APPLICATIONS OF GEOPHYSICS IN GEMSTONE EXPLORATION

By Frederick A. Cook

Advances in geophysical technology and computer imaging now permit mapping of geologic features at various depths beneath the Earth's surface in more detail than ever before. Geophysical methods, which for some years have been used to explore for diamonds (and many other minerals), also hold promise as important tools in both exploration for new colored stone deposits and assessment of known deposits. Particularly exciting are the use of seismic-reflection and radar-imaging techniques for high-resolution mapping of near-surface pegmatites, veins, metamorphic layering in crystalline rocks, and alluvial deposits in sedimentary rocks. These techniques can produce images of regions only a few centimeters to a few meters in size down to several meters to tens of meters below the surface. Thus, it is now possible to locate directly some buried structures containing gem deposits.

ABOUT THE AUTHOR

Dr. Cook is professor in the Department of Geology and Geophysics, The University of Calgary, Alberta T2N 1N4, Canada.

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Much of the exploration for gemstones (even diamonds, in some regions) is conducted with relatively simple, often primitive, techniques. In many areas of known gem occurrences, development and mining involve little more than shovels and screens for alluvial deposits, and explosives plus mechanical tools (such as pneumatic drills) for hard-rock deposits (e.g., pegmatites; figures 1 and 2). In areas where gems are not known to occur, most discoveries are made by chance. This contrasts with the exploration procedures routinely used for many other Earth resources, such as oil and gas or metallic minerals, in which years of regional geologic and geochemical mapping are usually followed by intensive periods of acquiring and analyzing geophysical data. Once target areas are located, more detailed—and usually more expensive—exploration methods (such as drilling or excavation) can be undertaken. However, geophysical techniques have seldom been used to delineate gemstone, particularly colored stone, deposits.

This article describes the principles behind geophysical exploration, together with some applications in diamond exploration and some potential applications in colored stone exploration. Different contemporary geophysical exploration techniques are highlighted, and suggestions are made with regard to how these techniques could be applied to certain types of gem occurrences. As consumer demand for gems continues to rise, and older deposits are depleted, geophysical prospecting has considerable potential for identifying new resources or new areas of gem mineralization at existing occurrences.

GEOPHYSICS AND GEMOLOGY

Geophysics is the application of physical principles (e.g., using magnetism, gravity, or electrical properties) to study the internal structure and geologic evolution of the Earth and other planets. In particular, physical principles are used to study the composition and geologic structure of rocks below the surface. Thus, geophysics includes a number of techniques that can help identify promising localities for mineral exploration.

Figure 1. The discovery of pegmatites, and of gem-bearing pockets in a pegmatite dike, is one of the greatest challenges in gem exploration. These bicolored tourmalines from the Himalaya mine, San Diego County, California, represent some of the fine gems waiting to be discovered in pegmatites worldwide. Courtesy of Pala International, Fallbrook, California; photo © Harold & Erica Van Pelt.

Gemology and geophysics are similar in many ways. The nondestructive techniques that a gemologist uses to determine the identity of a gemstone typically include determination of refractive index (speed of light ratios), specific gravity (density), thermal conductivity, and magnetism (occasionally), as well as describing or mapping internal characteristics (e.g., inclusions, internal growth structure, etc.). A geophysicist also uses generally nondestructive (sometimes called remote sensing) methods. Some of the most common techniques (table 1) include those that measure variations in the speed of vibrational waves (seismic refraction), in rock density (gravity), in the thermal state of the Earth (heat flow), and in rock magnetism (magnetics); as well as those that use imaging to map subsurface structures (seismic-reflection profiling, ground-penetrating radar).

There are essentially two branches of geophysics that apply to studies of rocks: (1) whole-Earth geophysics, and (2) exploration geophysics. In whole-Earth geophysics, geophysical methods are used to map deep and large-scale variations in the Earth's properties, such as the depth and configuration of the Earth's core, the internal characteristics of the Earth's deep *mantle* (the region of the earth between the crust and the core), the depth and structure of the *lithosphere* (the outer shell of the Earth, approximately 100 km deep on average), and the thickness and properties of the *crust* (the outermost layer of the lithosphere, about 10–40 km thick; see figure 3). The lithosphere is generally rigid and consists of a series of "plates" that shift relative to one another (i.e., plate tectonics), thus producing earthquakes, volcanoes, and uplift of mountains. The lithosphere usually reaches its greatest thickness (as much as 300–400 km) beneath ancient continents.

In exploration geophysics, on the other hand, geophysical techniques are used to search for hydrocarbon (oil and gas), mineral (gold, silver, lead, zinc,

Figure 2. This pegmatite pocket from California's Himalaya mine yielded thousands of carats of fine tourmaline. Unfortunately, the discovery of such pockets typically requires hundreds of meters of tunneling and a great deal of luck. Rapid improvements in geophysical prospecting techniques offer the hope that this situation will change in the near future. Photo © Harold & Erica Van Pelt.

etc.), and other economically significant deposits. Hydrocarbon and mineral deposits are usually located in geologic structures that are large enough (sometimes several square kilometers) to be easily mapped by geophysical imaging. Although geophysical results rarely can identify whether economically significant hydrocarbons or minerals are present, they often can pinpoint geologic features that may

TABLE 1. Common geophysical exploration methods and potential applications to gemstone exploration[a].

Method	Principle involved	Usual geologic application	Effective depth	Effective resolution
Gravity	Responds to variations in rock density	Mapping subsurface structure based on variations in density	Meters to 100s of km (depends on spacing of measurements)	100 m to 10s of km (depends on spacing of measurements)
Magnetics	Responds to variations in rock magnetism (usually iron content)	Mapping subsurface structure based on variations in magnetic properties	Meters to 50 km (depends on spacing of measurements)	A few m to 10s of km (depends on spacing of measurements)
Electrical	Responds to variations in electrical conductivity (metals or fluids)	Mapping fluids (e.g., ground water) and metal deposits	Meters to 100s of km (depends on measurement time)	10 m to 100s of km (depends on spacing of measurements)
Heat flow	Responds to variations in temperature at depth; thermal conductivity	Mapping variations in the outflow of the Earth's heat	1 km to 100s of km (depends on knowledge of properties at depth)	A few m to 10s of km (depends on knowledge of properties at depth)
Radioactivity	Responds to variations in radioactivity of rocks	Mapping concentrations of radioactive minerals	A few cm	A few cm to 100s of m (depends on spacing of measurements)
Earthquake seismology	Responds to variations in seismic-wave velocity (varies with rock density)	Mapping large-scale (lithosphere) and deep-Earth structure	To center of earth	10s of km (depends on frequency of signal and wave velocity)
Seismic refraction	Responds to variations in acoustic impedance (density × velocity)	Mapping crustal thickness and regional structure; depth to basement	10 m to 100s of km (depends on length of profiles; energy source)	10 m to 100s of m (depends on length of profiles; energy source)
Seismic-reflection profiling	Responds to variations in acoustic impedance (density × velocity)	Mapping detailed geologic structure and stratigraphy	100 m to 100s of km (depends on length of profiles, energy source)	A few m to 100s of m (depends on frequency of signal and wave velocity)
Ground-penetrating radar (Georadar)	Responds to contrasts in electrical conductivity	Mapping detailed geologic structure and stratigraphy.	Meters to 100 m	About 10 cm to 1 m (depends on frequency of signal and wave velocity)

[a]Not all of these methods are described in detail in the text as their application to gemstone exploration may be limited (e.g., electrical, heat flow). Nevertheless, they may be useful for reconnaissance work under favorable conditions. For additional information on the applications of these techniques, see Telford et al. (1976).

be promising targets. Unlike mineral and hydrocarbon deposits, however, many primary gem deposits—such as those in veins or pegmatite cavities (figure 2)—are no larger than a few meters in diameter. Because of their small size, these deposits are easily missed with conventional mining methods (e.g., trenching or tunneling), and most geophysical techniques cannot produce the resolution (detail) necessary to detect them.

Today, though, new methods of data acquisition and analysis (including sophisticated computer processing) enable some geophysical techniques to resolve geologic features that are as small as a fraction of a meter to a few meters in longest dimension and very shallow, within a few meters of the surface. In addition, improvements in our knowledge of deep geologic structures (tens to perhaps hundreds of kilometers below the surface) now make it feasible to use large-scale reconnaissance geophysical techniques to identify regions of the Earth within which certain kinds of gem deposits might be found. Thus, the science of geophysics has the potential to play an increasingly important role in the exploration and development of some gemstone deposits. It is even possible that specific exploration strategies could be developed using geophysical techniques to optimize: (1) opportunities of for success in exploring for gems, and (2) knowledge of existing deposits (e.g., their extent and thus, potentially, their value) .

THE "RESOLUTION PROBLEM"

The objective of all geophysical methods is to produce an image of the Earth's interior, usually by making measurements at the surface. The type of

Relative cost	Limitations	Comments	Potential application in gem exploration
Low ($100s per day); cost increases for greater detail	Inherent ambiguity between rock geometry and density limits usefulness in exploration	Used for reconnaissance work and as a measurement for density estimate	Reconnaissance; thickness of crust and lithosphere
Low ($100s per day); cost increases for greater detail	Inherent ambiguity between rock geometry and magnetism limits usefulness in exploration	Used to map kimberlite pipes; may also assist in mapping regional geologic structures in basement	Delineating kimberlites; mapping regional geologic structures
Low ($100s per day); cost increases for greater detail	Inherent ambiguity between rock geometry and conductivity limits usefulness in exploration	Used to explore for metal deposits; may assist mapping lithosphere thickness and basement structures	Reconnaissance; thickness of lithosphere; mapping kimberlites
Low, but usually requires costly drillholes at $1000s per drillhole	Requires drillholes, thus limiting number of measurements; inherent ambiguities in calculation	Used to calculate temperature at depth, geothermal energy	Reconnaissance; thickness of the crust and lithosphere
Low ($100s per day); cost increases for greater detail	Limited penetration; not useful for regional studies	Used to explore for radioactive mineral deposits	Might help to indicate presence of accessory radioactive minerals
Low to moderate; cost increases with number of receiving stations	Low resolution; not useful for detailed structure	Used for mapping variations of seismic velocity in the mantle	Reconnaissance; thickness of the lithosphere in diamond exploration
Moderate ($100s–1000s per day); cost per kilometer increases with number of receiving stations	Low resolution; not useful for detailed structure	Used for mapping variations in depth to mantle and depth to basement	Reconnaissance; thickness of the crust; depth to basement beneath alluvial deposits
High ($1000s per day); cost increases for greater detail	Relatively expensive; not easy to image shallower than 50 m	Most widely used geophysical method in hydrocarbon exploration due to good image quality	Reconnaissance; thickness of the crust; detailed structure; mapping of alluvial deposits
Low ($100s per day)	Signal can only penetrate up to 50 or 100 m; quality may be severely affected by surface material	Used in mapping near-surface features such as archeological sites, pipelines, tunnels, etc.	Alluvial deposits; delineating pegmatite cavities

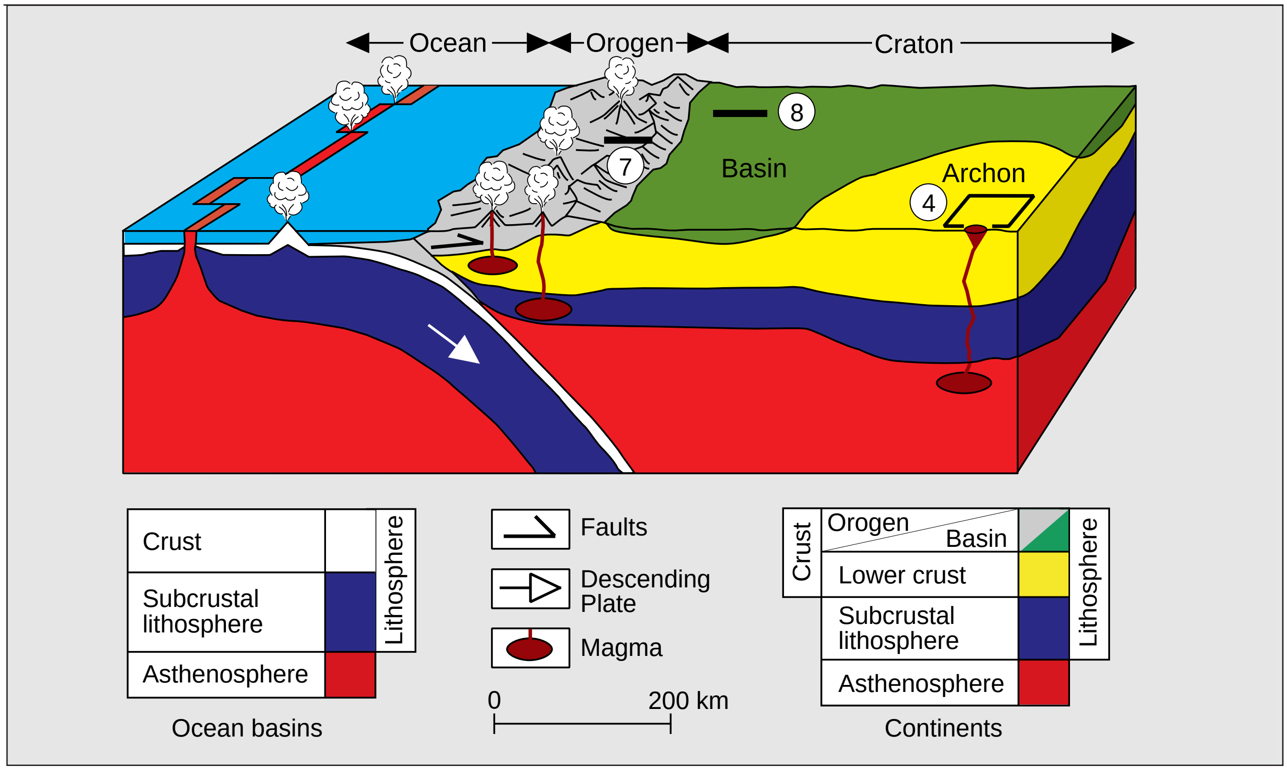


Figure 3. In this schematic diagram, normal lithosphere is segmented into the tectonic plates of the Earth's surface, with unusually thick lithosphere (combined crust and subcrustal) under archons (portions of cratons with an age of formation exceeding 2,500 million years [Janse, 1994]), where diamonds may form. Cratons are areas of the continent that have been stable for long periods of geologic time, and orogens are regions that have been subjected to folding and faulting. Geophysical techniques may be applied in different areas and at different scales to delineate gem deposits. For example, some methods are useful on a reconnaissance scale to delineate thick lithosphere, where most primary diamond deposits are found, as well as to identify regions of thin lithosphere, where economic primary diamond deposits are very unlikely to occur. Other geophysical methods are more useful for intermediate-scale exploration. Magnetic surveys, for example, respond to differences in properties between kimberlites and surrounding rocks and assist in locating specific areas for exploration (figure 4), whereas seismic profiles assist in delineating the deep geometry of mountains (figure 7) and basins (figure 8). Approximate positions of data in figures 4, 7, and 8 are shown as circled numbers.

image depends on what parameter(s) are measured by the particular method being used (again, see table 1). The value of a technique depends on its *resolution*, that is, its ability to distinguish responses from different types and sizes of geologic features.

In all cases, the measured response includes the combined effects of rocks between the target zone (area of interest) and the surface; in some cases, it also includes features below the zone of interest. Consider the following analogy. In measuring the density (specific gravity) of a gem, a gemologist weighs a sample first in air and then in water, and calculates the specific gravity according to how much water is displaced. In fact, however, the specific gravity of the sample is affected by the specific gravity of the gem material plus the specific gravities of any inclusions, some of which may be lighter (e.g., air or water) or heavier (e.g., heavy minerals) than the host gem. For example, an emerald that has many pyrite (S.G. ~ 5.00) inclusions will have a specific gravity that is greater than for beryl alone (2.70). The inclusions thus add *noise* (i.e., an unwanted signal) to the result, which causes the measured specific gravity to deviate from the theoretical value of the pure gem material or even from the value typical for relatively inclusion-free material.

The geophysical method analogous to specific gravity is the measurement and analysis of the Earth's gravity field (Box A; table 1). After accounting for large-scale variations caused by the Earth as a whole (such as its shape and size), the remaining signal (e.g., the pull of gravity) is a function of variations in the densities of rocks at depth. When a geophysicist measures the Earth's gravity field at a location on the surface, the reading includes the

BOX A: GRAVITY AND MAGNETIC METHODS

Subtle variations in the Earth's gravitational pull are brought about by differences in the density of large masses of rock. These variations can be identified by the gravity method, which is analogous to measuring specific gravity. In it, a gravity meter, or gravimeter—a sensitive mass-spring system that weighs about 5–7 kg (10–15 pounds)—is carried (usually on the ground, although sometimes in an airplane) from location to location, measuring the pull of the earth's gravity field (figure A-1). When a gravity measurement is taken over an object with a high density, the object pulls on the mass and is recorded as an increase in gravity (figure A-1); decreases in gravity occur over low-density objects.

Once appropriate corrections for elevation and latitude are made to the recorded gravity data, the resulting values (anomalies) represent variations in mass (density) at depth. A problem inherent in interpreting these kinds of data is that the actual measured value is the sum of responses of all mass variations at depth (e.g., A and B in figure A-1). This makes it difficult to determine the subsurface structure with much precision from this method alone, so gravimeter data are usually used in conjunction with magnetic and other data.

The magnetic field at any location is a combination of the field produced by the Earth's core plus effects from nearby magnetic objects, such as iron-bearing rocks. Magnetic data are acquired in much the same way as gravity data, except that a magnetometer is used to measure the magnetic field on or above the surface. Once the Earth's field is removed from the measured signal, the resulting anomalies can be interpreted in terms of geologic features. Normally, rocks that contain large amounts of iron (e.g., kimberlites) produce large magnetic anomalies (see text figure 4). One advantage that the magnetic method has over most other methods is that a magnetometer can be carried behind an airplane, thus allowing the acquisition of large amounts of data in a short time. Interpretation of magnetic anomalies is similar to interpretation of gravity anomalies. Aeromagnetic surveys have been broadly used in the exploration for diamond deposits in Australia, Africa, and, most recently, Canada.

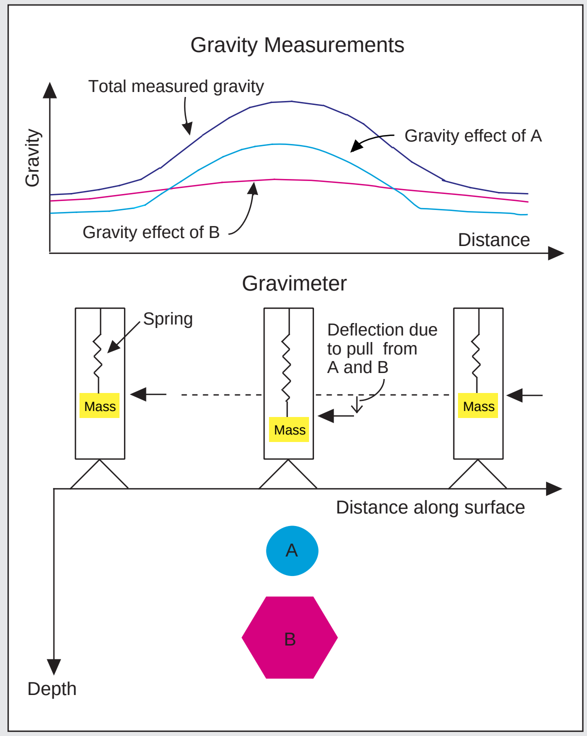


Figure A-1. In this schematic illustration of the gravity method, a gravity meter (gravimeter), which is essentially a mass-spring system, is placed at a series of locations along the surface. The displacement of the mass is a function of the strength of the gravity at each location. Following corrections for elevation and latitude, the remaining signal consists of a series of anomalies that represent the combined gravitational attraction of local geologic features (A and B in this figure).

combined effects of all rocks below the area being measured, from great depths to the surface. The analysis must account for as many effects as possible, so that resultant *anomalies* (in this context, deviations from uniformity or normal values in an exploration survey) can be interpreted. However, it is often difficult to separate the effects of different masses of rock, because their shapes and densities are not usually known. Because such detailed knowledge of subsurface rock types and geometries is not yet available, geophysicists cannot resolve variations in rock density to a few meters in size, as would be necessary for many gem exploration applications. Similar difficulties exist in measuring the Earth's magnetic field (table 1), although high-precision instruments and detailed measurements now permit greater resolution than ever before.

In fact, interpretations of virtually all geophysical measurements require careful understanding of the possible causes of the background noise that affects resolution. Usually more than one method of exploration must be applied before an economic

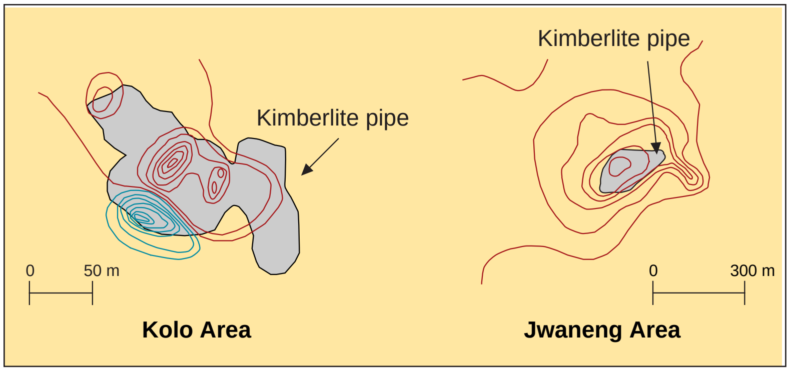


Figure 4. Magnetic anomalies from kimberlites tend to be roughly circular in map view (modified from Atkinson, 1989). On these maps of two kimberlites in Africa, Kolo and Jwaneng, the red lines represent magnetic highs (regions of high iron concentrations), the blue contours represent magnetic lows, and the gray stippled areas are outlines of the kimberlite pipes. Map information taken from Burley and Greenwood (1972, for the Kolo area) and Lock (1985, for Jwaneng).

deposit can be clearly identified. The problem of background noise is even greater for conditions of analysis that might provide the detailed resolution necessary to delineate most types of gem deposits.

Nevertheless, when much larger-scale variations are considered (such as changes in the lithosphere or locating some large features that may contain gems), geophysics can and does play an important role. Such is the case in diamond exploration.

CURRENT USE OF GEOPHYSICS IN DIAMOND EXPLORATION

Primary Deposits. Geophysical techniques are commonly used to locate promising regions for primary diamond deposits (Atkinson, 1989; Smith et al., 1996), which are found in two types of rare igneous rocks, kimberlites and lamproites. The magmas from which these igneous rocks crystallized originated in the Earth's mantle at depths of more than 150–200 km. As they ascended to the surface, these magmas traveled through the lower part of the continental lithosphere, where the diamonds probably formed (again, see figure 3). Sometimes, these magmas carried some of the diamonds along with them. We know, then, that primary diamond deposits form in regions where the continental lithosphere is thick (150–200 km or more); to be economic, the kimberlites or lamproites must be present at or near the surface (Levinson et al., 1992).

The presence of kimberlites or lamproites can be detected by geophysical methods, particularly by magnetic and electrical techniques. Kimberlites and lamproites typically have high iron concentrations, so they often are more magnetic and more electrically conductive than the rocks they have intruded (Atkinson, 1989; Hoover and Campbell, 1994; Smith et al., 1996). Furthermore, they usually form circular or irregularly shaped structures (in map view), so that they can be pinpointed by magnetic (figure 4) and electrical measurements (Smith et al., 1996), even if they are covered by a thin blanket of sedimentary rocks.

However, only a small fraction of kimberlites contain diamonds in economic amounts, and these tend to be in areas with thick lithosphere. Thick lithosphere is more likely to have economic kimberlite or lamproite deposits because diamonds form from carbon (or carbon-containing compounds such as methane and carbon dioxide) at pressures corresponding to 150–200 km depth. The lithosphere is usually about 100 km thick, so a 150–200 km thick lithosphere is uncommon and would appear as a "keel" or "root," much like the lower part of an iceberg. Thick lithosphere tends to occur beneath old continental *cratons* (those parts of the earth's crust that have attained stability, and have been little deformed for prolonged periods), because that is where there has been the greatest amount of time for the lithosphere to cool and thicken (billions of years, as compared to a few hundred million years for oceanic regions). Thus, methods that measure the thickness of the lithosphere can be valuable in assessing whether a region might contain diamondiferous kimberlites. Figure 5, for example, illustrates the various thicknesses of the lithosphere under North America, with specific reference to the recently discovered diamond deposits in Canada. Lithospheric roots are higher in density than the surrounding mantle material, so geophysical techniques that respond to density are useful (e.g., gravity and earthquake seismology; again, see table 1).

Measurements of seismic-wave velocity provide some estimation of variations in rock density as well as of the rigidity (strength) of the rocks. Because rocks in the mantle part of the lithosphere usually are denser and more rigid, they have higher seismic-wave velocities than adjacent rocks of the partly

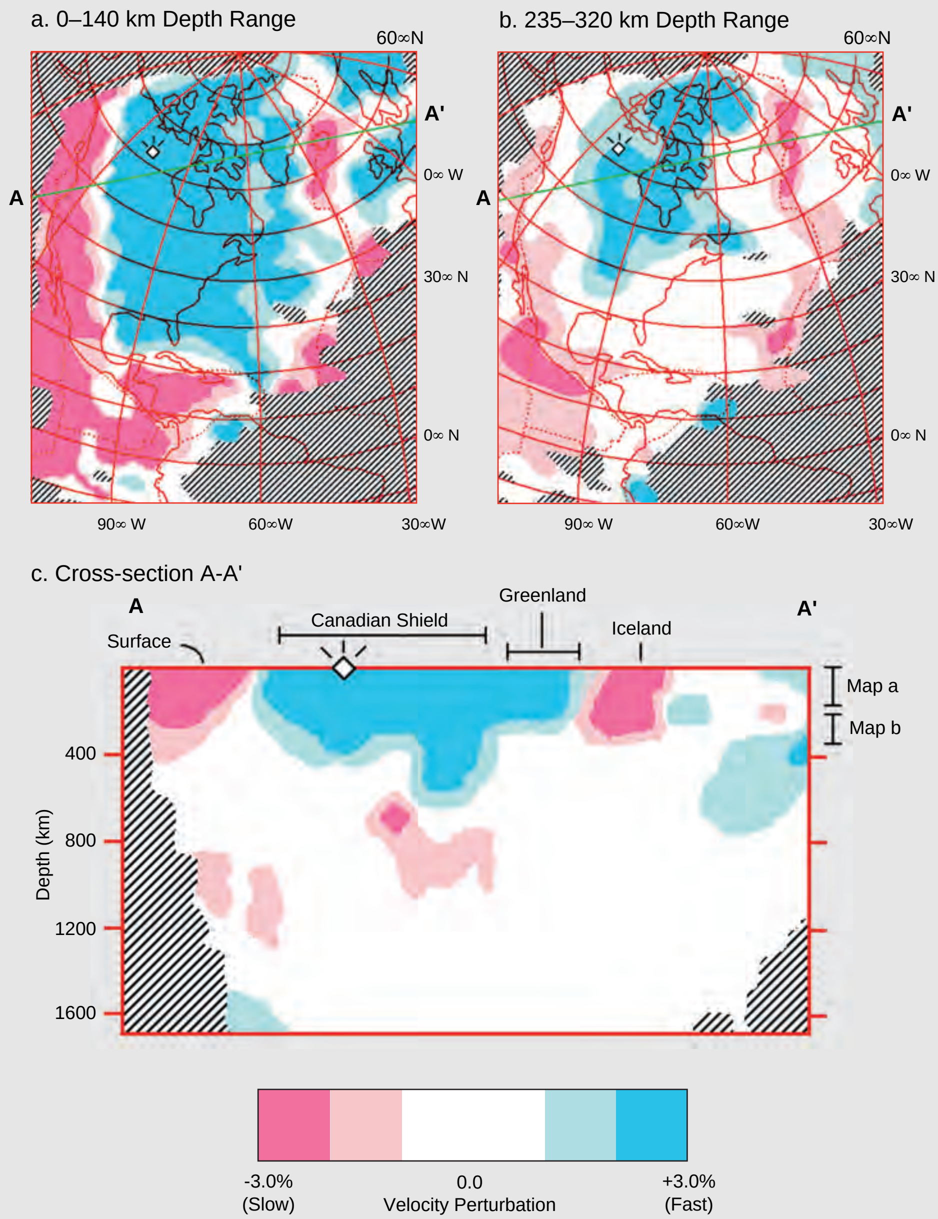


Figure 5. The thickness of the lithosphere beneath continents may be estimated by measuring the velocities of seismic waves. Two maps of North America (a and b) show estimates of seismic-wave velocity for different depth ranges. Areas of increasingly high velocity (and probably increasingly rigid material) are represented by light to dark blue, whereas areas of lower velocities (and probably less rigid, partly molten material) appear pink to red. (a) For depths from the surface down to 140 km, this map shows high velocities under the center of the continent, where the lithosphere is thick. The velocities tend to decrease slightly near the edges of the continent, where some partly melted rock is closer to the surface. (b) For the depth range 235–320 km, only the central part of the continent (Canadian Shield) has high velocities and, thus, more rigid rock; this is the area where major primary diamond deposits have recently been found (diamond symbol). In both maps, dotted lines represent the boundaries between tectonic plates, and the scale at the bottom indicates perturbation of seismic-wave velocity from expected values. A-A' is the location of the cross-section of (c). Diagonal-lined areas have no data. (c) Cross-section A-A' through the North American continent illustrates seismic-wave velocity as a function of depth. Again, the dark blue (high velocity) region extends to 300–600 km depth beneath the central part of the continent (Canadian Shield). The depth ranges of maps a and b are shown on the right of the diagram. Figures are modified from Grand (1987).

molten *asthenosphere* (the part of the Earth's mantle that is located below the lithosphere and that acts somewhat like a fluid; figure 3). The top of the asthenosphere is found typically between about 100 and 200 km, but it is sometimes much deeper beneath ancient cratons (again, see figure 3). Thus, maps of wave velocities (measured from earthquake waves) at different depths have anomalously high values (hence, high densities and greater strength) deep below the thick cratons (Grand, 1987). The dark blue areas of figure 5 represent regions with high density and are interpreted as the lithospheric roots. Once the lithospheric roots have been located, higher-resolution magnetic and electrical data may allow identification of anomalies associated with individual kimberlite or lamproite structures. These are the kimberlite structures that should receive the most intensive study (Atkinson, 1989; Smith et al., 1996). Of course, identification of kimberlite fields in areas of thick lithosphere does not guarantee that economic diamond deposits will be found. Without these conditions (kimberlites/lamproites *and* thick lithosphere), though, the possibility of economic primary deposits is severely diminished.

Atkinson (1989) states that geophysical techniques, specifically magnetics, were used as early as 1932 to locate the boundaries of kimberlite pipes. Gravimetric and resistivity surveys were also used for similar purposes. All these early attempts were conducted on the ground. Following World War II, however, aeromagnetic surveys were flown as part of exploration for kimberlite, with the Russians being the first to use this method extensively in Yakutia. Since the early 1970s, aeromagnetics have been used in many places, such as Australia and Botswana, resulting in the discovery in the late 1970s of the Ellendale lamproites in Western Australia. Today, geophysical techniques, particularly aeromagnetics, are used throughout the world in exploration for kimberlites, such as in the Northwest Territories, Canada (Smith et al., 1996).

Secondary (Including Alluvial) Deposits. Exploration for secondary diamond deposits (alluvial, beach, marine deposits etc.) involves identification of the sedimentary layers within which diamonds occur. Diamonds may be transported long distances (hundreds of kilometers) from their primary source locations, collecting in deposits that are no longer situated on thick lithosphere. Consequently, geophysical exploration for secondary diamond deposits requires techniques that allow mapping of detailed features at shallow depths. For example, in South Africa and Namibia, diamond deposits in river gravels are found at the edge of, or even offshore from, the African continental craton (Gurney et al., 1991), where the lithosphere is probably thin. In such cases, it is necessary to explore with methods that allow mapping of the shallow subsurface geometry of the diamondiferous sediment layers. Because this approach is essentially the same for all alluvial gems, colored stones as well as diamonds, it is discussed in greater detail below.

USES OF GEOPHYSICS IN COLORED STONE EXPLORATION

Colored stones are found in a much greater variety of geologic environments than are diamonds, and many of the most valuable gem deposits occur where the stones are concentrated into secondary (alluvial) environments after redistribution from their primary source locations. Also unlike diamond deposits, primary colored stone deposits—such as those found in pegmatites, in igneous intrusions in metamorphic or sedimentary rocks, in vugs in volcanic rocks, and the like—tend to be associated with geologic features on the order of a few meters or less. As is the case with diamonds, however, for a colored stone deposit to be economic it must be located within a few meters or tens of meters from the surface. Hence, whether the colored stone deposits being investigated are primary or secondary, the methods chosen must be able to delineate the near-surface geology in some detail.

In the past, geophysical techniques generally have not been as useful for mapping the extremely shallow part of the Earth (upper few meters to tens of meters) as they have been for greater depths; the more established techniques—such as gravity and magnetic measurements or electrical and seismic methods—simply have not had the resolution necessary to map the near-surface in detail. This is why we rarely hear of geophysics being used in colored stone exploration. However, this situation has changed in the past five to 10 years.

Some geophysical techniques are now being adapted for application to near-surface geologic interpretation, primarily to address geologic factors in environmental problems such as waste disposal (Beres et al., 1995; Lanz et al., 1994). Some of these methods are also being used in a limited way to explore for gemstones (e.g., Patterson, 1996; William Rohtert, Kennecott, pers. comm., 1997). Because most geophysical exploration techniques (such as gravity and magnetics; see Box A) can be acquired and processed with high resolution, they are appropriate for certain specific, near-surface, exploration targets. For example, magnetics may be useful in mapping locations of some gem-bearing igneous dikes that have intruded into sedimentary strata (because igneous rocks usually contain large amounts of iron compared to most sedimentary rocks), or in mapping iron-rich sedimentary rocks. In fact, magnetics have been used to map concentrations of ironstone deposits that contain precious opal in Queensland, Australia (Senior et al., 1977). Magnetic anomalies coupled with anomalies in radioactivity have also been helpful in outlining possible areas for exploration of red beryl in Utah (William Rohtert, pers. comm., 1997; figure 6).

Nevertheless, it is rare for these (gravity, magnetics) and most other geophysical methods to be used for mapping alluvial deposits or other geologic features (e.g., veins, cavities, pegmatites, metamorphic layering) that contain gemstones. The reason for this is exactly the same as that for the difficulties that arise in interpreting specific gravity readings: The ambiguities inherent in the analyses preclude obtaining the necessary subsurface geometry and resolution. Because these methods have somewhat limited use in colored stone exploration, they will not be discussed further.

There are, however, two methods that have proved valuable for mapping subsurface geology—seismic-reflection profiling (Box B) and ground-penetrating radar (georadar; Box C)—that may also have broad applicability to gemstone exploration. Although these respond to different physical properties, the images of subsurface geometry produced by both of these geophysical exploration techniques are consistently superior to those of the other methods for mapping geologic layering. Illustrations of these methods clarify their potential value.

Seismic-Reflection Profiling. *The Method.* Seismic-reflection profiling was first used in the 1920s to map subsurface geologic structures in the search for oil and gas. Since then, it has become the most important tool in exploration geophysics; more than 90% of geophysical exploration for hydrocarbons is accomplished with seismic profiling. This is because the technique produces results that are similar to geologic cross-sections (figure 7). Although interpreting these data often requires specific skills, particularly knowledge of how seismic waves propagate through rocks, with these skills

Figure 6. Kennecott geologists used a combination of magnetic anomalies and radioactivity anomalies to outline potential deposits of red beryl in Utah's Wah Wah Mountains. The 10 × 9 × 8 mm crystal and 0.76 ct cut stone shown here represent some of the fine red beryls found at this locality. Courtesy of Michael M. Scott; photo © Harold & Erica Van Pelt.

the geometry of the rock layers beneath the surface can often be determined with precision (again, see Box B).

The layers on the image in figure 7 represent reflections from boundaries between different rocks or, more specifically, between rocks with different properties (seismic velocity and density). By determining how fast the waves travel in the rock layers below the surface, we can convert the travel times to the reflecting surfaces to the depths of those surfaces (figure 7b). Thus, if a wave travels at about 5 km (3 miles) per second, a two-way (round-trip) time of 5 seconds represents 12.5 km depth (5 km/second × 5 seconds ÷ 2). With the data displayed this way, we are essentially looking at a cross-section of this portion of the Earth (about 50 km long × 20 km deep in the example in figure 7), in a manner similar to a CAT scan or an X-ray image of a portion of the body.

The profile in figure 7, which was taken in the Rocky Mountains of southwestern Canada, reveals a cross-section of some deformed (faulted and folded)

BOX B: SEISMIC-REFLECTION PROFILING

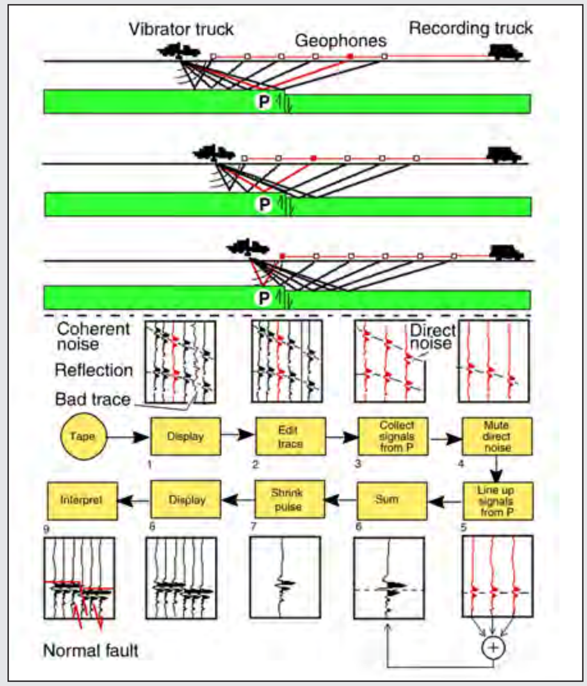


Figure B-1. This schematic drawing shows the many steps (described in the box) that are required to collect and analyze data in the seismic-reflection profiling technique (modified from Cook et al., 1980).

In seismic-reflection profiling, vibrational waves are generated on the Earth's surface and travel into the subsurface; there, they reflect off rock layers and return to the surface, where they are received by a row of sensors. It is the most common geophysical technique in hydrocarbon exploration and has been developed to a very sophisticated level. As for all of these techniques, the basic components for seismic-reflection profiling are field acquisition, data processing, and interpretation (figure B-1). In data acquisition, a source of elastic (vibrational) energy such as a small explosion or a large vibrator truck (figure B-2) produces the signals that penetrate into the Earth and are reflected back. A series of sensors (geophones; figure B-3) are positioned along the surface and are connected to a recording truck by cable or radio communication. These sensors measure variations in arrival times and amplitudes of waves, which relates to the densities and velocities of the different rock types. At the recording truck, the received signals are recorded through a computer onto magnetic tape.

The geometry of the field recording allows signals from a single point on a boundary (P in figure B-1) to be recorded at different geophone positions as the process is repeated at subsequent locations. This means that the separate reflections from P can be added together in data processing to enhance the signal from the layer boundary and thus identify the rock formation (or type of formation) that boundary represents.

Data processing is usually time consuming, and requires that a highly trained individual make judgments about parameters as different computer programs are applied (figure B-1). The basic sequence requires inputting the data from a field tape to the computer facility, displaying the field data (step 1 in figure B-1); editing bad traces (step 2; a trace is the series of signals recorded at a specific geophone for a single source vibration); collecting the signals of vibrations that were reflected from a single point from different geophone locations (step 3); removing noise from the waves that travel along the ground surface, rather than from those that reflected from depth (step 4); lining up these signals (step 5) and summing them into a single composite trace (step 6); applying different filters to enhance the pulse (step 7); and displaying the final section for each reflection point (step 8). Data presented in this article were processed through these steps. The final procedure is to interpret the data (step 9 in figure B-1), which requires that the analysts use as much geologic information as possible, as well as any other relevant geophysical information, to optimize the result. Because seismic-reflection profiling has potential for identifying relatively small geologic features (see discussion in the text), it has promise for gem exploration.

Figure B-2. Vibrator trucks—typically three or more in tandem—are commonly used as a source of energy for seismic-reflection work. Each of these trucks vibrates a signal of known frequency and energy for several seconds. These signals travel into the Earth until they are reflected back to the surface by a rock layer. Photo courtesy of K. W. Hall.

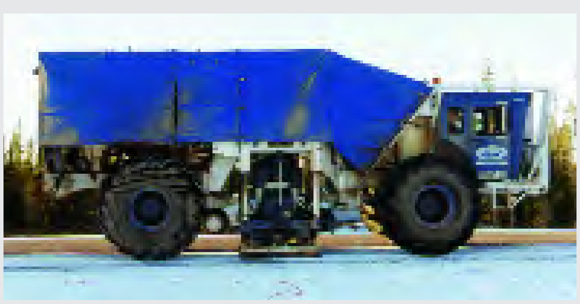
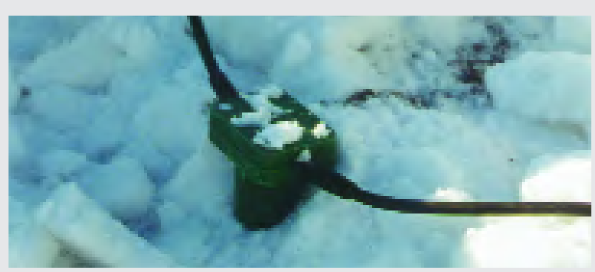


Figure B-3. Geophone sensors, each about 4 cm across the top, are placed on the ground surface to record the vibrations returned from beneath the surface. Photo courtesy of K. W. Hall.



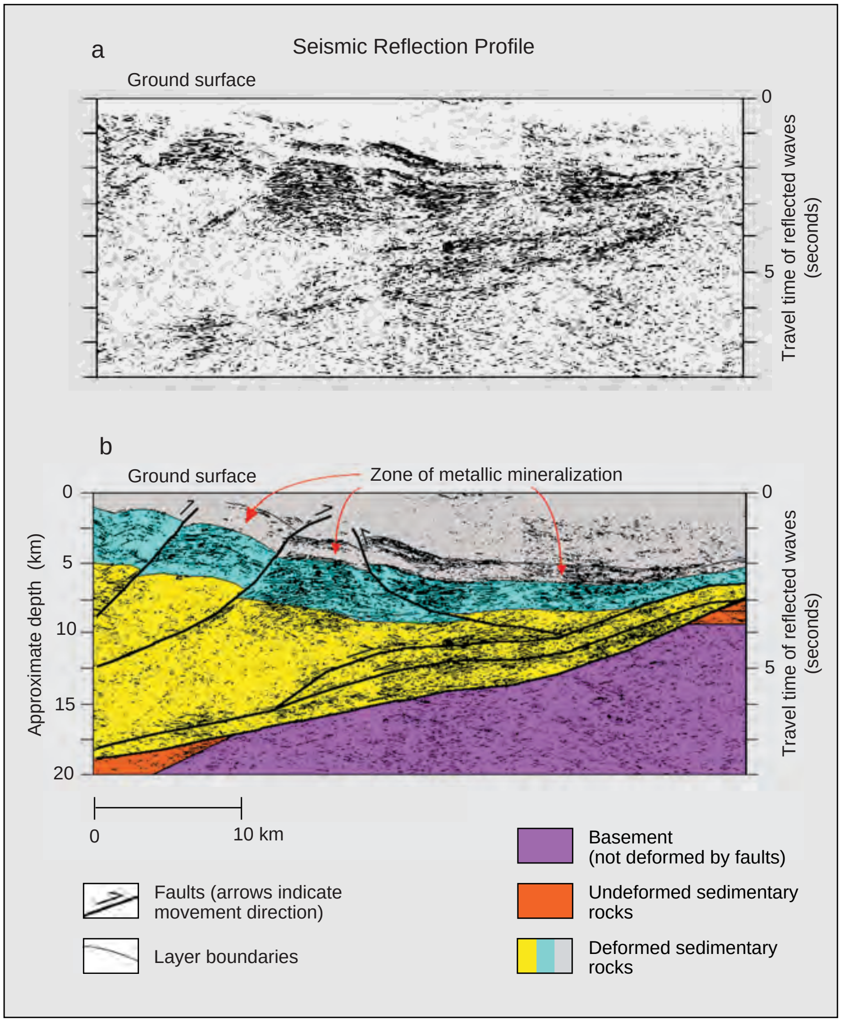


Figure 7. (a) This seismic-reflection profile, taken in the Rocky Mountains of southwestern Canada, is plotted with the horizontal axis as distance along the ground surface and the vertical axis as time (in seconds) for waves to travel from the surface (0) to a reflecting boundary (linear features on the data) and back to the surface. (b) Geologic interpretation of the data in (a) reveals different rock types, as shown by the colored areas, and faults. In this interpretation, sedimentary rocks were deformed by folding and faulting above undeformed basement rocks. A drill hole (not shown) about 10 km to the left of this profile penetrated a zone that was found to have large concentrations of metallic minerals (lead, zinc, silver). See figure 3 for the position of this profile relative to other geologic features. Adapted from Cook (1995).

sedimentary rocks. A drill hole located 10 km to the left of the section intersected the prominent layers observed; thus, these layers could be interpreted with some certainty. Furthermore, the drill hole also intersected a zone of metallic (lead, zinc, silver) mineralization that has not been exploited. This mineralization zone is associated with a stratum that can be followed as a recognizable layer, sometimes even across faults, for tens of kilometers on these and related seismic-reflection data. Thus, while the method does not actually produce images of the lead, zinc, or silver minerals, it does allow us to map the geometry and extent of the layer that may contain the minerals.

The large-scale profile (about 100 km long) in figure 8 illustrates an application of the method in a reconnaissance survey. This seismic-reflection cross-section of an area in western Canada required about two to three weeks of field work and another four to six weeks of computerized data analysis (again, see Box B). Layers are visible from near the surface to the base of the section (about 30–40 km depth). In this instance, the method provided an image of a previously unknown, ancient (Precambrian, or older than 570 million years) basin that lies above westward-thinning crust and below young, flat-lying sedimentary rocks (figure 8b; Cook and Van der Velden, 1993).

While details of the interpretation are not of major importance here, it is easy to see how seismic-reflection profiling can be used to map the deep geologic boundaries, and thus how it could be a valuable reconnaissance tool. But is this technique applicable to the very shallow part of the Earth, where gemstones might be recoverable? To a large extent, the answer to this question depends not only on the depths in question, but also on how small a feature the technique can detect; that is, on the resolution of the signal.

Resolution of the Data. The resolution of seismic-reflection data depends on the wavelength (L) of the

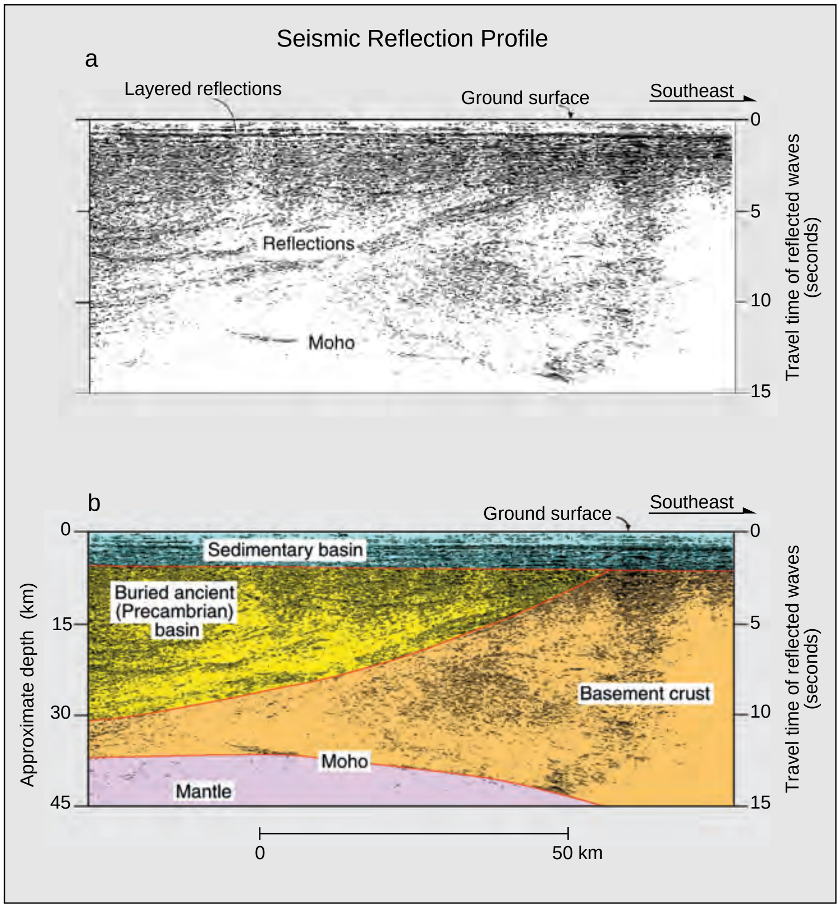


Figure 8. (a) This seismic-reflection profile taken in northeastern British Columbia shows a decrease in thickness of the crust (depth to the top of the mantle, or Moho). (b) Interpretation of the data reveals that the flat layers between 0 and about 2 seconds are relatively young sedimentary rocks, which rest on Precambrian crystalline (granite and metamorphic) rocks (orange—right) and Precambrian sedimentary basin rocks (yellow—left). The Moho (Mohorovicic discontinuity), the transition from the crust to the mantle, lies at about 45 km on the southeast and about 35 km on the northwest. Inasmuch as some gem deposits may depend on variations in crustal thickness (e.g., some gem corundum deposits appear to be located in areas where the crust is 40 or more km thick; Levinson and Cook, 1994), mapping the thickness of the crust could prove valuable for reconnaissance. (For this figure, the approximate depth values have been calculated assuming an average seismic-wave velocity of 6 km/sec, rather than 5 km/sec as in figure 7, because of different characteristics of the rocks.) Figure is modified from Cook and Van der Velden (1993).

signal, which is a function of the frequencies (f) of the waves that are used, as well as on their velocities (V) through the rocks. The following equation summarizes the relationship between these parameters:

$$L = V / f$$

In general, the smaller the wavelength of the signal, the smaller the feature that can be detected and the higher the resolution of the measurement. In practice, it is possible to obtain seismic frequencies up to about 100 cycles per second in the shallow subsurface (first 20–50 m), where the seismic-wave velocity varies from about 6.0 km/sec in many crystalline (e.g., granite) rocks to about 2.0 km/sec in loose sedimentary rocks (e.g., gravels). Using f = 100 in the equation above, we find that L = 60 m (0.06 km) for granites and L = 20 m (0.02 km) for loose sedimentary rocks. The resolution of the method is determined by the lower limit of size of the feature that can be imaged. In seismic profiling, geophysicists have found that this limit is about one-fourth times the wavelength of the signal, or about 15 m for granitic rocks and about 5 m for loose sedimentary rocks. This means that we can, in principal, map features on the order of 5 m thick in some areas (e.g., alluvial deposits), which approaches the resolution necessary for effective gem exploration. For example, it might be possible to map the locations of large dikes (e.g., pegmatites) or the geometry of important geologic layers, such as a gem-bearing gravel. However, it would still be difficult to identify pockets or cavities smaller than 15 m in diameter.

We cannot change the speeds of the seismic waves in the rocks (which largely depend on the kinds of minerals the rocks contain), but we can vary the frequency of the source of seismic waves to improve the resolution. However, the Earth does not always cooperate, because it absorbs high-frequency signals very easily. (This is why the booming low frequencies of a stereo sound system can be heard for a long distance, while the higher- frequency signals are readily absorbed.) Additional technical problems make it difficult to use the seismic-reflection technique for depths less than about 20 m. Nevertheless, as technical advances improve seismic-reflection profiling for applications to geologic problems in the shallow subsurface, it may become an important tool in gem exploration.

Cost. Another important consideration is that seismic-reflection profiling can be relatively expensive; exact costs depend on the parameters (e.g., the spacing of the receiver points) that are used in the field. Although acquiring high-resolution shallow data is usually less expensive than acquiring deep reflection data (because the area surveyed is smaller), survey costs of several thousand dollars per day are not unusual, and a proper survey usually takes one or more weeks. Thus, even if the technique is refined to the point where meter-scale resolution is possible in the uppermost few meters, the costs may be prohibitive for many gem-exploration applications. Fortunately, there is a less-costly alternative for some situations—georadar.

Georadar. *The Method.* Also known as ground-penetrating radar, or GPR, georadar is finding a number of geologic applications in the shallow subsurface (Box C). Radar has been used for about 15 years to map thicknesses of ice sheets and glaciers. More recently, it has been applied in mapping underground pipes and building foundations, shallow archeological sites (Imai et al., 1987), the geometry of landfill sites (Lanz et al., 1994), the geometry of sediment deposits (Beres and Haeni, 1991; Smith and Jol, 1992; Beres et al., 1995), and fracture systems in some crystalline (metamorphic and igneous) rocks (Piccolo, 1992; Grasmueck, 1996). Based in part on work by Grasmueck (1995, 1996), and in part on results from the author's own experiments (figure 9), it is proposed here that, if carefully performed, radar may be applicable to gemstone exploration in many instances.

When most of us think of radar, we think of air traffic controllers or military personnel monitoring the positions of airplanes or missiles. However, if a radar (radio wave) signal is directed into the ground, it can penetrate some distance and then reflect off rock layers beneath the surface (again, see Box C). The distance that a radar signal penetrates depends on the absorptive properties of the rocks through which it is traveling. The property that most affects penetration is probably electrical conductivity, a measure of how easily an electrical signal travels through a material. The more electrically conductive a material is, the more it absorbs a radar signal. Metals, as well as clay-rich and saltwater-rich materials, are very electrically conductive; consequently, they prevent radar signals from being transmitted very far because they absorb much of the energy. Like ice, fresh water, and air, granite is largely transparent to radar signals; thus, the signals travel through it readily. This characteristic is key to the success (or failure) of the method. When a radar signal impinges on a boundary between nonconductive and conductive materials, some of the energy reflects back to the surface, where a receiver can measure it. Where there are large contrasts in electrical conductivity, large amounts of signal energy may be reflected.

As with a seismic section, the travel time to and from each reflector is measured and, if the wave velocity is known, the depth can be determined. Reflected signals received by instruments on the surface are recorded in the field and stored for later computer enhancement. Many of the computer-enhancement techniques that have been developed for seismic-reflection images are also applicable to radar images (Fisher et al., 1992; Grasmueck, 1996). The result, when recording a single profile or line, is a cross-section—much like a seismic-reflection section—that has a series of coherent signals, each of which corresponds to a reflection from a rock interface (or an abrupt change in rock properties) at depth.

There are, however, two major differences between seismic-reflection data and georadar data. First, the frequencies and velocities of radar signals are much higher than those of seismic data: Radar signals travel at the speed of light in air (300,000 km per second) and about one-third of that speed in granite (Davis and Annan, 1989). Second, radar signals respond to the electrical properties of the material, whereas seismic signals respond to the *elastic* properties of the material. (Elastic properties are measures of how easily a material deforms, such as when it vibrates.) Both of these characteristics of radar (higher frequencies and electromagnetic waves), prevent radar signals from penetrating very deeply into the rocks; in figure 9, for example, the radar section corresponds to only 60 m of rock, as compared to the 45 km depth for the seismic section of figure 8b. Even more importantly, radar signals in the shallow subsurface often have wavelengths of about one meter or less, providing a resolution to 0.25 m (25 cm), which is potentially useful for gem exploration.

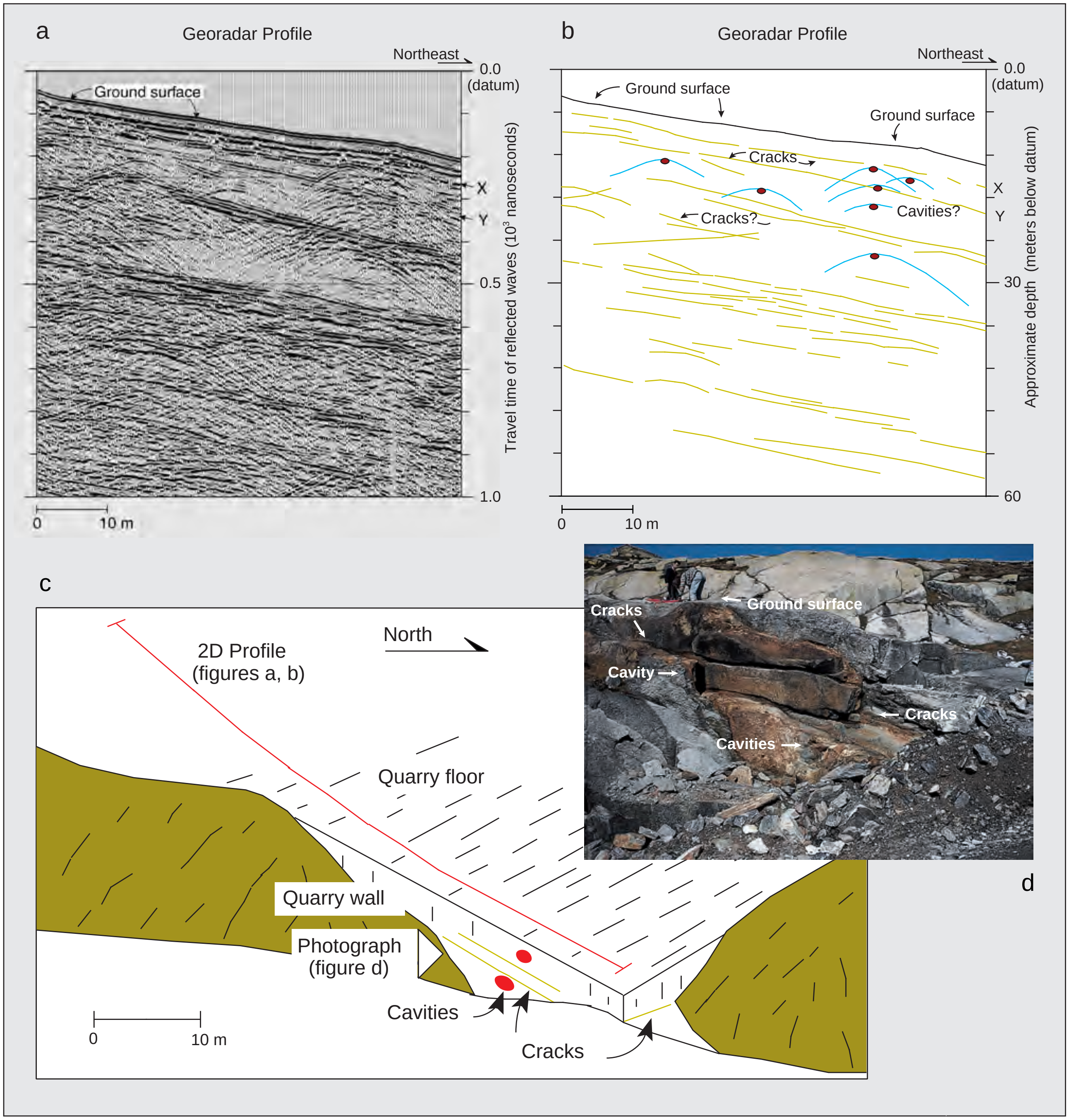


Figure 9. This georadar profile (a) was recorded by the author in a gneiss in southern Switzerland. Here, reflections are caused by differences in electrical properties, and the depth of penetration is about 50–60 m (compare with figures 7 and 8). Thus, the resolution is significantly more detailed than that for seismic profiling. Note that the datum (0.0 time line) is above the northeast-sloping ground surface. Interpretation of the data (b) reveals that prominent reflections at a depth (below the ground surface) of about 3 m (reflection X) and 6 m (reflection Y) on the right side of the section are probably cracks that are only a few centimeters thick (as interpreted on another dataset in the area by Grasmueck, 1995; see also [d] below). Red dots represent discontinuities, such as cavities or small faults, that give rise to the arcuate features (blue lines). The schematic diagram in (c) illustrates the relationship between the location of the georadar profile of (a) and (b) and the photograph of (d), an outcrop where a zone of mineralization (including cavities and small faults) is exposed. The outcrop is in a quarry wall immediately beneath the ground surface on the right side of the profile in (b).

Georadar in Three Dimensions. Most georadar recordings, as with most seismic-reflection recordings, are made along lines that result in a two-dimensional profile (horizontal distance in one direction and vertical depth, or distance through a feature, in the other; see Box C and figure 9). However, pockets or cavities that are small (e.g., one meter or less in diameter), but nevertheless productive, would be easy to miss unless profiles were recorded very close together. In such a situation, it might be desirable to acquire data in three dimensions (two horizontal and one vertical; figure 10), as described, for example, by Beres et al. (1995). Although three-dimensional data require somewhat more effort in both recording and data processing, the resulting information provides images of the internal structure of a volume of rock, rather than a single cross-sectional profile; features such as cavities or mineralized zones may be much more apparent and less likely to be missed. Preliminary results from an experiment conducted by the author and a colleague (J. Patterson) within a pegmatite have shown that it is possible to outline the three-dimensional geometry and size of a pocket.

Georadar is not very expensive relative to seismic profiling. A three-dimensional survey, with accompanying profile lines like the one shown in figure 10, requires about two to four person days of field time and perhaps two to four weeks of computer work. A similar three-dimensional seismic-reflection survey would have required 10 times as much effort.

Possible Uses of Georadar Profiling in Gemstone Exploration. Three characteristics of georadar make it a potentially useful method for gemstone exploration:

1. Radar provides very high resolution (to as small as 25 cm) images of the near-surface environment (in some cases, in the first few meters to tens of meters beneath the surface).
2. Georadar data are comparatively inexpensive to acquire and process.
3. Crystalline (granitic and metamorphic) rocks, in which many gem deposits typically occur, are relatively transparent to radar signals. However, the cavities or pockets that contain the gems (e.g., fluid-filled fractures, hydrothermal veins, clay-filled pockets in pegmatites, etc.) are likely to have electrical properties very different from the surrounding rocks. They could therefore produce very prominent reflected signals (figures 9a and b).

As noted earlier, most economic gemstone deposits presently are found at the surface or within a few meters to tens of meters of the surface. Examples include various alluvial deposits (where diamonds, rubies, sapphires, spinels, and many other gems are found), silica-rich sedimentary or volcanic rocks (such as some opal deposits in Australia and Mexico, respectively), pegmatite dikes (where quartz, beryl [figure 11], tourmaline, and a variety of rare gems are found), and lamprophyre (ultramafic) dikes (such as Yogo Gulch, Montana, where sapphires are found). Each of these deposit types may, if conditions are appropriate, be amenable to exploration using georadar or, in some cases, other geophysical tools.

For example, exploration for gemstones in sedimentary rocks, such as alluvial and some opal deposits, requires mapping of the subsurface geometry of the sedimentary layers. Georadar, and sometimes high-resolution seismic-reflection data, can be very effective tools for constructing such maps. The data illustrated in figure 10 were recorded to map the three-dimensional geometry of sedimentary layers near the surface (Beres et al., 1995). Detail is provided to 15 m depth. If one of the layers in such a survey (e.g. that labeled R2) were known to have high concentrations of gems (diamonds, corundum, spinels, etc.), it would be easy to follow that layer in the subsurface to predict its extent, its continuity, and thus the potential value of the deposit.

Exploration for primary deposits in granitic and metamorphic rocks is equally promising. Radar is already being used to locate high-quality (unfractured) ornamental rocks in quarries (Piccolo, 1992); thus, there may be applications for locating zones of high-quality jade or other massive gem materials. Highly fractured, lower-quality material would have measurably different properties from solid material.

Radar has been tested in some pegmatite deposits in California (Patterson, 1996), and at the Alma, Colorado, rhodochrosite deposits (Brian Lees, pers. comm., 1996) with limited success. In both areas, georadar has been useful for mapping subsurface structures. At the Colorado rhodochrosite deposits, for example, the technique has been successfully used to map faults associated with the deposit. However, it has been less successful in producing images of crystal-bearing pockets, probably because the pockets are very small (commonly less than 25 cm; Brian Lees, pers. comm., 1996).

BOX C: GEORADAR

Radio waves reflecting from contrasts in electrical conductivity can be detected by sensitive antennas. The georadar method is similar to seismic-reflection profiling in that a source of energy (radio waves in this case) is sent through a transmitting antenna (antenna T in figure C-1 and C-2) into the ground, and the returned signal is detected and collected at a receiving antenna (R in figure C-1 and C-2). The received signal is stored on a computer for later display and data processing. The simplicity and portability of georadar systems (figure C-3) allow the instruments to be used horizontally, such as into or through walls (e.g., figure C-2). Anomalous objects such as cavities (e.g., in a pegmatite) would appear as traces with unusual shapes or arrival times (figure C-2).

Figure C-1. This schematic diagram illustrates the georadar method for profiling along the Earth's surface. The transmitting antenna (T) sends a pulse into the ground, where it is reflected back to a receiving antenna (R). The signal is sent through cable to a computer, where it is stored on disk for later display and processing.

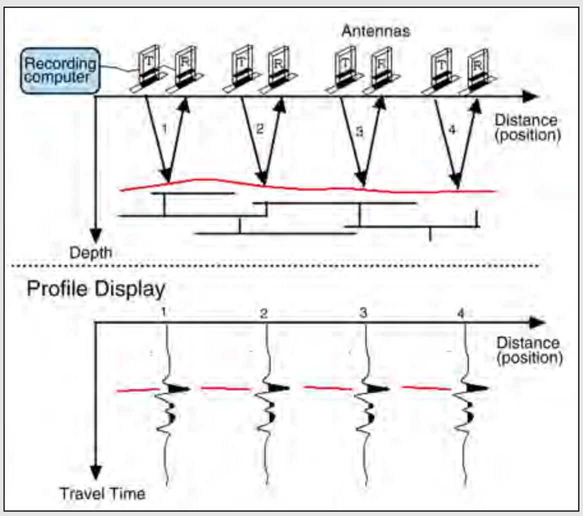


Figure C-2. This schematic diagram illustrates the georadar method for recording waves that are transmitted through an object (a wall) to detect anomalous zones such as cavities. Here the transmitting and receiving antennas are placed on opposite sides of the wall, and the anomalous zone appears in the data as an unusual waveform or arrival time.

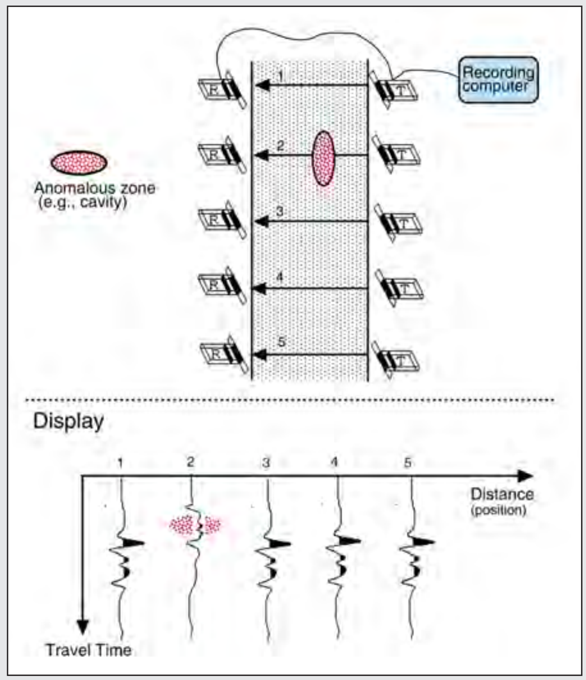


Figure C-3. The equipment required for georadar is very portable, and the procedure is not labor intensive. In this photo of a georadar field crew working in western Canada, the person in the foreground is setting the antennas, one for transmitting the radar pulse and the other for receiving the returned signal. The person in the background is carrying the instruments that control the signals and record them onto magnetic tape or disk. The wire along the ground connects the antennas to the recording instruments. Photo courtesy of D. G. Smith.

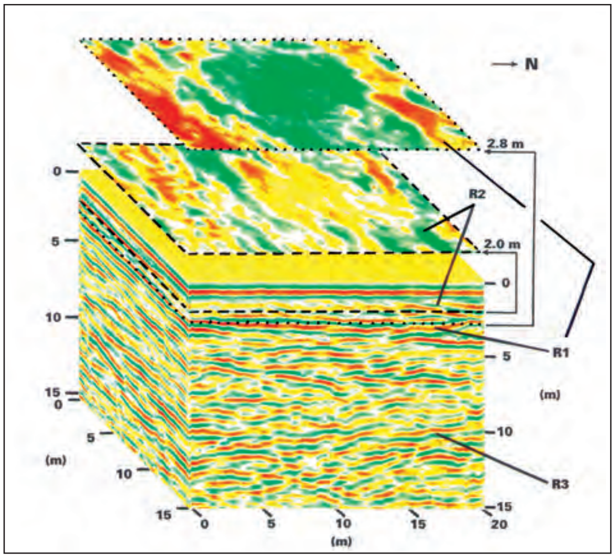


Figure 10. (top) These georadar data were acquired in northern Switzerland to map sedimentary (alluvial) structures in the near-surface (modified from Beres et al., 1995). R1, R2, and R3 are positions of reflected signals. Horizontal "slices" at 2.8 and 2.0 m are shown above the cube to illustrate how reflections R1 and R2 can be followed in three dimensions. If R2 were a gem-bearing gravel, it could be mapped easily over the region to determine both its lateral and vertical extent. R3 is another boundary at about 10 m depth. Knowledge of gem concentrations within this structure could thus be used to predict the total value of the deposit. The colors represent reflected waves from different layer boundaries. (Bottom) A two-person radar team works on sedimentary strata exposed in cross-section. The right-dipping layers are about the same size as layers R2 above, thus illustrating the kind of detail that may be possible with this georadar application. Photo courtesy of D. G. Smith.

Limitations of Georadar in Gem Exploration. Georadar is not a panacea for gemstone exploration at shallow depths. Some gem deposits in sedimentary rocks, such as some alluvials and some opal deposits, may have large quantities of clay near the surface. In such cases, the radar signal might not penetrate more than a few centimeters (Davis and Annan, 1989), and thus georadar would not be appropriate.

Pegmatite deposits in which the granitic rocks have weathered to produce a layer of surface clay are also problematic for radar, again because the clay absorbs much of the signal. This is commonly the case in southern California (Jeffrey Patterson, pers. comm., 1996). However, exposed pegmatites and deposits in relatively dry, sandy regions or in glacially scoured areas could be excellent environments for radar detection of underground cavities and fractures (figure 9). Hence, georadar may be an appropriate tool for the first 20–40 m depth if there is not a layer of clay or saline fluid near the surface. If the desired target is at a greater depth, or if the surface is not conducive to radar-signal penetration, other methods such as reflection seismology or magnetics (see table 1) may be appropriate. Therefore, surface and near-surface conditions must be investigated, usually with field observations or other tests, before deciding which technique(s) to use.

STRATEGIC APPLICATION OF GEOPHYSICS IN GEMSTONE EXPLORATION

Application of geophysical methods to gemstone exploration begins with establishing the nature of the target. In some cases, geophysical programs that address continental-scale measurements may be useful to identify regions appropriate for more intensive exploration. This approach is commonly used in exploring for diamonds, but it may also be applicable in exploring for gem corundum. Some gem corundum is found in alkali basalts that originated as magma below 50 km depth and picked up corundum from the lower crust (30–50 km) beneath continents as the magma traveled to the surface (Levinson and Cook, 1994). Thus, methods that allow the thickness of the crust to be mapped from place to place could be valuable. The seismic section of figure 8 is an example of a change in the thickness of the crust from about 40 km on the east to about 30 km on the west. Alkali basalts found east of this change would be more likely to contain corundum than those found west of it, if the theory

Figure 11. Georadar has great potential in pegmatite exploration, with the potential to locate gem pockets such as the one in which this superb aquamarine crystal (7.5 cm long) was found. Courtesy of Michael M. Scott; photo © Harold & Erica Van Pelt.

proposed by Levinson and Cook (1994) is correct; that is, that alkali basalt–hosted gem corundum originates in thick crust.

For other types of colored stone deposits, geologic mapping and serendipity will necessarily continue to play major roles. However, geophysics may be useful in delineating the extent of a newly discovered deposit, as well as in identifying specific targets (e.g., cavities) to investigate. In these cases, it is likely that high-resolution seismic reflection and, especially, georadar will soon become important exploration tools.

Following is a strategy to evaluate the potential usefulness of geophysical methods in a particular exploration venture:

1. Define the target (potential gem deposit, or regional structure) in terms of its:
   a. Size: If the target is the entire thickness and lateral extent of the lithosphere, and the desire is to establish likely regions for detailed work (e.g., diamond exploration), then only low-resolution techniques may be required.
   b. Depth: The greater the depth of a target is, the lower the resolution that can be provided by geophysical techniques.
   c. Geologic environment: Alluvial deposits may be imaged by techniques that provide stratigraphic information; primary deposits may require more direct images, such as of cavities.
   d. Physical properties: Knowledge of physical properties allows predictive models to be constructed. Such properties include seismic-wave velocity, density, magnetic characteristics, and electrical conductivity.
2. Acquire existing "test" data. "Regional" data sets (e.g., gravity, magnetics, occasionally seismic) often are available from government agencies. Such data can provide a considerable amount of background information, such as the thickness of the crust, the lithosphere, and so on.
3. Evaluate the costs versus the potential return.

Initial field testing is advised, particularly with high-resolution techniques such as radar. For example, it may be worthwhile to record a single radar profile to determine if near-surface clay layers are a problem. Such a test could also indicate whether a larger-scale survey, or even a three-dimensional survey, might be appropriate.

SUMMARY

Today, geophysical methods are sometimes used in diamond exploration, but they are not commonly applied for either exploration or exploitation of colored gemstone deposits. Part of the reason for this is historical: People searching for gems have not previously used these techniques and often are not familiar with them. Much of the reason, however, is technical: Geophysical methods simply have not had the resolution to be effective in either finding or delineating gem deposits, which are typically small. In addition, many geophysical techniques are expensive and require sophisticated equipment and technical expertise.

As technology progresses, however, the resolution of these techniques is being enhanced. Seismic-reflection data, for example, may now resolve features as small as a few meters; 10 years ago, it was difficult to resolve features of even 20 m. Georadar, too, was in the early stages of development as an application to subsurface studies a decade ago. Since then, the methods for acquiring and processing such data have improved measurably. It is now possible to analyze georadar data in the field with small recording systems and computers; more than five years ago, the equipment was much more cumbersome, if it existed at all.

In the future, as resolution continues to improve, and as data collection and analysis become even easier, it is likely that these and other geophysical techniques will become valuable tools for gemstone exploration. Even today, georadar holds potential for locating gem-bearing structures in pegmatites, alluvial beds, and alkali basalts, among other types of occurrences.

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