATA through which the borehole passes encompass 1.4 billion years of earth history. The sedimentary and volcanic rocks found at depths of up to 6,800 meters (*gray*) date from the Proterozoic era, which began 2.4 billion years ago. The deeper granitic strata (*pink*) were laid down as long ago as 2.7 billion years during the Archean era, the first era of geologic time. It was expected that the well would pass from granitic rocks into a basement layer of basalt at a depth of 9,000 meters, where an abrupt change in seismic-wave velocity occurs. Instead it was found that the velocity change marks the base of a 4,500-meter-thick zone of rock that has been shattered by the pressure of water driven from crystalline minerals during metamorphism.



ROCK PRESSURE, derived from measurements of acoustic-wave velocity through the rock near the hole, frequently deviates from the linear increase with depth (*dotted line*) expected in homogeneous material. The zone of anomalously high pressure at a depth of 3,200 meters reflects the high density of impervious strata at that depth. The disproportionately low pressures from about 4,000 to 9,000 meters mark a zone of fractured rock.

The drilling of the wells will help, in turn, to perfect the interpretation of seismic data. Direct readings on conditions and core samples from the wells will establish secure correlation between geodynamical boundaries in the earth's crust and upper mantle and observed structural and compositional boundaries and contacts. This work will help also to improve the resolution and accuracy of seismic recordings and thereby increase the amount of information that can be extracted from indirect geophysical observation. Anomalies in the propagation and velocity of seismic waves not correlated with structural data from the wells may present significant new questions for study.

Drilling will continue at the Kola and Saatly wells. They will serve as laboratories for intensive study of the physiology as well as the anatomy of the crust at those sites. The next three superdeep (more than 7,000 meters) wells are to be drilled at Muruntan, Anastasievsko-Troitskaya and near the Caspian Sea. The drilling of six deep (more than 4,000 meters) wells will proceed simultaneously, three of them in gas- and oil-bearing regions and three in ore-bearing regions. Thus in addition to answering fundamental questions about the structure of the continental crust, the deep seismic profiles combined with direct observation in the deep and superdeep wells will assess major geotectonic elements in the U.S.S.R. considered to hold significant resources.