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Introduction to Potential Fields: Gravity

Introduction

Gravity and magnetic exploration, also referred to as “potential fields” exploration, is used to give geoscientists an indirect way to “see” beneath the Earth’s surface by sensing different physical properties of rocks (density and magnetization, respectively). Gravity and magnetic exploration can help locate faults, mineral or petroleum resources, and ground-water reservoirs. Potential-field surveys are relatively inexpensive and can quickly cover large areas of ground.

What is gravity?

Gravitation is the force of attraction between two bodies, such as the Earth and our body. The strength of this attraction depends on the mass of the two bodies and the distance between them.

A mass falls to the ground with increasing velocity, and the rate of increase is called gravitational acceleration, *g*, or gravity. The unit of gravity is the Gal (in honor of Galileo). One Gal equals 1 cm/sec^2.

Gravity is not the same everywhere on Earth, but changes with many known and measurable factors, such as tidal forces. Gravity surveys exploit the very small changes in gravity from place to place that are caused by changes in subsurface rock density. Higher gravity values are found over rocks that are more dense, and lower gravity values are found over rocks that are less dense.

A modern pioneer—U.S. Geological Survey geophysicist takes a gravity reading on the Oregon Trail.

How do scientists measure gravity?

Scientists measure the gravitational acceleration, *g*, using one of two kinds of gravity meters. An absolute gravimeter measures the actual value of *g* by measuring the speed of a falling mass using a laser beam. Although this meter achieves precisions of 0.01 to 0.001 mGal (milliGals, or 1/1000 Gal), they are expensive, heavy, and bulky.

A second type of gravity meter measures relative changes in *g* between two locations. This instrument uses a mass on the end of a spring that stretches where *g* is stronger. This kind of meter can measure *g* with a precision of 0.01 mGal in about 5 minutes. A relative gravity measurement is also made at the nearest absolute gravity station, one of a network of worldwide gravity base stations. The relative gravity measurements are thereby tied to the absolute gravity network.

What is a gravity anomaly?

Gravity meters measure all effects that make up the Earth’s gravity field. Many of these effects are caused by known sources, such as the Earth’s rotation, distance from the Earth’s center, topographic relief, and tidal variation. Gravity caused by these sources can be calculated using realistic Earth models and removed from the measured data, leaving gravity anomalies caused by unknown sources. To the geologist, the most important unknown source is the effect of the irregular underground distribution of rocks having different densities.

A sequence of gravity corrections are applied to the original gravity reading and result in various named gravity anomalies. The **observed gravity** anomaly has been corrected for Earth rotation, latitude, tidal effects, and gravity meter fluctuations.

The **free air** gravity anomaly has been corrected for the gravity effect caused by the elevation difference between the station and sea level (a correction for distance) and is a standard for oceanic gravity interpretation. The **Bouguer** (pronounced Boo-**gay**´) gravity anomaly has been further corrected for the mass that may exist between sea level and the observer (a correction for mass) and is a standard used in geologic interpretation on land. A **simple-Bouguer** anomaly has undergone a simplified removal of topographic effects, which suffices in relatively flat areas. A **complete-Bouguer** anomaly contains a terrain correction that uses a more complete representation of the local topography, which is necessary for accurate gravity values in mountainous areas. The **isostatic** (pronounced iso-**stăt**´-ic) gravity anomaly is calculated by subtracting the gravitational effect of low-density mountain roots below areas of high topography. Although these roots have never been seen, their isostatic effect has been measured and models calculated using topography. Isostasy is typified by floating icebergs that have 90% of their mass of ice below water that supports a smaller mass of ice projecting above water.

What is a gravity map?

A gravity map is made using numerous gravity measurements across the area of interest. Gravity surveying by aircraft is still a new science, so most gravity measurements are made on the ground at discrete stations. Because access is often a problem, gravity stations may be randomly spaced, although detailed surveys are usually made at regular intervals.

Gravity measurements are often processed to a complete-Bouguer or isostatic gravity anomaly. These data are then gridded, so that the randomly spaced data are converted to a representation of the gravity field at equally spaced locations. The distance chosen between grid points depends on the average distance between gravity stations. Too large a grid interval would not use all the information from the original data set, whereas too small a grid interval fragments the continuity of anomalies across a region—either result is a poor representation of the true gravity field.

Gravity anomaly maps can be shown as color figures—with warm colors (reds and oranges) showing areas of higher gravity values and cool colors (blues and greens) showing lower values—or as contour line maps, where each contour line follows a constant gravity value.

What is rock density?

Density is a rock property described by the ratio of mass to volume. Rock densities commonly range between 2.0 and 4.0 grams per cubic centimeter (g/cm^3). Pure water, by comparison, has a density of 1 g/cm^3. Each rock type can have a range of density values, and tables in the scientific literature show the general range of densities for various rock types. Often, the geoscientist will collect samples of exposed rocks in the study area and measure their densities to estimate the actual density of the rock unit where it is buried.

Various rock types within a study area often contrast enough in density to cause gravity anomalies. For example, sedimentary rocks that fill basins almost always have low densities and are characterized by gravity lows on anomaly maps. Mafic rocks, which contain high-density minerals, often are associated with gravity highs. The scientist can use these differences to map large regions where rocks are inaccessible or concealed, to look for faults that juxtapose rocks of different densities, or to infer structures such as basins, arches, and buried intrusions.

What is a derivative gravity map?

A gravity anomaly map contains information about rock density, and depth and distribution of anomaly source rocks. Maps can be derived from the original gravity anomaly grid by using mathematical tools to enhance parts of the gravity field. Derivative maps can show, for example, anomalies that have been mathematically filtered for size and that show deeper or shallower sources. Other derivative techniques can magnify gravity gradients, places where the gravity field changes from high to low—these places often mark edges of rock units or faults, or they can mimic a geologic map by converting (or “terracing”) the gravity anomalies into discrete, bounded units representing rock units. All of these maps can be used together to make a geologic interpretation.

Additional information

U.S. Geological Survey Open-File Report 95–77 lists many USGS computer programs and databases used to create gravity maps, and it is available on the web site listed below.

Information on gravity base stations and availability of gravity maps and data in specific areas can be obtained from:

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Introduction to Potential Fields: Magnetics

Introduction

Magnetic and gravity exploration, also referred to as “potential fields” exploration, is used to give geoscientists an indirect way to “see” beneath the Earth’s surface by sensing different physical properties of rocks (magnetization and density, respectively). Gravity and magnetic exploration can help locate faults, mineral and petroleum resources, and ground-water reservoirs. Potential-field surveys are relatively inexpensive geophysical methods and can quickly cover large areas of ground.

What is magnetism?

The force a magnet exerts on an iron filing or the force the Earth’s magnetic field exerts on the needle of a compass are two common examples of magnetism. A magnetic field has both intensity and direction. The strength of the magnetic force depends on the amount of magnetic material present and its distance and direction relative to the detector. The Earth’s magnetic field probably is caused by movement of partially molten iron in the Earth’s outer core. The magnetic field strength increases from 25,000 nanoteslas (nT) at the magnetic equator to 70,000 nT at the magnetic poles. (One nanotesla equals 1 gamma, and 10^5 gammas equals 1 oersted.) The Earth’s magnetic field changes in intensity and direction slowly over time.

Like all dipole magnets, the Earth has a magnetic field (also called the core or main field) that has a North and South Pole. The angle between a compass needle and true north is called the magnetic declination. The north-seeking end of a compass needle that is free to orient itself in an up-down direction will point down in the Northern Hemisphere and up in the Southern Hemisphere. The angle between the needle and horizontal is called the magnetic inclination.

How do scientists measure the magnetic field?

Geoscientists measure the Earth’s magnetic field intensity to an accuracy of 0.1 nT using magnetometers. Magnetic surveys usually are conducted from an aircraft. Ground surveys also can be made and are especially useful for locating buried metallic objects such as waste barrels.

An aeromagnetic survey is flown using an aircraft (airplane or helicopter) to which a magnetometer is attached. The most common aircraft magnetometers measure the total intensity of the magnetic field, but not its direction, along continuous flight lines that are a fixed distance apart. The aircraft can be flown at a constant barometric elevation (such as 9,000 ft above sea level) or at a constant distance above the ground (such as 500 ft above terrain, also called a “draped” survey).

Magnetometers measure all effects of the Earth’s magnetic field. Because the field changes slowly over time, models of this field, called the International Geomagnetic Reference Field (IGRF), are updated every 5 years. The IGRF for the time and location of a magnetic survey is calculated and removed. The magnetic field is also subject to complex short-term variations such as magnetic storms. For purposes of correcting aeromagnetic survey data, a base magnetometer records magnetic levels at a fixed location within the study area, and these variations are removed from the airborne magnetic data. What remains is the magnetic field largely associated with magnetic minerals in crustal rocks.

What is a magnetic anomaly?

Although the force of the Earth’s magnetic field is not very strong, it is large enough to magnetize certain kinds of rocks that contain iron or other magnetite-bearing minerals. Magnetic anomalies, therefore, are the differences between measured magnetic values and the values predicted from the model of the Earth’s core field. They are caused by variations in magnetization of crustal rocks. Measurements of many rock samples show that most sedimentary rocks are generally not magnetic, whereas igneous rocks rich in iron minerals often are very magnetic.

Because of the dipolar nature of magnetism, a single magnetic body can cause either a positive or negative magnetic anomaly or both (especially if the Earth's magnetic field at the time of rock formation is reverse of the present-day field), or it can cause a more complex magnetic pattern caused by tilting of the magnetic body itself.

What is a magnetic anomaly map?

A magnetic anomaly map is made from recorded flight-line measurements across the area of interest from which the Earth's field has been removed. These data are then gridded so that the flight-line magnetic data are converted to a representation of the magnetic field at equally spaced locations along and between the flight lines. Magnetic anomaly maps can be shown as color images—with warm colors (reds and oranges) showing areas of higher magnetic values and cool colors (blues and greens) showing lower values—or as contour line maps, where each contour line follows a constant magnetic value.

What is rock magnetism?

Magnetic susceptibility is a rock property describing the amount of magnetizable material in a rock. It is a dimensionless unit, and 1 electromagnetic unit (emu) in the cgs (centimeter-gram-second) system equals 4π SI (System International) units.

Rocks containing magnetic minerals may have two kinds of magnetization: ***induced*** and ***remanent***. Induced magnetization exists only in the presence of an external magnetic field. Remanent magnetization, however, is frozen within the rock, and the rock remains magnetized in a field-free area. Sometimes the direction of the Earth's field at the time of rock formation or alteration is preserved. The study of rock paleomagnetism is based on this property and, in some places, can be used to show rock movement through time. Studies of remanently magnetized rock show that the magnetic North and South Poles have reversed through geologic time. Remanent magnetization, therefore, can also give some indication of the age of magnetization. Both induced and remanent magnetization vanish above the Curie temperature (about 580°C for magnetite).

What is a derivative magnetic map?

A magnetic map contains information about both rock magnetization changes across an area and depth to the source of the anomaly. Maps can be derived from the original magnetic anomaly grid by using tools to enhance parts of the magnetic field.

In general, the deeper the magnetic source, the broader and gentler the gradients of the resulting anomaly will be. Also, in general, the shallower the magnetic object, the sharper and narrower the resulting anomaly. Derivative maps can show anomalies that have been filtered for size and shape to emphasize either shallow or deep sources. Another type of derivative map, called "reduced to the pole," can correct the anomalies for inclination and declination differences caused by location and produce the magnetic field of the bodies as though the area were moved to the North Pole. This simplifies complex anomaly shapes caused by dipole effects of the Earth's magnetic field and centers the anomaly over its source. Another derivative method can magnify magnetic gradients, places where the magnetic field changes from high to low—these places often mark edges of rock units or faults. All of these maps can be used together to make a geologic interpretation.

Additional information

U.S. Geological Survey Open-File Report 95–77 lists many USGS computer programs and databases used to create magnetic maps:

http://minerals.er.usgs.gov

Information on the availability of magnetic maps and data in specific areas and other general information on USGS airborne coverage can be obtained from:

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