Geophysics at the National Underground Science Laboratory (NUSL)

Geophysics - A Proven Tool In Underground Laboratories

Geophysics provides the link between the geosciences, geoengineering, and the needs of the particle physics experimenters. Measurements of the physical properties of the rock mass both near drifts in the underground and at distances away from the free surfaces is important during the construction phase and during the maintenance phase of the facility. It is most appropriate that this subdiscipline of physics will be in a position to assist the experiments of the particle physics community. Geophysical techniques as site characterization tools can be tailored to investigate the regions close to the "surface", in this case the faces of the drifts, or more deeply. Typical rock parameters of interest include the electrical properties of the rock, the acoustical properties, the distribution of densities, and the distribution of magnetic properties within the rock mass. Creation of the NUSL will be an excellent opportunity to apply the tremendous advances in underground geophysics, which evolved during the last 20 years. These advances represent a wealth of innovative techniques often developed in concert with the design and construction of underground structures. Many of the subsurface sites are a result of construction for waste management purposes, but they also include specialized regional observatories developed in scientific underground laboratories. The great depths required by the NUSL and the lateral extent of the required excavations will allow geophysics to provide a suite of tools to assist in the development of methods to increase excavation efficiency, to increase safety, to characterize the rock mass at depth in terms of stress and rock mechanics properties. Because the NUSL will require a large mass of rock overlying the experiment, it will be possible to conduct geophysical experiments that will take advantage of the access to the underground and which will contribute to the understanding of Earth structure on a more regional or global basis.

Near Surface and Near Field Geophysics

The formation and characterization of inhomogeneities of the rocks and hydrogeologic features around the mine is a dominant theme of the proposed investigations associated with underground structures. These inhomogeneities include fractures, faults, intrusive bodies, and local pockets of mineralization. These features are important because they provide potential pathways for movement of fluids in the subsurface, potential reservoirs for subsurface fluids, and, in the case of the proposed NUSL, offer prime locations for the location of microbial communities in the subsurface. Therefore, the location and characterization of geologic inhomogeneities, both in the near surface, in the immediate vicinity of the mine (near field), and at greater distances from the mine (far field), is an important aspect of investigations at NUSL.

Geophysical techniques have been developed which have yielded great resolution and information about the physical properties of rock and soil. Elastic moduli parameters (density, and seismic velocity), and electrical properties (conductivity and permittivity) variations in the subsurface can be measured remotely by near surface geophysical measurements. The instruments for making these measurements on the surface and in boreholes have been used routinely for several decades in the mining, environmental, and engineering applications including electromagnetic and electrical methods (e.g. Pellerin and Alumbaugh, 1997) and seismic tomography (e.g. Scott, et al., 1999).

Geophysical techniques have been developed for near surface applications over the past fifteen years for a variety of problems, including: 1) locating zones of mineralization, 2) locating fracture zones, and 3) imaging geologic and hydrogeologic features in the subsurface. The most commonly used geophysical methods for near surface applications include: 1) magnetics, 2) electromagnetics, 3) seismic, 4) microgravity, 5) resistivity, 6) induced polarization, and 7) ground penetrating radar (GPR). Magnetic, resistivity, gravity, induced polarization, and electromagnetic methods can be used to locate the lateral positions of many types of buried objects, and be used to indirectly infer the location of the objects, but these methods cannot be used to produce a pseudo image of the objects. GPR and the seismic techniques are currently existing methods that can provide pseudo time-depth images of the subsurface. GPR can be used to produce a high-resolution map of the near-surface (<10 m), or in the immediate vicinity of the mine. Seismic methods can be used for depths greater than 10 m depth or greater than 10 m from boreholes.

Nearly all geophysical techniques have been adapted for borehole applications. Magnetic, density, elastic, radioactivity, and electrical properties measured in the immediate vicinity of boreholes provide a very accurate estimate of these physical properties. Geophysical measurements can also be made between pairs of boreholes, between a borehole and the mine, between the mine and the surface, or between a borehole and the surface. Measurements between two boreholes are often called cross-hole (or hole-to-hole) measurements, while measurements between a borehole and the surface are called hole-to-surface measurements. The objective of cross-hole geophysical measurements is to provide an image (or tomogram) of physical properties between boreholes (or between a free surface and a borehole). Hole-to-hole and hole-to-surface measurements generally provide a better estimate of physical properties than standard surface geophysical techniques.

Applications of Near Surface Geophysics to NUSL

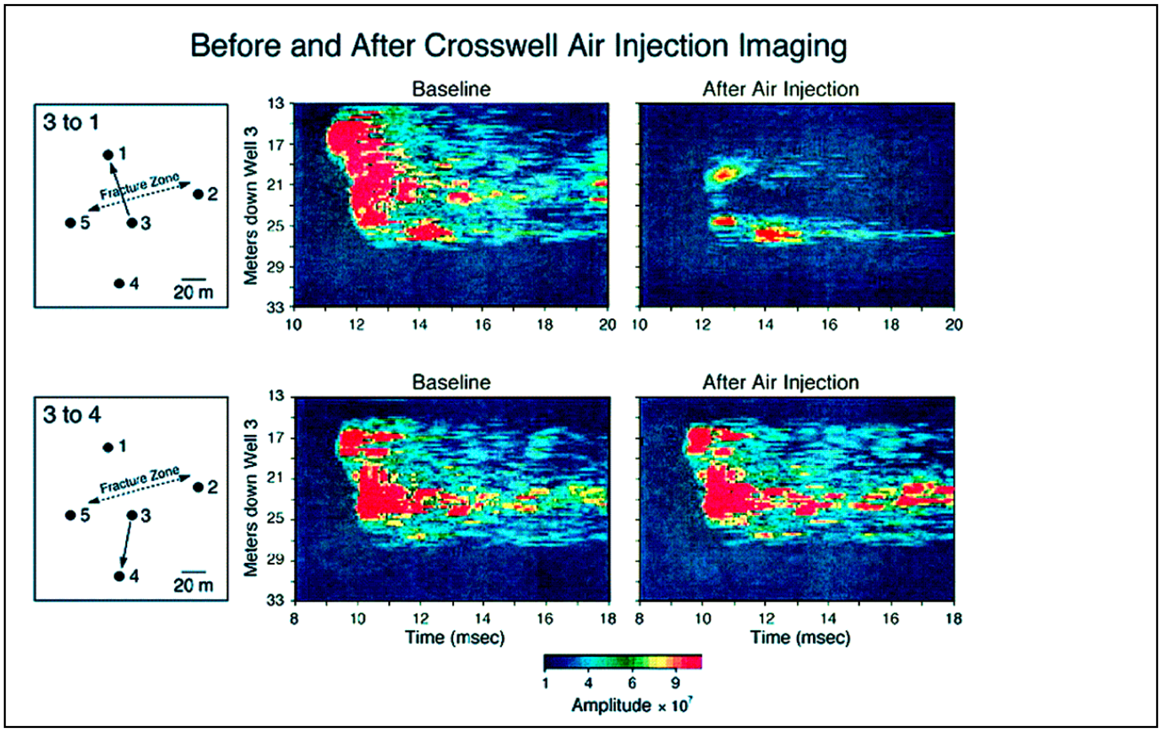
1. In-situ measurement of physical properties

Geophysical well logging measurements can be used to quantitatively measure the conductivity (the reciprocal of resistivity), the compress ional and shear wave velocities, the density, the magnetic susceptibility, the electrical polarizability, and the natural radioactivity of rocks adjacent to a borehole. These measurements can be used to interpret rock type and hydrogeologic properties of the area in the immediate vicinity of the borehole.

2. Fracture detection near the mine and near the surface-

Because fractures are filled with fluid, either electrically conductive in the case of water or insulators in the case of air, they are particularly amenable to investigation by electrical and electromagnetic methods that are sensitive to changes in electrical conductivity. Although GPR is an excellent tool for this type of application, it has a relatively shallow depth of penetration under most circumstances. As the rock volume of interest becomes larger, other methods involving the determination of electrical resistivity through direct electrical methods or electromagnetic induction methods can probe deeper into the rock to detect and delineate fracture systems.

Effects of the fracturing on the passage of seismic energy can be used effectively to map out the extent and, in some cases, the aperture of the fracturing. The figure below shows the effect on the seismic amplitude due to injecting air into a fracture.



The NUSL will also be an exceptional test bed for the creation and evaluation of new geophysical tools. As excavation progresses, it will be possible to perform fracture saturation experiments, followed by geophysical investigations, followed by "ground-truth" mine back experiments.

Rock mechanics and physical properties

Knowledge of the seismic velocities of the rock can provide valuable information about the bulk physical properties of the rock including how the rock will deform under a given stress. This type of information can be invaluable during the construction phase of the project. At a more detailed level, tomographic representations of the changes in velocity and attenuation can show how the rock varies spatially.

The state of stress within a given volume of rock is often of concern during the construction of large underground cavities, such as will be required for the physics experiments at NUSL. Rock deformation is a dynamic process that transfers stress from one portion of the rock to another. The resulting strains often cause microseismic activity that can be detected by accelerometers distributed through the rock mass. In this manner, the volumes of the rock with greater strains might be expected to produce larger number of microseisms as the rock deforms under the transferred stress. This type of instrumentation would be useful not only during the construction phase but also during the long-term monitoring phase to assess the rock mechanics health of the facility in the laboratory areas as well as in any areas of the underground that are closed off for extended periods of time without active visual monitoring.

Regional Geophysical Observations

The thickness of rock required by experiments at NUSL will prove to be useful for geophysical observations and instrumentation that benefit from a large areal extent as well as accessibility to a great depth of rock. Examples of such an application might include the construction of large, three-dimensional seismic arrays. These arrays would take advantage of quieter conditions away from the surface and would remove the constraint of being confined to a nearly planar surface. Conceivably, the instrumentation could be placed within a volume extending thousands of meters in all directions. The borehole seismometers at the Gran Sasso Underground Laboratory, Italy, were installed to take advantage of the quieter conditions found in the subsurface. The low-noise environment found in the underground environment allows the collection of seismic data that is superior to that acquired closer to surface sources of noise.

<u>*Geophysics at a Homestake NUSL*</u>

Seismic Observatory:

In the case of a NUSL located at the Homestake Mine, the complex of underground drifts represents an unprecedented opportunity to construct and operate a unique seismological observatory. With a modest number of instruments, about 10 three-component seismometer packages, such a facility has the potential to be one of the most sensitive and most versatile seismological observatories in the world, capable of detecting signals from thousands of seismic events per year located in all parts of the earth. A general purpose facility is proposed, capable of recording both very long period waves and very short period waves, capable of recording waves from teleseismic, regional, and local events, and capable of determining both the distance and direction of these events. With little additional cost, the facility could also record seismic signals from small events within the NUSL, such as rock bursts or collapses.

There are several reasons why the NUSL has the potential to become a very high quality seismological observatory. First and foremost is the opportunity to operate seismographic stations away from the noisy environment that exists at the surface of the earth. Because of cultural noise, because of noise caused by wind and barometric changes, because of scattering from topography, and because of scattering from the high degree of heterogeneity in physical properties that exists near the surface, the surface of the earth is not a good place to operate a seismographic station. In spite of this fact, it has been necessary in the past to operate most seismographic stations either at the surface or in shallow vaults a few meters below the surface. In recent years there have been efforts to install instruments in shallow bore holes, typically at depths of 100 to 200 meters, and this has led to major improvements in signal quality in many cases. However, the cost and restrictions of working in small boreholes has significantly limited this type of installation. Thus it is clear that the opportunity to carefully install seismometers at a depth of over 2 km below the surface has enormous potential for recording seismic signals with a fidelity that has not been achieved in the past.

Another advantage of operating a seismological observatory at the NUSL is its location near the center of a continent in a stable geological setting. It is far from the most important sources of natural noise, such as oceans, and far from the most important sources of cultural noise, such as large metropolitan areas. It is well documented that older continental shields such as found in this region are capable of propagating seismic waves with much less attenuation than younger more tectonically active regions such as the western United States. This fact, together with the siting of seismometers at depth so as to avoid the highly attenuating materials near the surface of the earth, suggests that it may be possible to observe seismic waves emerging from the earth's mantle that have more high frequency content than is observed at most seismographic stations. This additional high frequency content translates into improved precision for a wide variety of seismological studies, such as detection of weak signals, location of seismic events, determination of source processes, deciphering triplications in travel time curves, and measuring polarization anomalies of S waves.

The large complex of drifts at the NUSL provides a unique opportunity to install an underground array, which has numerous advantages over a single seismographic station. Whereas a single station samples the ground motion in time, an array samples the ground motion in both time and space. This means that it is possible to determine both the time that a signal arrives and the direction that it is traveling. This capability is extremely useful in the common situation where signals from several different directions are arriving at the same time. The array can be aimed, much like a telescope, to look in a particular direction. Furthermore, the availability of data from an array makes possible a wide variety of signal processing and signal enhancement methods that are not options with data from a single station. Depending upon the spatial coherence of signal and noise, these array-processing methods can greatly increase the signal-to-noise ratio of the seismic data. The presence of both a vertical array, which is never possible with a surface installation, and a horizontal array further expands the variety of processing methods that can be used.

The proposed seismological observatory would be composed of three main elements, a single very broadband three-component station, a broadband vertical array of three-component stations, and a broadband horizontal array of three-component stations. The ability of the facility to record high frequency ground motion could be enhanced by adding accelerometers at some or all of the stations.

A single very broadband station could be located at about the 4850 ft level recording signals in the frequency range of 10^{-4} to 10^{1} Hz. The vertical array would have three-component stations at the 8000 ft level, the 4850 ft level, and approximately the 1500 ft level. This arrangement would provide a vertical array with 3 elements and an aperture of about 2 km. The lower limit of the frequency response for these instruments would be about 3×10^{-2} Hz, and the upper limit would be adjustable in the range of 10^{1} to 10^{2} Hz. These instruments, which would be less expensive and easier to operate than the single very broadband station, should be small enough so that they can be installed in shallow boreholes drilled off the drifts.

The horizontal array would have instruments similar to the vertical array and would be installed at maximum horizontal distances in the north, south, east, and west directions from the center of the facility, preferably at about the 4850 ft level. A couple of additional stations at intermediate distances are recommended. This arrangement would provide a horizontal array with about 6 elements and an aperture of about 6 km.

Depending upon the interests of other scientists participating in the NUSL, it would also be possible at little additional cost to install high-frequency accelerometers at some of all of the array stations. These instruments could be used to monitor the seismic waves generated by any small events within the mine complex, such as rock bursts or collapses. These instruments would also provide a measure of the background levels of ground motion, which can be an important parameter in the operation of certain types of sensitive scientific instruments.

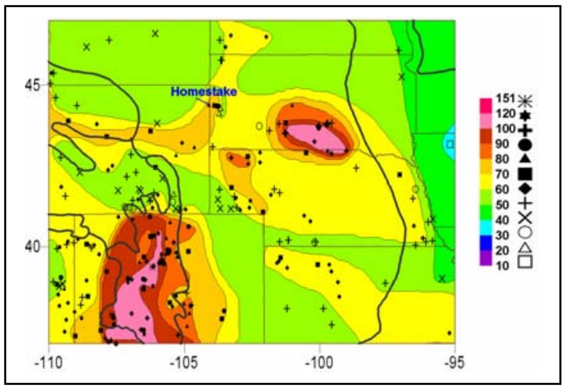
Most of the stations should be located some distance away from operations that involve mechanical motions or produce vibrations, although this aspect of the operation can be simply tested at the time of installation. The locations of all the seismographic stations are quite flexible and thus it should be easy to accommodate logistical concerns in determining the locations. In short, it would be prudent to place a three-dimensional array of three-component seismographs in any underground facility. If some of the elements of the seismic array, as described above, were themselves part of a smaller array (such as approaching one-fifth of a wavelength), then it may be possible to measure the bulk seismic properties of the mine itself using distant seismic sources (Robertsson and Muyzert, 1999).

With respect to other seismographic stations that have operated in the vicinity of the NUSL, the most relevant is the Regional Seismic Test Network (RSTN) station RSSD that was operated in the Black Hills between 12 December 1982 and 22 October 1986 by Sandia National Laboratories (Ballard, et al., 1989; Gupta and McLaughlin, 1988). State-of-the-art borehole digital seismometers with 16 bit precision were placed at a depth of 110 meters below the surface in the Englewood limestone. The geographical coordinates of the station were 44.1204 degrees N and 104.0362 degrees W. Sampling rates were 1 sps on the long period channels and 40 sps on the short period channels. This station was part of a test network and thus never intended to operate for an extended period of time, but it produced high quality data while it did operate as part of the network.

Heat Flow Studies and Other Regional Geophysics:

The heat flow in the Black Hills uplift is sampled at only one place, i.e. the Homestake Mine (Blackwell, 1967; Ashworth, 1983; Chancellor, 1981). Reliable thermal data for the Middle Rocky Mountains Wyoming Basin province are very sparse. The Archean part of the province appears to have heat flow that is normal for stable North America in spite of the tectonic effects of the Laramide Orogeny. In contrast there is an abrupt transition at the Wyoming/Colorado border from normal the high heat flow associated with major crustal thickness changes and close to the Proterozoic/Archean boundary. Whether this is a Cenozoic feature (the northward end of the Rio Grange rift) or an older one is unresolved at this time.

However, the heat flow in the Black Hills appears to be more typical of the Proterozoic of Colorado, even though it is far from Colorado and the heat flow in the Great Plains around it is normal as in the Archean of Wyoming. So there is an apparent heat flow anomaly in the Black Hills. Whether this anomaly might be due to variations in crustal radioactivity, tectonics, climatic effects, or error of measurement is unknown. Thus the opportunity to refine the heat flow in the mine is an important one. The intrinsic interest of the deep behavior of temperature is the crust is also significant. Noble (1949) postulated that changes in thermal gradient in the Yates shaft were due to glacial climatic effects. Blackwell (1967) argued that the changes were due to thermal conductivity effects. But the geologically related thermal setting of the mine is complex (steeply dipping, highly anisotropic rocks) and the basic temperature data of very limited extent and reliability. In reference to this type of setting it is worthy of note that the German deep bore hole had a completely unpredicted deep temperature whose origins even now are debated among the possibilities of climatic, structural, and fluid flow.



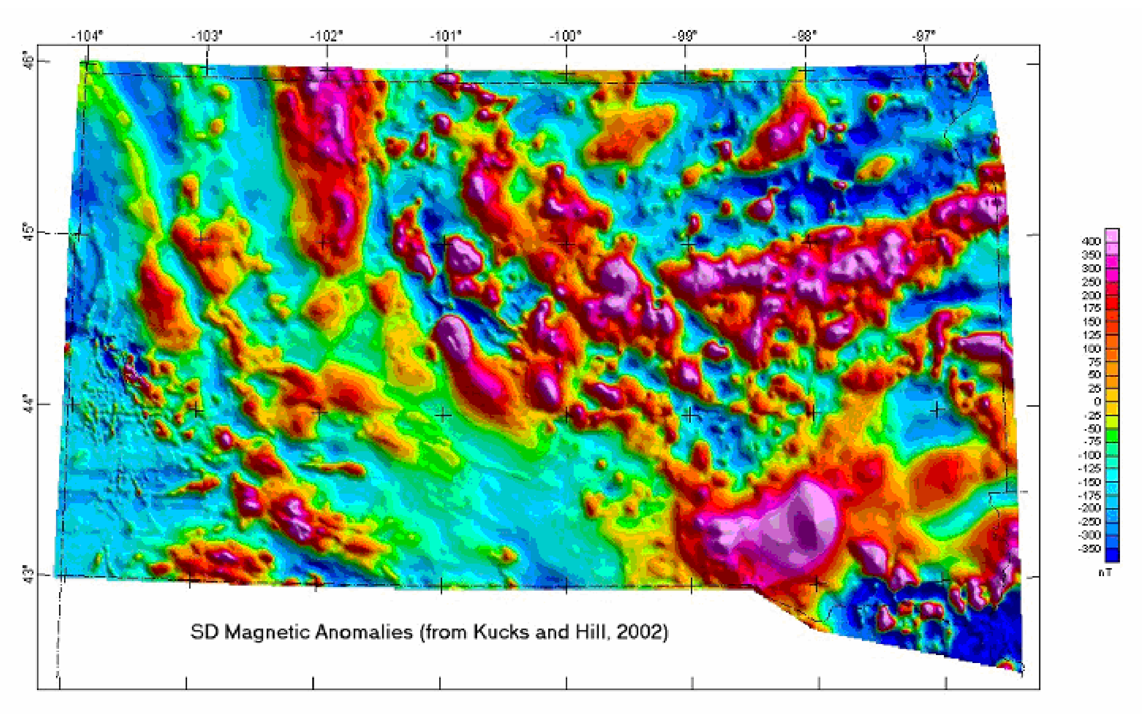
Heat flow map of the northcentral US. Units are mW/m^2.

Other investigations of a more regional nature may be aided by geophysical studies. Examples include studies of the regional heat flow and its relation to groundwater and changes in the gravity field due to fluctuations in groundwater amount, i.e. microgravity, Information from these types of studies may offer additional information on the local or even regional ground water system, which would be particularly important given the uncertainty in estimating the effects of dewatering due to the construction of the NUSL. Insights on the electrical structure of the crust and upper mantle both near the site and on a regional basis may be possible by performing electromagnetic studies using large antennas at the site of NUSL.

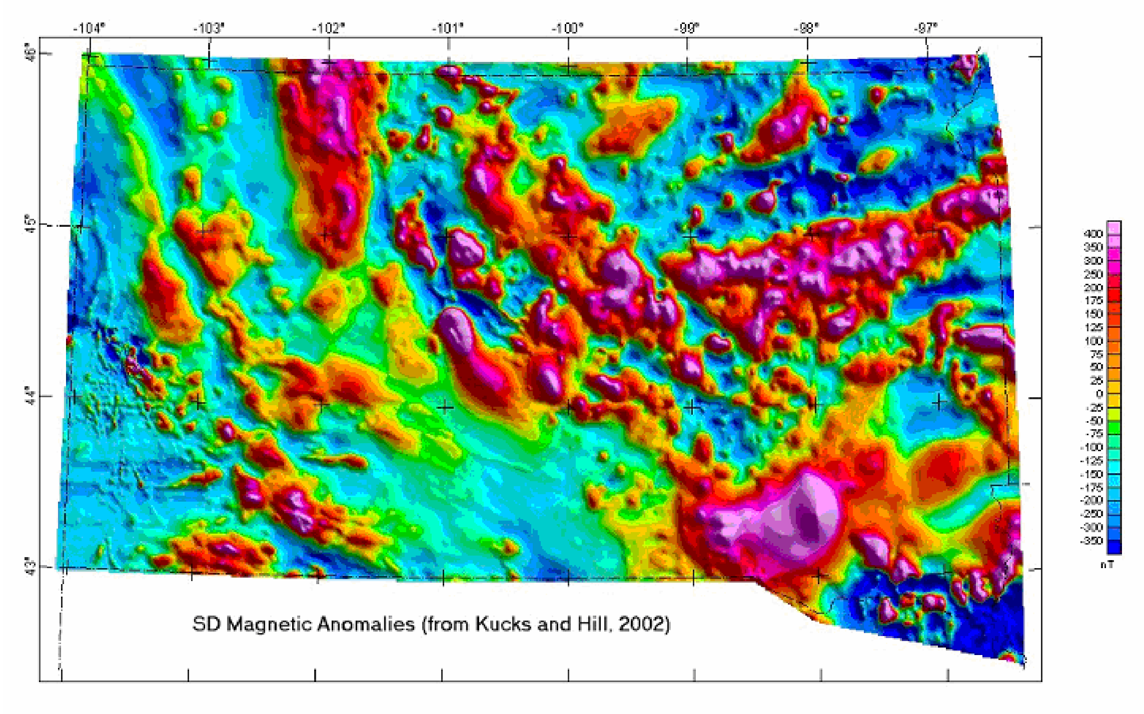
Studies specific to the Homestake area itself, however, include geophysical studies of the mine as an ore deposit (Heran, 1992), gravity work within the mine (Nutsch, 1989), magnetic and gravity anomalies of features (Everson and Roggenthen, 1988), and induced polarization studies within the mine itself (Mathison and Sumner, 1967).

Regional Geophysical Background

The general geophysical picture of the South Dakota region is dominated by variations within the Precambrian crystalline basement with input from Tertiary intrusive rocks in the northern part of the Black Hills (Kleinkopf and Redden, 1975). Kucks and Hill (2002) show the aeromagnetic anomaly and Bouger anomaly patterns for South Dakota, respectively. The eastern part of the state is dominated by NE trending magnetic and gravity highs resulting from rocks associated with the Superior province. The Black Hills and western side of the state are part of the Wyoming Archean Province, whereas the central part of the state appears to be the suture zone along which the two archean provinces were joined at approximately 1.9 Ga. In the vicinity of the Homestake Mine the 50 – 60 My intrusive rocks have magnetic signatures characteristic of reversely magnetized bodies and, in many instances, have sufficient strengths of magnetization to be easily recognized on regional aeromagnetic maps.



SD Magnetic Anomalies (from Kucks and Hill, 2002)



SD Magnetic Anomalies (from Kucks and Hill, 2002)

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