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Introduction

Geophysics is the study of the earth, based on the principles and laws of physics. The study of the earth, based on the laws of the gravity and the magnetic fields, is known as the gravity and the magnetic methods of geophysical exploration. They are known as the natural methods as they employ the natural fields, namely, the gravity and the magnetic fields of the earth. Contrary to them, there are methods which employ artificial fields created specially for those surveys in an area such as electrical and seismic methods. As the gravity and the magnetic methods employ natural fields of the earth, they are the oldest geophysical methods used for the study of the earth and are easy to operate and cost effective compared to the other geophysical methods. Therefore, they are ideally suited for reconnaissance survey of large areas to limit the areas for detailed investigations. The gravity and the magnetic methods being directly related to the physical properties of the rocks, namely, the density and the susceptibility, respectively they are found to be very useful by field geologists and geophysicists in mapping and identification of various rock types. They are also used for direct detection of minerals with large contrast in density and susceptibility compared to country rock.

The earth has its own gravity and the magnetic fields, which gets modified in the presence of rocks of different properties. The earth's natural field F1 gets modified to F2 near a structure (Fig. 1.1) or anomalous body depending on its shape, size, depth and the physical properties like density or susceptibility in case of gravity and magnetic methods, respectively. The differences between the two fields (F2 - F1) is known as geophysical anomaly, namely, the gravity anomaly or the magnetic anomaly in the two cases. It depends on the configuration of the body, depth and physical properties of the causative sources. These fields are measured with the help of sensitive instruments at the surface of the earth or using different platforms, for example ship, helicopter, aeroplane and satellite depending on the target, their size, desired accuracy of the survey and accessibility to the survey area. The data is processed to obtain the gravity and the magnetic anomalies with respect to the ground position, which, in turn, are related to the surface or subsurface rocks, structures and their physical properties. The two most important characteristics of the anomalies are their spatial size and magnitude, which are popularly referred to as wavelength and amplitude, respectively. Broadly, the geological studies for which the gravity and magnetic methods have shown promise, are as follows:

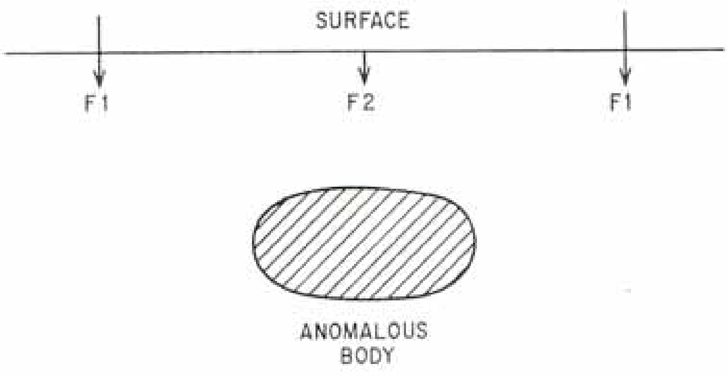

Fig. 1.1 F1 is the normal earth's gravity/magnetic fields which get modified to F2 in the vicinity of sub-surface anomalous bodies or heterogeneity. (F2-F1) is known as gravity/magnetic anomaly which depend on shape, size, depth and physical parameters, namely, density/ susceptibility of the anomalous body which can be derived from the observed/ measured anomaly.

1.1 Geological Studies and Gravity and Magnetic Methods

Gravity and magnetic methods are related to variations in density and susceptibility of rocks, respectively and produces complimentary images of structures which are integrated to provide their details. In fact, they are also integrated with all other available data sets to map subsurface structures. Their applications to various geoscientific studies are briefly described below while their detailed applications integrated with other geophysical - geological data sets are discussed and demonstrated in the forthcoming chapters.

1.1.1 Geodynamics and Plate Tectonics

Since 1912, when Alfred Wegener proposed the theory of continental drift that has explained several geological observations in a unified manner, it therefore, formed one of the most important aspects of geodynamics. However, it did not account for the forces responsible for drifting of the continents and was therefore, replaced by plate tectonics during 1960s, which accounted for these forces due to mantle convection (Uyeda, 1978).

Plate tectonics is presently one of the most important aspects of global geodynamics. Gravity and magnetic methods are used to study the different aspects of geodynamics and plate tectonics of a region. Some of their applications in this regard can be briefly described as follows. However, there are several other applications of geophysical methods in general and gravity and magnetic methods, in particular, that are outlined in the forthcoming chapters.

(i) Plate Tectonics

Plate tectonic theory provides a unified model to explain most of the tectonic processes observed on the surface of the earth and subsurface. It is briefly outlined here to introduce this topic that is essential to discuss gravity and magnetic anomalies due to its certain aspects in Chapters 2 and 3, respectively. However, it is discussed in great detail in chapter 5 though same illustrations are referred here. Accordingly the earth's upper layer (lithosphere) is divided into different plates, which are separated by mid oceanic ridges and subduction/collision zones along plate boundaries as shown in Fig. 5.13. Plates may consist of both continental and oceanic parts representing both continental and oceanic lithospheres. It shows some major and some minor plates which are separated by ridges and subduction zones referred to as divergent and convergent plate boundaries where different plates diverge and converge, respectively. Some important mid-oceanic ridge systems are Mid-Atlantic Ridge, Indian Ocean Ridge system, East Pacific Rise etc., named after the oceans they occupy. Collision and subduction zones are found on other side of the plate accompanied by fold belts on continents and trenches in oceans, respectively such as Himalayan Fold Belt and Andaman-Sumatra-Java (Sunda) trench (HIM, ASJ; Fig 5.13). Besides these two features, the third important element is known as Transform faults, which are similar to strike slip faults along which the two plates slip past each other. San Andreas Transform fault system along west coast of USA is one such example (SAF, Fig. 5.13). Chamman fault in Pakistan (CH; Fig. 5.13) related to Pakistan Fold Belt between the Indian and the Eurasian plates is an example of transform fault related to the Indian plate.

Mid oceanic ridges are linear features where volcanic rocks wells up from inside the earth and spreads over the ocean bottom forming the ridges, which diverge the plates on either sides and are therefore known as divergent margins (Fig. 1.2). Mid oceanic ridges are, therefore characterized by mafic volcanic rocks and magnetic profiles across them show normal and reverse polarity of rocks located almost symmetric with respect to the ridge, which is discussed in detail in Section 5.2. These are known as sea floor spreading magnetic anomalies and their polarity indicate the polarity of earth's magnetic field at the time of their formation. On the other hand, along convergent margins plates on the surface of the earth converge and collide and in the process, one subducts under the other and is therefore known as subduction zones (Fig. 1.2). As shown in this figure, magma erupts and spreads at Mid Oceanic Ridges and pushes the oceanic lithosphere on either side as indicated by arrows. Once the oceanic lithosphere encounters a continental shelf as shown on either margins of this figure, it subducts below the continental crust as it is comparatively heavier (higher density) than the latter. The contact of the two is characterized by deepest parts of the ocean known as trenches where deep basins are formed. During its movement, it may encounter some localized sources of magma such as plume which may give raise to chains of volcanoes that are known as sea mounts in case of oceans. Once the zig saw puzzle of sea floor spreading magnetic anomalies were sorted out and continents were brought back in time, they appeared to join together. This gave rise to plate tectonic theory, which in most simple form suggests that the earth is made up of several plates, which move and collide with each other and on collision, form the mountain chains and depending on the density of rock types subduct one under the other. They are chanacterized by seismic actiurty due to intense tectonic activities at plate boundaries.

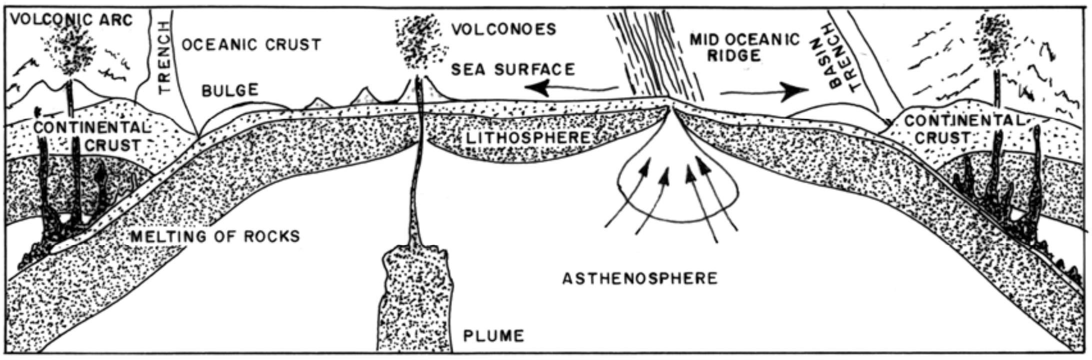

Fig. 1.2 A schematic section of Mid Oceanic Ridge where two plates diverge due to intrusion of magmatic material from asthenosphere forming oceanic crust. During plate motion, they encounter continental shelf where they would subside due to their higher density compared to continental crust. The subducted material melts at the depth giving rise to volcanic arcs. During plate motion, it may encounter plumes giving rise to volcanic chains.

Based on direction of forces in two cases, viz. mid oceanic ridges and subduction zones (Fig. 1.2), the tectonics related to them are termed as extensional and convergence tectonics. The subducted material at certain depth, melts due to frictional heat and high temperature to give rise to magma, which rises through fractures and faults giving rise to volcanic chains known as island arcs or magmatic arcs. However, in case of collision between two continental plates, such as Indian - Eurasian plates, the rocks are deformed as both are of almost same density. In such cases, the upper part of the crust forms the mountain chain through thrusting and folding, while its lower part slips one under the other causing thick crust and several related tectonic activities like earthquakes, volcanoes etc., Due to weight of the overriding plate, the subducting plate flexes and causes bulging of the subducting plate as it happens in case of cantilever beams in civil engineering (Fig. 1.2). This implies that while material is generated at mid oceanic ridges from within the earth, it is consumed at plate boundaries during subduction providing a mass balance in earth's system. Plate tectonics is important not only for tectonics and geodynamics but is also important for resource exploration. Most of the mineralized sections of base metals, precious metals (gold), chromites etc., occur along fold belts (mountains) that are formed due to collision of two plates as shown in Fig 1.2. In this regard, ancient fold belts of Archean- Proterozoic period (Appendix I) assume special significance as discussed in Chapters 7 and 9. It is also important for hydrocarbon exploration as most of the sedimentary basins are formed along fold belts (Fig 1.2) or along rifted margins that are essential elements of plate tectonics.

They are characterized by specific features which produce typical gravity and magnetic anomalies as discussed in sections 2.9 and 3.8 respectively. Gravity and magnetic methods used for various applications in plate tectonics are briefly as follows:

(a) Reconstruction of continents and their movement during different geological periods based on direction of magnetization and seafloor spreading magnetic anomalies.

(b) Crustal structures and physical properties of rocks (density and susceptibility) with depth.

(c) Continuation of large-scale structures from one continent to the other before their breakup based on their gravity and magnetic signatures.

(d) Mantle dynamics related to plate tectonics based on satellite gravity anomalies.

(ii) Crustal Structures

The top most layer of the earth is known as crust. Its structure and composition plays a vital role in geodynamics of a region. Gravity and magnetic methods are extremely useful for crustal studies, which can be summarized as follows:

(a) Delineation of deep seated structures in the upper mantle and the crust and their physical properties, viz density and susceptibility.

(b) Variation in the crustal thickness (depth to Moho) based on gravity anomalies.

(c) Curie point geotherm based on magnetic data, which is defined as the temperature beyond which magnetization in rocks cannot exist. It is equivalent to the Curie point of magnetite equal to 570^{o} C. In some sections, it may coincide with Moho or may be deeper or shallower depending on heat flow in the region.

(d) Compensation of surface load and rheological properties of the crust and the lithosphere based on isostasy such as elastic thickness, flexural rigidity etc., based on gravity anomalies and topography which is described in Chapter 4.

(iii) Plume Tectonics

Plumes are large bodies of gaseous and fluids, which rise from inside the earth (Fig. 1.2) and give rise to large scale volcanic provinces in different parts of the world such as Deccan trap and Rajmahal trap in India, Karoo volcanics in Africa, Columbia flood basalt in USA and islands of Reunion, Kerguelen etc. Some of them are discussed in Chapter 5. Due to their high density and high susceptibility, gravity and magnetic methods are widely used for their studies, which are as follows:

(a) Delineation and demarcation of plume affected surface/subsurface regions

(b) Assessment of their physical properties like bulk density and bulk susceptibility and based on them identification of rock types.

1.1.2 Resource Exploration – Hydrocarbons, Minerals and Groundwater Exploration

The application of gravity and magnetic methods to resource exploration such as oil, mineral and groundwater exploration is generally indirect, which are basically used to limit the area of investigation and delineate structures that are important for this purpose. However, in case of exceptionally heavy and magnetic minerals, they can be used directly to explore them. Their specific applications for this purpose are as follows that are discussed with details in Chapter 9.

(i) Geological Mapping

Geological mapping is an important aspect of resource exploration. Regional gravity and magnetic surveys are found to be extremely useful for this purpose as they provide information about subsurface structures and depth extent of exposed structures. In this regard, airborne-surveys are found to be specially useful. Some of the usages of these methods for this purpose are as follows:

(a) Delineation and demarcation of different geological provinces and tectonic units such as basins, rifts, cratons, collision zones etc., and their three dimensional extensions.

(b) Delineate large scale structures such as lineaments, faults, fractures, joints, intrusives etc.

(c) Delineation of different rock types based on their physical properties, viz. density and susceptibility.

(ii) Hydrocarbon Exploration

Application of gravity and magnetic methods for hydrocarbon exploration is primarily reconnaissance in nature to limit the areas for detailed exploration. They are presently widely used along with other exploration strategies. Some of the usages of these methods in collaboration with other geophysical methods for integrated exploration programs in this regard are as follows:

(a) As a reconnaissance method to limit the area for detailed investigation by more involved and costly geophysical methods such as seismic surveys.

(b) Evaluate basement depth and three-dimensional basement configuration in sedimentary basins.

(c) Delineate structures such as faults, anticlines, synclines etc., in the basement and overlying sediments.

(d) Shallow structures in sediments for gas occurrences.

(iii) Mineral Exploration

Most of the minerals being characterized by specific density and susceptibility, these methods are widely used for this purpose, which can be briefly described as follows:

(a) As a reconnaissance method to limit the area for detailed investigation.
(b) Delineation of mineralized zones and the structures like lineaments, faults and fractures, which control the mineralization in an area.
(c) Direct detection of heavy/light and magnetic minerals such as iron ores etc., and their extensions depending on their physical properties, viz. density and susceptibility.

(iv) Groundwater Exploration

The application of gravity and magnetic methods for groundwater exploration are mostly indirect and serves as a complimentary method to electrical methods. Some of the usages of these methods for this purpose are as follows:

(a) Delineation of bed rock topography and structures.
(b) Delineation of faults and fractures in hard rock areas, which might be water bearing.
(c) Delineation of large scale lineaments specially airborne magnetic lineaments, which defines different hydrological regimes.

1.1.3 Environmental Studies – Seismotectonics and Near Surface Geophysics

Gravity and magnetic methods are widely used for environmental natural hazard assessment. There are two aspects to it, firstly the hazard assessment such as tectonics related to seismic activity known as seismotectonics and secondly for evaluation of engineering sites. Engineering geophysics is related to selection of suitable sites for large scale construction where gravity and magnetic methods are widely used to delineate shallow structures such as faults, fractures, lineaments etc., Environment is in fact a part of geosciences and gravity and magnetic methods are used for several studies related to environment.

(i) Seismotectonics

Seismic activity in a region depends on tectonics of region, which can be inferred to a great extent from gravity and magnetic surveys. Some of the usages of these methods for this purpose are as follows:

(a) To delineate the tectonics specially faults related to seismic activity.
(b) To determine the characteristic parameters of faults related to seismic activity.
(c) Temporal variations in the gravity field due to dynamic changes at plate boundaries based on satellite gravity measurements.
(d) Coseismic changes based on gravity measurements before and after an earthquake.

(ii) Engineering Sites

These investigations are classified as Near Surface Geophysical Problems. Engineering geophysics involves the application of these methods to delineate local tectonics at the construction sites. Some of the usages of these methods for this purpose are as follows:

(a) Delineation of structure such as faults, fractures etc., at the site of large scale constructions such as power plants, dams, reservoirs etc.
(b) Bed rock investigation for its depth, nature and structures related to its stability.
(c) Nuclear waste disposal sites regarding their stability and absence of faults, fractures, lineaments etc., in these sections.

(iii) Climate Changes

Availability of high resolution satellite altimetry data for long periods (8-10) years have made it possible to study factors related to long range climatic changes. The following aspect of satellite altimetry is relevant for climatic changes:

(a) Mean Sea Level changes with time based on satellite altimetry.

(b) Changes in ice mass loss and its transfer in Greenland and Antarctica based on changes in the gravity field inferred from satellite altimetry which is connected to greenhouse effect and global warming.

(iv) Mining Geophysics

It involves the application of these methods for the problems related to mining. The application of these methods for this purpose are as follows:

(a) Delineations of faults, fractures, lineaments etc., similar to other applications discussed above.

(b) Delineation of voids, water fills and land fills etc., in the mining areas.

(iv) Volcanoes and Volcanic Activity

Volcanic rocks being usually characterized by specific density and susceptibility, gravity and magnetic methods can be effectively used for their studies. Some of the applications are as follows:

(a) Nature of volcanic activity in terms of their physical properties, viz density and susceptibility and probable composition.

(b) Onset of volcanic activity based on borehole gravity measurements in surrounding regions of known volcanoes.

(c) Surface/subsurface region affected by volcanic activity.

(v) Land Slides

Land slides in hilly terrains usually occur along fault planes and fractures, which can be delineated based on gravity and magnetic surveys as described above in case of other applications.

(vi) Impact Craters

Meteorites being igneous mafic or ultramafic rocks, they are characterized by high density and high susceptibility, which can be studied using these methods. Some of the applications are as follows:

(a) To infer their physical properties like density and susceptibility

(b) Their effects depth-wise on impact at the surface of the earth.

1.1.4 Different Modes of Surveys – Ground, Marine, Airborne and Satellite Surveys

In case of gravity method, the most popular mode of survey is ground gravity survey. In oceans, marine surveys or satellite altimetry is widely used for preparation of 2-dimensional gravity maps whose resolution, however, is limited due to height of satellite and data gaps between different passes.

In case of magnetic method, the most popular and useful mode of survey is airborne magnetic survey due to speed of survey and possibility of measuring field at closed interval in otherwise inaccessible regions. Airborne gravity surveys, however, are not very popular due to inaccuracies in the measurements of the gravity field from aeroplanes and cost involved in such surveys. However, due to improvements in technology and cost effectiveness, it is now being increasingly used to survey inaccessible regions as discussed in Section 2.6. Shipborne gravity and magnetic measurements are carried out for surveys in oceans. Satellite derived magnetic and gravity data are used for delineating deep seated structures in the lower crust and upper mantle specially in inaccessible regions such as hills (Himalayas), forests, oceans etc. (Sandwell and smith, 1997, Mishra et al., 2004, Reigberg et al., 2005). Satellite derived magnetic data are also used for estimation of depth to Curie point geotherm below which magnetization of rocks does not exist (Mishra and Venkatrayudu., 1985). In fact, gravity maps of oceans and delineation of large wavelength gravity anomalies (> 1000 km) are possible only by satellite based surveys, which enables to probe deep into the mantle.