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# Deep Seismic Sounding with Nuclear Explosives in the Soviet Union

J. F. Scheimer and I. Y. Borg

*Summary.* A large geophysical program of exploration that uses deep seismic sounding has been under way in the Soviet Union for decades. Underground nuclear explosives have been used as strong seismic sources since 1971. The wide spacing between these seismic sources—for example, 500 kilometers—has permitted seismic exploration of inaccessible areas in traverses up to 3000 kilometers in length. During the same time an ultra-deep drilling program has also been under way. The data gathered have been used to elucidate details of the crust as well as to describe layering and inhomogeneities in the underlying mantle. By Soviet account, deep seismic sounding has been instrumental in confirming the existence of numerous sedimentary structures containing oil and gas fields in western and eastern Siberia.

The Soviet Union has a long tradition of conducting deep seismic sounding by conventional methods, that is, high explosive sources, to generate signals for reconnaissance exploration of the country. Incompletely appraised Soviet resources lie principally east of the Urals, in Siberia and the Far East. It is estimated that development of those resources currently consumes one-seventh of the country's total capital investment budget (*1*). The size and undeveloped aspect of much of the country make exploration difficult. The virtual inaccessibility of large portions of the country during part of the year causes additional problems in placing seismic equipment in the field and carrying out continuous seismic surveys. Very strong seismic sources that can be recorded by widely spaced arrays and that allow the use of significantly longer lines of seismic recorders have obvious advantages. In addition, a strong signal is desirable since greater crustal detail can be extracted if seismic waves are recorded that are converted from *P* (pressure) to *S* (shear) waves at discontinuities in the earth where wave velocities change. The use of such large sources also shifts the predominant frequency of recorded signals to lower frequencies, that is, 1 hertz.

### The Soviet Program of Peaceful Uses of Nuclear Explosives

The Soviet deep seismic sounding (DSS) program, for which nuclear explosions are used as the source of strong seismic signals, is part of the Soviet program of peaceful uses of nuclear explosives. The program was the focus of considerable attention during the negotiations for the Threshold Test Ban Treaty (TTBT) and the Peaceful Nuclear Explosives (PNE) Treaty during the 1970's. Throughout the negotiations the Soviets insisted on the right to continue their program, including the use of high-yield and multiple explosives. The PNE Treaty negotiations were concluded in 1976, but, like the TTBT, the treaty was not ratified by the United States. Nonetheless, both countries indicated a policy of adherence to the TTBT prohibition on tests with yields greater than 150 kilotons. Without treaty ratification, however, exchange of information called for by the PNE Treaty has not been forthcoming.

Although the Soviets continued the nuclear DDS program during the negotiation period, there were only a few published accounts of the results or even references to the use of nuclear explosives (*2*). In contrast, other applications of nuclear explosions up to that time were described in some detail during the international exchanges (*3*). The reasons for failure to describe the DSS technique, its results, and its value may relate to initial difficulties in reducing and synthesizing the vast amount of data acquired. However, by 1977 several long, deep seismic refraction lines had been described. These lines coincided with a series of strong signals recorded by various international seismological observatories and were attributed to nuclear explosions. Detailed interpretations of these profiles have provided a model of the mantle to depths of 100 to 120 km, which is consistent with use of large sources, such as nuclear explosions.

It has been more than 12 years since the first seismic lines that are presumed to be based on nuclear explosions were recorded in the Soviet Union and considerable information is now available. Nonetheless, the Soviet program is unfamiliar to a large segment of the Western seismological community. In this article, we review what is known of this novel method of probing the deep crust and upper mantle of the earth.

### Soviet Deep Seismic Sounding Program

Seismologists in many countries (*4*) have undertaken programs of large-scale seismic exploration, but few countries have programs as massive as the Soviet DSS program. This began in 1939 with the first experiments in obtaining seismic records with durations up to 1 minute.

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J. F. Scheimer is head of the Seismological Research Center of the Institute of Geophysics and Planetary Science, University of California, Livermore 94550, and I. Y. Borg is a senior geologist, Lawrence Livermore National Laboratory, Livermore.

The early Soviet program involved strictly reflection experiments; the equipment and processing required for refraction experiments were developed during the next decade. By 1950, explosive sources in water were used to record the first true DSS lines in northern Tien Shan, Kirghiz S.S.R. The basic recording and interpretive methodologies did not change for many years.

No reversed profiles (*5*) were reported before 1953, when a description appeared of a seismic profile from northern Tien Shan (*6*). Through the 1950's and 1960's a number of lines were recorded, and the Soviet literature includes reports on the development of new instrumentation, including multichannel recording, noise studies to determine the best frequency ranges, and, eventually, the development of more sophisticated land and ocean-bottom recorders. Early analysis was focused primarily on wide-angle reflected *P* and *S* waves. Later analyses were extended to the first refracted wave arrivals as well as conversions of *P* waves to *S* waves.

The primary proponent of this early work was Gamburtsev (*7*). The first lines that he organized were often in mountainous areas and did not lend themselves to long, continuous profiles such as are usually used in refraction studies in the West, where instrumentation is set up every kilometer or so starting from the source. This gave rise to the deployment style known as "piece-continuous." In addition, Gamburtsev determined that most areas of the Soviet Union could be studied with chemical explosive sources and observed by recorders with responses in the range from 5 to 15 Hz. This initial determination was reinforced later by detailed noise studies conducted by the O. Yu Schmidt Institute of Physics of the Earth in the 1950's. The graphical interpretation methods originally used by Gamburtsev were employed on virtually all DSS lines into the 1970's (*8*).

## Observational Techniques

Soviet investigators differentiate between three types of observational techniques for DSS: continuous, piece-continuous, and point soundings, terms not commonly used in the West. Continuous recording is analogous to the multichannel deployments of seismic receivers used in reflection seismic exploration. In this deployment mode, from 12 to 96 recording sites are connected by cables to a central recorder, which is, typically, an analog or digital recording system, such as that used in normal oil exploration work. In these deployments, recording sites are changed after each new shot, but there is always some overlap with prior sites. Thus, as the line is extended, recordings are made for many combinations of shot and receiver separations. Spacing between the source and nearest receiver site and between the many receiver sites typically ranges from tens of meters to hundreds of meters. The area in which this type of deployment can easily be used is limited by the available cable lengths to lay the lines and the available manpower to move the receiver string between shots. The advantages of such deployments are that standard commercial oil prospecting gear can be used and that the crustal structure is delineated in great detail. The disadvantages are, clearly, great cost and limited line lengths.

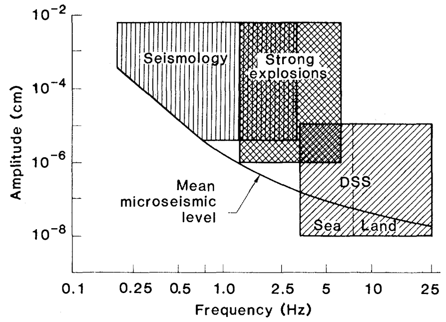

Fig. 1. Amplitudes and frequencies of waves recorded in deep seismic sounding for earthquakes and for strong explosions up to 10 kilotons (*33*). In order to record over very large distances with reasonable resolution, a high-amplitude source with a broad spectrum is desirable. Although earthquakes, labeled "Seismology," are possible sources, their use is impractical. Small, artificial sources, labeled "DSS," do not have the desired characteristics; hence the Soviets argue for the use of "strong industrial explosions."

One way to avoid the cost of continuous lines is to space out the continuous sections. In this mode of deployment, the areas between the continuous sections may either be unoccupied or filled in with single receivers. Along the sections of these lines that are continuous, one can recover phase velocity information about each identifiable wave group. This helps in determining which arrivals on the recorded traces should be correlated with one another (*9*). Lines that combine such densely sampled continuous sections with sparse recording sites in between are described as piece-continuous. For example, a 200- to 300-km profile with three to five source points may contain three to six segments, each 20 to 30 km long in which there are continuous recording arrays (*2*).

The third deployment method, point soundings, is directly comparable to typical crustal refraction studies in the United States. In this mode, individual stations are deployed at wide separation. For example, if shots are 500 km apart, individual recorders might be 7 to 12 km apart. In the Soviet Union these are typically self-contained analog recorders. This method is used both on land and at sea.

Each of these three methods of deployment lends itself to obtaining refraction lines of different lengths. The continuous method is quite expensive for long lines, and the point sounding method is designed for such lines. The tradeoff is, of course, in the detail that can be achieved. The piece-continuous method is a compromise.

The DSS program in the Soviet Union uses three types of sources: earthquakes, nuclear and chemical explosions, and truck-mounted vibrators. The frequency ranges and signal strengths associated with these three broad classes of sources are shown in Fig. 1. The regional surveys over roadless tracts use explosions of two sorts: detonations of TNT weighing up to 5 metric tons and "large industrial explosions" that are presumed to be in the kiloton range. These large shots are located along a proposed profile at intervals of 500 to 700 km; smaller TNT charges are separated by 60 to 100 km (*10*).

## Distinguishing Nuclear Explosions and Earthquakes on Seismograms

To assess the Soviet Union's use of nuclear explosions in the DSS program, the seismological community must be able to distinguish between large explosions and earthquakes. The study of discrimination between earthquakes and underground nuclear explosions is a significant segment of the research being conducted in support of test ban treaty verification. Though there is some difference of opinion as to the mimimum size of nuclear explosions and earthquakes that can be reliably differentiated, the general principles are clear (*11*, *12*). A major first-order discriminant is the depth of the event. The ultra-deep drill holes discussed below do not penetrate to depths greater than 15 km; even at a depth of 10 km, it would be extremely difficult if not impossible to emplace a nuclear device for a fully instrumented test. Also, earthquakes of magnitudes comparable to the sizes of the large sources used in DSS work (body-wave magnitude, $m_b \simeq 4.0$ to 5.0) are largely confined to well-known and well-defined seismogenic zones.

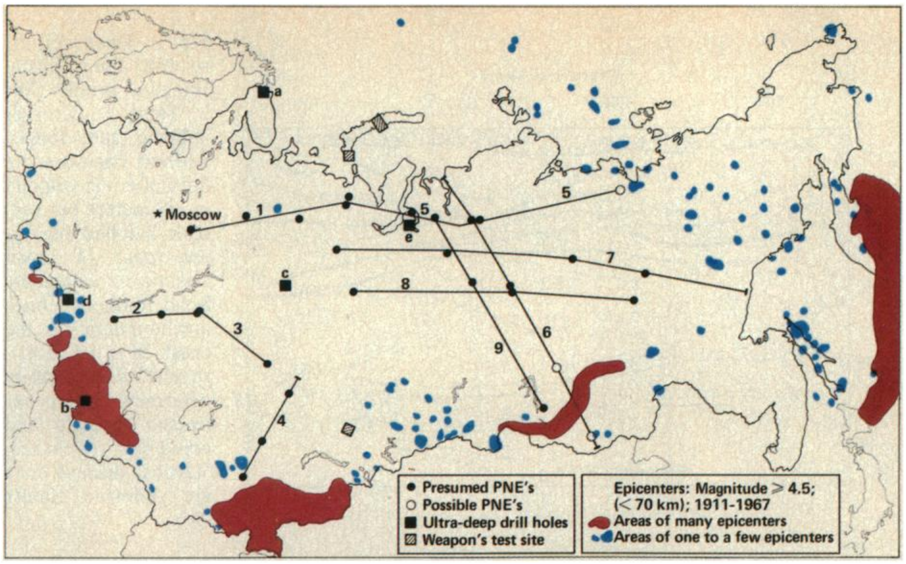

Fig. 2. Deep seismic sounding lines in the Soviet Union for which nuclear explosions were used. Regional seismicity indicated in color is from data compiled by the Military Geology Branch of the U.S. Geological Survey in 1972. PNE, peaceful nuclear explosion.

For those seismic events which, on the basis of depth, might be identified either as earthquakes or explosions, there are a number of well-known discriminants. Explosive sources are nominally spherical, isotropic sources of *P* waves, with little or no *S* wave production. This has significant effects on the observed seismic signals. The first effect is that the first arriving signal at all seismic recording stations will be compressional for the explosive source, whereas for earthquake sources there will be a quadrantal distribution of compressional and dilatational first arrivals. This discriminant is not 100 percent reliable, especially when the signal-to-noise ratio is small.

A more reliable discriminant, which also results from the relative dearth of shear waves produced by explosives, is the ratio of the magnitudes of surface to body waves ($M_S$:$m_b$). Body-wave magnitude is related to the amplitude of the *P* waves, and surface-wave magnitude is a measure of the amplitude of surface waves. Nonisotropic sources such as earthquakes produce relatively more surface-wave energy, so that the ratio of surface-wave magnitude to *P* wave magnitude is larger for earthquakes. There are other discriminants that can be applied, but these suffice for most events larger than $m_b = 4.0$.

Small chemical explosions underground are often not detected by national seismic networks. Although large chemical explosions are often recorded, the problem of distinguishing them from nuclear explosions has not been solved. One possible difference is related to the firing mode used for large chemical charges which results in a slow rise time. This could have a tendency to "smear out" the first arrivals at very nearby seismic stations. An example is the 2-kiloton chemical explosion at the Old Reliable copper mine at Mammoth, Arizona, in 1972, which was recorded by the U.S. Geological Survey National Earthquake Information Service (NEIS) as an event of $m_b \sim 4.5$. The charge consisted of 80,000 50-pound bags of ammonium nitrate that were placed at three levels in the mine.

In reviewing the Soviet DSS program we have relied on data published twice a year by the International Seismological Centre (ISC) in England as well as data published annually by the National Defense Research Institute in Sweden (*13*). The ISC compendium lists all probable explosions by region together with any confirming information, such as a U.S. Department of Energy announcement that a nuclear explosion was set off at the Nevada Test Site or that one was detected and identified in Russia. Reporting observatories are identified, and the recording time, epicentral coordinates, depth, and magnitude adopted by ISC are given.

Because the ISC catalog is not up to date, we used the Swedish publications to identify the most recent suspected nuclear explosions in the Soviet Union. A preliminary list of observed nuclear explosions is published by the Defense Research Institute in Stockholm, which has a branch involved in seismic discrimination and nuclear explosion monitoring. The seismic network is located in Sweden and operated by the Hagfors Observatory. Precise locations are given by NEIS, although NEIS does not identify whether the source of the event is an earthquake or an explosion.

## Unidentified Explosive Seismic Sources

Although Soviet literature rarely provides any detail concerning the specific seismic sources used in their DSS studies, in their general treatises on the subject widely spaced sources are described as "large industrial and special (atomic) explosion" (*2*, pp. 29 and 59). Because the term "industrial explosion" is often distinguished from TNT explosions and because "industrial explosions" in boreholes are described as "several orders larger than TNT charges, which can weigh 5 tons or more" (*14*), we have come to equate "large industrial explosions" in the Russian literature with underground nuclear explosions (Fig. 2). Although it is often possible to associate most DSS lines with nuclear explosions identified by ISC or the Hagfors Observatory, some long sections of a few lines are not associated with identified explosions. Nonetheless, strong artificial seismic sources are suspected to have been used because of the great distances involved, the large amount of structural detail described along the sections, and the uncommon depths in the mantle for which data are available—up to 120 km.

In these instances we examined the complete ISC listings of recorded earthquakes and inspected the data for events that could in fact have been explosions but were overlooked or not described as such in final listings. The time frame of interest was indicated by the timing of other nuclear explosions along the DSS line, since the lines have tended to be conducted between July and October of the same year. General criteria for identification as a DSS event included occurrence in a nonseismically active area of the Soviet Union, magnitudes ($m_b$) of 4.5 to 5.8, no report of an earthquake by any Soviet seismological station to ISC, and occurrence within a few seconds of the hour.

In recent years the presumed nuclear explosions have been set off late at night or early in the morning, probably to minimize disturbance to any nearby inhabitants and to ensure low background noise. The reported depth of origin of these events has not proved to be a useful parameter in recognizing man-made signals. Some of the likely nuclear DSS explosions identified from the other criteria discussed above have depths of focus such as 19 to 25 km or 33 km (*15*) in

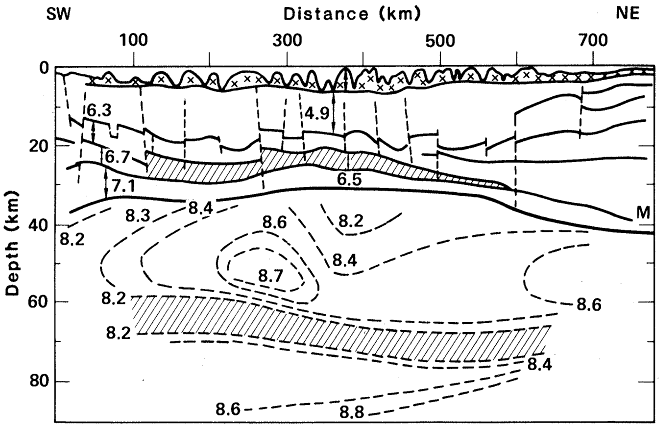

Fig. 3. Deep seismic section along Elista-Buzuluk profile (line 2, Table 1). Crosses indicate salt domes. Dashed contours are lines of equal velocity in kilometers per second; hatched regions are areas of lower seismic velocities. Solid horizontal lines are boundaries in the crust; M is the Mohorovičić discontinuity determined from refracted arrivals and converted phases. Vertical dashed lines are inferred faults (*34*).

international and U.S. compilations. Apparently uncertainties in depth are of this order for some signals—one reason why the ISC or Hagfors did not identify them as explosions. The three additional explosions thus identified are indicated on Fig. 2 as possible nuclear explosions.

## The Nuclear DSS Program Since 1970

By 1980 the Soviet DSS program had expanded appreciably. To date we are aware of nine long seismic lines that have been recorded presumably with the use of nuclear explosives (Fig. 2). Data collection and reduction from nuclear DSS lines has been done chiefly under the auspices of the Soviet Ministry of Geology. A group called the Special Regional Geophysical Expedition, Soyuzgeofizika or Spetzgeofizika, is associated with many of the published descriptions, and investigators from the O. Yu Schmidt Institute of Physics of the Earth in Moscow often collaborate in development of new analytical techniques or interpretation.

Eight of the nine seismic lines for which we are reasonably certain nuclear explosions were used have been described in varying detail in the Soviet literature. The use of nuclear explosions on the other one is deduced from the characteristic sequences of explosions, many of which have been recorded in areas devoid of an industrial base or known mineral or hydrocarbon development. The lines range from 800 to 3200 km in length (Table 1); the longest lines are the most recent. In at least one instance, line 7, which extends from the Ob River almost to the Sea of Okhotsk, five smaller chemical explosions apparently were part of the DSS line (*16*). A similar use of small chemical explosions may in fact be an integral part of other long DSS lines described in Table 1.

The first DSS line that we are aware of for which a nuclear explosion was used as a seismic source was started in July of 1971 near Vorkuta. Technical aspects and advantages of the use of nuclear sources had been discussed in the Russian literature before that (*17*). By 1973, Vol'vovski (*2*) included the one nuclear line in his list of DSS profiles between 1957 and 1971 (Fig. 2). At that time the highest density of lines by region was near the Black Sea in southern Russia, followed by the Caucasus, Ukraine, and the southeastern "sub-Urals." In 1971 the density in these regions was 8 to 9 km of DSS lines per 1000 km$^2$. By contrast the resource-rich western Siberia had a density of 0.7 km per 1000 km$^2$ (*2*, p. 11). Not surprisingly, deep seismic sounding after 1970 was focused in areas east of the Urals. Before 1970 most of the land area was investigated by continuous profiling methods. The length of travel time curves on the average did not exceed 300 to 350 km, and the depths probed rarely exceeded 50 km.

Ocean studies for which point sounding methods were used accounted for one-third of all DSS work conducted before 1971. In point sounding at sea smaller charges could be used to delineate structure than those required for comparable distances and depths on land.

## Results of the DSS Program

Although the principal impetus behind the Soviet DSS program is its usefulness in exploration, the bulk of the literature describing parts of the program focus on the structure of the upper mantle that has been deduced from the seismic data. This is a reflection on the use of the strong man-made sources (nuclear and chemical explosions) that permitted probing of depths of 150 to 200 km.

In the decade that nuclear explosions have been used, data analysis has improved considerably. For example, the Kineshma-Vorkuta profile studied in 1971 (line 1, Figure 2) shows a minimum of crustal and mantle detail. The analysis provided wave velocities at and locations of principal horizontal discontinuities and not much more. By contrast the Elista-Buzuluk line, run in 1972 and first

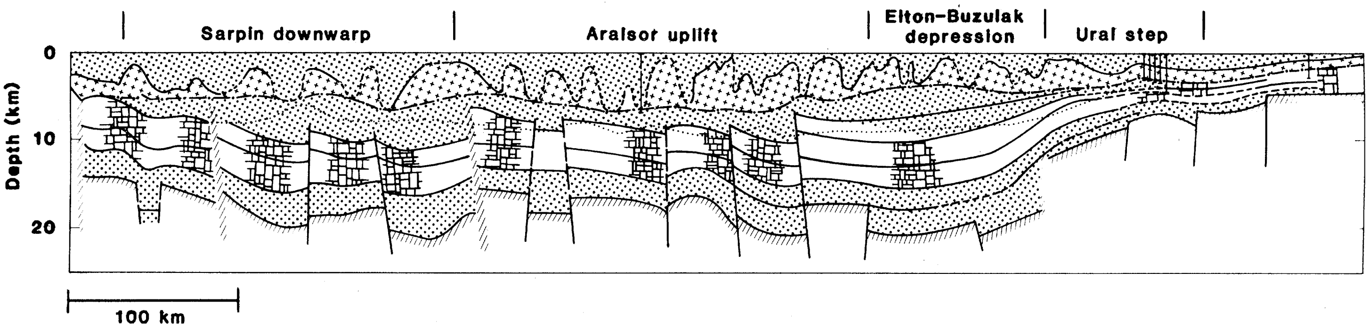

Fig. 4. Crustal detail along Elista-Buzuluk profile of Fig. 3. Crosses indicate evaporites; the dot pattern, clastic sediments; and the brick pattern, carbonates. Deep fault zones are hatched, whereas other faults (solid lines) and probable faults (dashed) are inferred from seismic data. Existing drill holes are indicated. The dotted quasi-horizontal line in the sediments beneath the evaporites is the P1 seismic horizon, which is the top of the carbonate complex [modified from (*35*)]. The crustal detail suggests the use of conventional DSS sources.

described in 1977 (*18*), shows detailed structure (Figs. 3 and 4), as does the Vorkuta-Tiksi DSS line described a year or so later (Table 1). The increased detail is due to the improved developments in recording and interpreting the complex data. The Kineshma-Vorkuta data were collected by portable six-channel systems that used three-component sensors and the "Taiga" magnetic recording system (*19*). By the late 1970's at least six additional channels were used, and more receiving stations were equipped with digital recording equipment.

Regional seismic studies have provided much new information on the structure of the crust and mantle. Even when distances between stations are large, 5 km, for example, resolution of the data allows identification of structures 60 to 80 km long. For example, the large Kotui trough in northwestern Siberia was first identified from such data, and the existence of the Kochechum-Turinsk basin in east Siberia was confirmed. In the ideal situation, data from analysis of large, widely spaced explosions are combined with data from seismic sounding of a more conventional sort. Information from other types of geophysical surveying, such as gravimetric, aeromagnetic, or electrical resistivity, must be integrated with that from the seismic networks. Logging in stratigraphic wells is also critical to a complete picture. By all accounts this is currently a weak link in the exploration effort in the Soviet Union (*10*). Nonetheless, in eastern Siberia alone, in the past 20 years DSS has been reported as confirming ten gas and gas condensate fields at 15 explored sites within the Yenisei-Khatanga trough and another ten at drilled locations within the Vilyui "syneclise" (*20*) and adjacent Verkhoyansk trough to the east.

The area occupied by the Tunguska syneclise has proved particularly difficult to probe by conventional means because of numerous magmatic traps and extensive unconsolidated tufogene, or volcanic aerial, deposits. Data obtained at 70 percent of the sites could not be interpreted because of excessive seismic "noise" and the very low amplitude of useful reflections. Four nuclear DSS lines (lines 6, 7, 8, and 9 in Table 1) cross a part of the syneclise, but detailed profiles have not been published outside the Soviet Union. Considerable information concerning the upper regions of the mantle has been gained from analysis of the nuclear DSS shots. Yegorkin and coworkers from Soyuzgeofizika have been at the forefront of this effort for almost a decade. Among other results, uplift of the Mohorovičić discontinuity (Moho) has been confirmed in regions with large platforms and troughs. Lowered velocities in the mantle beneath the Moho have also been observed in orogenic or rift zones—for example, at Lake Baikal (*22*). Velocities in the mantle are thought to vary below almost all ancient platforms in the Soviet Union (Fig. 5). The low velocity zones shown in Fig. 5 are inferred from travel times because of difficulties in interpreting the amplitudes (*21*). Nonetheless errors in depth to the low velocity zones are estimated to be about 5 km and errors in its thickness, about 10 km. In an effort to reconcile the disparities between the depth-velocity curves for the two perpendicular Siberian sections (Fig. 5C), Vinnik and Yegorkin (*21*) appeal to extensive azimuthal mantle anisotropy or partial melting leading to preferred orientation of olivine crystals. Velocity inversions of comparable magnitude have not been reliably demonstrated in either the Canadian shield (*22*) or in northern Australia (*23*), so that the phenomenon has not been confirmed outside of the Soviet Union.

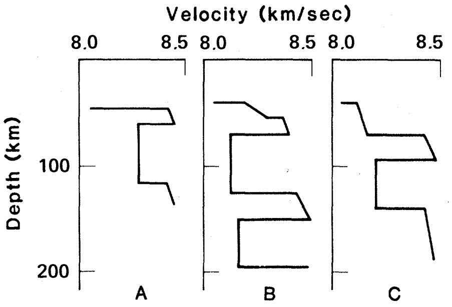

Fig. 5. Mantle velocity profiles: (A) Russian plate; (B) Siberian platform, east-west profile; and (C) Siberian platform, north-south profile (*21*).

## Ultra-Deep Drill Holes in Soviet Exploratory Effort

The exploration of crustal and mantle structure by deep seismic sounding has been accompanied by an extensive deep drilling program throughout the Soviet Union. In January 1972 the deepest well (Aralsor SG-1 in the peri-Caspian basin) was 6808 m deep (*24*); only 59 wells had penetrated 5000 m depth (*25*). The U.S. drilling record of 9159 m was set in 1972 at Baden 1 in Oklahoma.

Starting in the fall of 1970 a series of ultra-deep wells were started in the Soviet Union in order to test turbodrilling methods and equipment, recover rock samples, explore potential mineral- and oil-and-gas-bearing strata, and provide correlation with data provided by DSS surveys. In September 1979 the Kola SG-3 hole was started (a in Fig. 2) at the intersection of two local seismic lines. By September 1983 the hole was about 12,000 m deep, with a target of 15,000 m. The data gathered at the Kola hole were extensive, but most important in the context of deep seismic sounding was the revelation that some discontinuities recorded in geophysical surveys proved to be fracture zones rather than boundaries between rock types (*26*).

The Saatly SE-1 hole in Azerbaijan was started in 1977 (b in Fig. 2) and targeted for 15,000 m. In June 1983 it had passed 8200 m and was uncased below 3500 m. It has proven the existence of hydrocarbons in deep Paleozoic formations. Three additional ultra-deep holes were planned for 1981 through 1985. The first is in the Verkhnyaya Tura metal-mining district in the Urals (c in Fig. 2). Another, the Anastas'yev-Troitsk, is in the northern Caucasus (d in Fig. 2), and the last, the Tyumen hole, is in the

Table 1. Soviet DDS lines derived from probable nuclear explosions.

| Line | Name | Year | Number of explosions | Length (km) | Year described | Reference |
|---|---|---|---|---|---|---|
| 1 | Kineshma-Vorkuta* | 1971 | 4 | 1500 | 1973 | (*2*, p. 15; *29*) |
| 2 | Elista-Buzuluk* | 1972 | 2 | 800 | 1977 | (*18*) |
| 3 | Ural'sk-Kustanai | 1972 | 2 | 850 | 1978 | (*29*) |
| 4 | Karatau Ridge–Tengiz Lake* | 1973 | 3 | 900 | 1977 | (*18*) |
| 5 | Vorkuta-Noril'sk* | 1974 | 2 | 1150 | 1978 | (*30*) |
|  | Noril'sk-Tiksi* | 1975 | 2 | 1800 | 1978, 1980 | (*31*, *32*) |
| 6 | Dikson-Khilok* | 1977 | 4 | ~2800 | 1978, 1980 | (*31*, *32*) |
| 7 | Berezovo-Amka | 1978 | 4 | 3200 | 1981 | (*16*) |
| 8 | Bol'shoi Salym River–Sinyaya River* | 1979 | 3 or 4 | 3300 | 1982 | (*10*) |
| 9 | Noril'sk-Baikal | 1982 | 3 | 2000 |  |  |

*Names given by the Soviets to DSS lines.

northern part of the "super-giant" (>100 trillion cubic feet) Urengoy gas field (e in Fig. 2) (*27, 28*). In the case of the Tyumen hole the purpose is to evaluate the Mesozoic and Paleozoic sections for oil and gas, determine seismic velocities, study lithologic properties, and determine zones of overpressure and underpressure.

Six deep holes, as opposed to ultra-deep holes, are planned in oil-bearing regions (Dnieper-Donets, Astrakhan arch, and Timan-Pechora) and mining regions (Muruntau gold area in Uzbek S.S.R., Noril'sk nickel province, and Krivoi Rog iron region).

The depths to be reached in the deepest holes planned are on the order of 13 to 15 km and hence cannot provide any corroboration of interpretations made of DSS data that probe to between 80 and 100 km. The ultra-deep holes nonetheless do enhance interpretation of shallow data, whether garnered from conventional high explosive or other seismic sources or from nuclear explosions. Some of the proposed ultra-deep holes are in fact close to nuclear DSS lines (Fig. 2).

## Conclusions

The Soviet program of deep seismic sounding is designed to explore the vast expanses of that country with underground nuclear explosions augmented by ultra-deep drill holes. The fact that the program has been operating since 1971 and shows every promise of continuing is testimony to its successes and usefulness to Soviet objectives. Such a notable program has been possible despite an apparent dearth of digital recording equipment and advanced analytical tools. The use of large seismic sources has allowed elucidation of crustal detail and mantle structure down to a depth of 200 km. Analysis of data has revealed gross inhomogeneities in the mantle underlying the Soviet Union. Comparable structures have not been described on other continents.

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# The Significance of Responses of the Genome to Challenge

Barbara McClintock

There are "shocks" that a genome must face repeatedly, and for which it is prepared to respond in a programmed manner. Examples are the "heat shock" responses in eukaryotic organisms and the "SOS" responses in bacteria. Each of these initiates a highly programmed sequence of events within the cell that serves to cushion the effects of the shock. Some sensing mechanism must be present in these instances to alert the cell to imminent danger, and to set in motion the orderly sequence of events that will mitigate this danger. But there are also responses of genomes to unanticipated challenges that are not so precisely programmed. The genome is unprepared for these shocks. Nevertheless, they are sensed, and the genome responds in a discernible but initially unforseen manner.

An experiment conducted in the mid-1940's prepared me to expect unusual responses of a genome to challenges that the genome is unprepared to meet in an orderly, programmed manner. In most known instances of such challenges, the types of response are not predictable in advance of initial observations of them. Moreover, it is necessary to subject the genome repeatedly to the same challenge in order to observe and appreciate the nature of the changes it induces. Familiar examples are the production of mutation by x-rays and by some mutagenic agents.

It is the purpose of this discussion to consider some observations from my early studies that revealed programmed responses to threats that are initiated within the genome itself, as well as oth-