Chapter 1
Introduction

1.1 The Subject and Scope

1.1.1 Gravity

Gravity interpretation is an important endeavour in the quest for understanding the Earth. This is so for several reasons. The shape and mass distribution of the Earth are governed by the central force of gravity counteracted mainly by the molecular and atomic forces against compression and deformation. Ongoing geodynamic processes are driven mainly by thermal disturbances of the equilibrium which gravity tries to achieve, to maintain or to restore. The processes generate density distributions which produce observable gravity signals which are the target of gravity study. Near the surface in the Earth's crust geological structures resulting from past geodynamic processes are "frozen in" and preserved over long periods, as the gravitationally driven forces inherent in the structures are too weak for the strength of the material to be overcome. Natural resources of all kinds are hidden in the structures. Gravity is an economic tool for exploring and discovering the resources.

The relationship between mass and effect is "asymmetric", the effect directly calculable but not vice versa. The resulting notorious ambiguity is the main drawback of gravity interpretation and gives it a "poor reputation". However, in many respects the reservation is not justified if gravity interpretation is seen in perspective. In the first place, information gained from gravity is not in every respect ambiguous; the ambiguity is in the geometrical density distribution, in particular the important parameter of depth. No ambiguity exists in the presence of an object of potential interest inferred from the presence of an observed gravity anomaly, although the opposite is not true: the lack of a gravity anomaly does not necessarily mean that no mass anomalies exist underneath. Equally, the horizontal location (coordinates) of the "centre of gravity" and the total amount of the anomalous mass are unambiguously obtained from the gravity anomaly. The depth of the anomalous mass and its shape or distribution *are* ambiguous. However, the ambiguity is reduced, even by only qualitative arguments, and some aspects of the interpretations can be highly probable. The ambiguity is further reduced by additional "a priori" information from many other sources such as other geological and geophysical data. If such data with uncertainty limits are well known, the problem of gravity interpretation can be "solved" by inversion, especially by "Bayesian inversion" which attempts to achieve the best compromise between all pieces of available information within their particular uncertainty limits, usually called "errors".

An important related aspect is that any data manipulation motivated by many different purposes is explicitly or implicitly an act of interpretation or at least affects the subsequent modelling, inversion and interpretation. Often data on a profile or a map are filtered or smoothed, perhaps to emphasize certain geologically interesting features or simply to render a clearer picture. It must be kept in mind that this does not go without effects on the final geological models. It is advisable to check the results, e.g. by filtering the inverted results with the same filter as applied to the original data. If the filtered results and the unfiltered ones are the same, then filtering is independent from the inversion results. Otherwise filtering did remove some effect present in the model itself which means that the residuals (unfiltered observations minus model effects) increase and the results are distorted.

1.1.2 Motivation

Passing on the experience gained with this type of gravity interpretation, and the insight into the teaching and learning processes involved, are the prime motivation for writing this book. An overview is attempted of the whole field as we know it at the beginning of the 21st century, both from the perspective of basic research and from the application to problems of exploration. Many new developments have taken place, partly in industry with its financial and technical capabilities not available to universities. It seems timely to write such a treatise, although it is difficult to obtain an overview of all the new developments.

The classical 1961 book by K. Jung: "*Schwerkraftverfahren in der Angewandten Geophysik*" (*Gravity methods in Applied Geophysics*, KJ61) is long out of print; it is still quoted even in the English language literature, because of its in-depth and far-sighted treatment of the subject, including topics which became really useful only with increasing computing power. We attempt to follow Karl Jung's footsteps and to present a concise treatise covering subjects from potential field theory, the observation techniques, reductions and data analysis to quantitative interpretation methods and inversion. KJ61 has, indeed, been an important guide in writing the present book. Naturally the authors (WJ and PS) have taken advantage of their knowledge, not only of Jung's book but also from personal study and advice. WJ had Karl Jung as his PhD advisor and PS did his PhD thesis on inversion with WJ as advisor.

There is a lack of recent texts in gravity interpretation. One exception is Blakely (1995), though his emphasis differs. Of course, the numerous books published on applied geophysics in general over the years, devote one or two chapters to gravity, and the other potential field of magnetics. Of these, the two classic books by Grant and West (1965), (GW65) and Telford et al. (1990) have been consulted extensively.

1.1.3 Aims

The aim of this treatise is to give students and professionals insights into potential field interpretation, based on the fundamental theory, especially the gravity field (Chap. 2). The interest in potential field theory goes back to astronomy and geodesy and was summarized in Newton's laws. Gravity is the main subject, but a brief introduction into the theory of magnetics (2.11) is added. While the emphasis is on geophysics and its geological applications, geodesy is intimately connected to gravity, and it is an important goal to bridge the gap between these different specializations.

It is the intention of the authors to give an overview of gravity observation (Chap. 3) as well as reduction and data analysis (Chap. 4). The principal aim of sharing our experience with, and insights into, gravity interpretation leads us to structure its discussion into three chapters: qualitative interpretation (Chap. 5), quantitative interpretation (Chap. 6) and optimization and inversion (Chap. 7). The notion of gravity *anomaly* is central to the whole subject and must be carefully reflected upon, and it usually means an ensemble of differing values in space, i.e. more than a single anomalous point value; it is an important aspect to which we shall return many times, especially in 1.4; 2.6 and 2.9; 3.4; 4.3, 4.6 and 4.77; and of course, in Chaps. 5, 6 and 7 as interpretation always concerns fields, not single points.

Interpretation involves, beside the determination of the source distributions, also their geological implications. "Geological" refers to any aspect of Earth structures and processes, irrespective of scale. In view of the double role of gravity in driving processes and generating useful signals, geodynamics is an important aspect. These aspects are closely related to each other and must be envisioned together when interpreting gravity anomalies, the more so, the bigger the volumes considered. They must be especially taken into account in problems of gravity inversion which attempts interpretation on a rigorous mathematical basis, by models within quantifiable error bounds.

It is our aim to show that in spite of the notorious ambiguity of the inverse problem in potential field theory, gravity is a very useful tool for studying the Earth's interior. True: only the forward problem has unique solutions, and the inverse problem is non-unique. If the source distribution is known, the field distribution is uniquely determined by mathematical relations involving integrals over the mass distributions or convolution of the mass with certain kernel functions. However, there are infinite numbers of mass (or magnetisation) distributions which generate the same gravity (or magnetic) "image". It is emphasized that the solution or model space (or domain) can be reduced with the aid of additional a priori information, and only with it, no matter whether it provides tight or loose constraints. It must thus be carefully evaluated. The task will be to find solutions that are reasonable, plausible or probable compromises between all pieces of information, even if they are in mutual conflict.

The task involves more than mathematical methods and requires more than knowledge of available methodologies. What is needed is something like feeling or intuition based on experience of successful solutions of the problem of gravity interpretation. Intuition may be defined (Wikipedia) as the gift of forming spontaneous, subconscious ideas, for example, insights into complex relationships or inventions – without explicit analytical deduction. Intuition involves an element of chance, but as Louis Pasteur is quoted: "chance in a prepared mind". It is also called "serendipity". It is hoped that the reader will gain some of this through studying this book. But intuition has also the other side of experience generally being guided by "current wisdom" and thus not without bias which may block the imagination. Imaginative minds are needed to transgress such limitations to open up new avenues of thinking about gravity interpretation. Quite often gravity anomalies do guide researchers to well constrained geological solutions or models.

1.1.4 Special Aspects

Some aspects are somewhat unconventional and novel. For example, in the integration of gravity effects of extended mass volumes (Sect. 2.8) a special approach is taken. The long known principle of integration along "rays" from the observation point to mass elements contained within a solid angle from the observation point P (KJ61, 148-155) is exploited systematically. Because this does not generally give the wanted vector effect, it has to be complemented by considering the gravitational components parallel to causative straight mass lines and planes. This way, many of the occurring forward problems are conceptually more easily treated than by schematic classical integration over customarily defined bodies. The widespread misconception that the gravity vector effect of an arbitrary body principally points to its centre of mass was mentioned in the Preface.

Although gravity is central to this treatise, observations of other field quantities (Sect. 2.7.2) are included and need not be transformed into gravity before modelling. As additional errors affect the transformations, it is principally better to model the observations directly; the expressions are provided in Sect. 2.7.2. For purposes of aiding creative imagination, transformations remain, of course, useful, as maps remain important when most data analysis and interpretation are done digitally, i.e. "invisibly".

1.1.5 The Book and the Reader

Experience is acquired by doing, not by theoretical or exclusively technical learning. Experience can be shared. Experience is gained by practicing problem solving.

Feeling and intuition grow with experience possibly guided by a book like this one. It provides the necessary theoretical and practical foundations and includes exercises. Practical problems of gravity inversion are posed and readers can do them. That will lead to surprises and failures as well as successes.

Students new to the field may follow the book and do the exercises along the way. Remember that some patience is needed when, in the beginning, a problem seems unfamiliar and complex. Early attempts to understand a section or to solve a problem may be fraught with mistakes, but with persistence the misunderstandings disappear and solutions fall into place. Or it may become clear that a problem posed cannot be solved. The authors themselves have gone, and are still going, through such a process, and the book can be a guide or a map helping the wanderer to find her/his own way with her/his own short-cuts and detours. For some of us it may be very helpful to always have a pencil and a piece of paper at hand and immediately sketch the situation described in the text. The human mind, while individually very variable, seems to strongly cooperate with the whole person and her/his body; maybe, it is the time and effort spent on sketching which gives the brain the time needed to grasp an idea fully.

Readers familiar with the basics can begin with the chapter on inversion and consult the earlier chapters when necessary; cross references are given frequently. Chapters 2–4 introduce the basic concepts of potential theory, of measuring gravity and of data treatment and analysis. Chapters 5 and 6 deal with qualitative and quantitative interpretation and Chap. 7 discusses gravity inversion extensively.

One last word about how to find more on gravity and new developments driven by new technologies of observation and computation or other earth science aspects. Today the internet is a source of useful science information, but can be difficult to use discriminately by those lacking basic knowledge and judgement in the fields of enquiry. The individual cannot hold all the wanted details in mind, but basic knowledge is the precondition for judging the available information and making use of it. This book wishes to provide the basic knowledge and understanding for further studying and applying the science of gravity interpretation.

1.2 Historical Review

1.2.1 Astronomy, Geodesy, Geophysics, 18th and 19th Centuries

Gravity is an everyday experience so that it is hardly noticed in daily life. Only if we have to lift a heavy weight or climb a steep mountain do we feel gravity, and we observe the notorious falling apple. Weight and gravity are not the same, gravity abstracts weight from mass; weight is the product of gravity and mass. Galileo Galilee may have been the first to clearly understand that gravity is the common acceleration all masses experience in free fall, i.e. “free” from any obstruction, air included. Isaac Newton, the first to postulate central forces acting through empty space, explained the observations, especially Kepler's three laws of planetary motion, and derived mathematically his two fundamental laws of mass gravitation and inertia. Gravitational attraction decreases with distance r as $1/r^2$. This can be understood as a quality of Euclidian space with the assumption of a constant gravitational flux (see Sect. 2.1 and 2.7.5; Eq. 2.1.1), emanating from any massive body, and evenly spreading over spherical surfaces which grow in area proportional to r^2. In contrast to magnetic flux, the notion of gravitational flux is not established, but nevertheless equally useful. Modern space and satellite geodesy must consider relativistic aspects; however, this subject does not affect today's down-to earth geophysics where, generally, classical Newtonian physics in space and time is fully adequate.

That gravity varies along the Earth's surface was experienced by the early explorers who took pendulum clocks along their voyages and noticed that, near the equator, the clocks ran late. With time, systematic variations of gravity were discovered all over and compared to the gravitational attraction of large masses calculated from Newton's law. Measuring the Earth, for example, the length of the meridian, in the 18th and 19th centuries clearly demonstrated the importance which gravity has for the figure of the Earth and for measuring it. Observation of deflections of the vertical by astronomical and geodetic means, gravity measurements with pendulums, since P. Bouguer (1698–1758), and measurement of gravity gradients with the torsion balance became the domain of geodesy. They also brought insights into the principles of mass layering, isostasy was suggested by G.B. Airy (1801–1892) and J.H. Pratt (1809–1871) as the Himalayan masses appeared to be compensated by a mass deficit at depth (a review, as an example of internet-based information is given in http://www.univie.ac.at/Wissenschaftstheorie/heat/heat-3/heat393f.htm).

1.2.2 20th Century

Measuring gravity directly, in the 20th century, became an important tool for mineral and hydrocarbon exploration. These achievements made it necessary to work out applications of Newton's law theoretically which is the essential basis for all gravity interpretation. Thus, gravity on Earth can be safely founded on classical Newtonian physics (although observations with the aid of satellites are bringing us into the age of Einsteinian relativity). Theory for gravity interpretation has been laid down in many classical works on geodesy and geophysics; the present treatise attempts a condensated presentation of the essential aspects in Chap. 2.

Progress in gravity research is closely linked to the observational precision, which is driven by the advance of experimental physics. Methods of gravity observation evolved slowly in the 18th and 19th centuries, when pendulums, telescopes and torsion balances were the exclusive tools. The 20th century brought an explosion of new instrumental developments, especially the gravity meters. Rather recently, borehole gradiometers of highest sensitivity have been constructed, tested and employed in exploration. Since artificial satellites have been launched, a new era of gravity observation from space has begun, and the best knowledge of the Earth's gravity field is now being gained by combinations of terrestrial and space observations of different nature. Beside gravity itself, the gravitational potential has become observable indirectly by radar satellites that measure the ocean surface topography which, to a first approximation, is the equipotential surface of the geoid. Measuring accuracies are reaching levels permitting the distinction of the sea surface topography from the geoid such that the effects of ocean currents, temperature and salinity variations can be isolated which is of high relevance for oceanography and climate research. A brief account of today's methods is given in Chap. 3.

Gravity measurements need to be reduced (Chap. 4) by numerically removing several calculable effects which obstruct their efficient interpretation. For the reductions, the geodetic coordinates or locations, including height or elevation are needed. Thus, the recent tools of satellite geodesy, especially GPS and GLONASS and future improved systems, as the European GALILEO, have an immense impact on gravity measurement, analysis and interpretation.

Besides, a contemporaneous technological development of great consequence to gravity research is the dramatic increase of computation power. The basic theory was worked out and many applications were formulated long before the advent of efficient numerical computation, but its possibilities have made it necessary to design new program tools that considerably enhance the usefulness of gravity studies. They involve handling of large digital data sets, their representation and analysis by spherical harmonics and Fourier series, modelling of complex structures (Chap. 6) and visualization. But that has not made simple modelling superfluous, because complex models can be applied reasonably only with the aid of good human imagination and intuition which are strongly aided by developing a feeling for the nature and size of model effects (Chap. 5). For this, i.e. the interaction of the human mind with computing power, visualisation is essential. It is not just nice, but is a tool for uncovering problems, suggesting solutions and also facilitating communication between scientists of different fields.

The reliability of gravity interpretation strongly depends on the accuracy of all data input. The more the errors are reduced and the more reliably they are estimated, the more successful can gravity inversion (Chap. 7) become, provided that also the additional or a priori information from other sources has a similarly improved quality.

1.2.3 Geodesy and Geophysics

Geodesy and geophysics have diverged in their development accommodating to their individual need and emphasis. Separate terminologies are now in existence which hamper communication and mutual learning from each other. Examples are "gravity anomaly", "gravity disturbance", "correlation", "nullspace", etc. The central theme of geodesy is measuring Earth and thus questions of errors or accuracy are of paramount concern; typically, a geodesist will ask a geophysicist, how accurately (s)he wants to have certain observations to be made. But the geophysicist is concerned with the more or less inaccessible interior of Earth and cannot generally anticipate what is needed, so may not be able to answer such a question precisely, except saying: "as accurate as possible". Moreover, the existence of uncontrollable effects, for example, of local density variations, limits the required precision. Only if both sides have a basic common understanding of each other's problems and thinking, will they be able to unite their efforts. It is time to attempt bridging the gap. As the present authors come from these two fields, geophysics and geodesy, they hope to be in a good position for such an attempt. It must include geology that is the object of much of geophysical research and has incorporated most of the geophysical insights into Earth's interior. The view of the triple geodesy – geophysics – geology is to be complemented by all other branches of the earth sciences which as a whole might best be called "geology" in the widest sense as the study of the Earth.

1.3 Purposes of Gravity Measurements

Today's aims of measuring gravity, as in the past, have a wide scope which extends with increased precision and in combination with other improved measurements, e.g., of distances and coordinates. Applications are inherent in *geodesy* – paramount for defining the Earth's shape, for example, in combination with levelling and other methods of surveying. This is especially evident with the Global Positioning System GPS which gives the radius of a point from the Earth's centre and requires knowledge of the geoid – the gravitational equipotential surface – to provide the point elevation above sea level. In *geophysics* and geology the aim is exploration of the Earth's interior and gravity has also important bearing on oceanography, archaeology, engineering and even on theoretical physics. In geodynamics temporal gravity change is becoming a topical subject as the space-time behaviour reflects processes as loading or unloading and flow inside the Earth. Precise recording of temporal gravity variation can reveal mechanical properties and even deep processes as Earth core oscillations.

A division is usually made between general geophysics and applied geophysics. It is rather artificial, since geophysical gravity observations are frequently applied to problems outside gravity. Nevertheless, a gap in outlook and terminology has developed also between these branches or communities of geophysics because there are differences in emphasis and aims of research in industry which must produce economic value, and university motivated by fundamental science. Both are equally important in human culture. Different motivations unavoidably influence thinking, but seeing this should also stimulate learning from each other. Thus, this book wants to serve both communities and to provide a basis for many kinds of application.

1.4 Gravity and Gravity Anomalies

"Gravity interpretation" means precisely "interpretation of gravity anomalies". As emphasized in Sect. 1.1.3, gravity anomalies are the very object of interest, although an anomaly always requires two things: an observation and a norm or reference or something expected to represent a normal field. We consider anomalous the deviation of the observation from the expected. The gross variation of gravity on Earth quite closely corresponds to what is expected from an idealized Earth with no lateral variations of structure and density, such as would be the case if a fluid would perfectly accommodate to the forces originating only from self-gravitation and rotation. One has come to call such an Earth the "normal earth". But, beyond the parameters of the normal earth and its gravity field, there are deviations, and it is these deviations from the norm that are here of interest, i.e. the gravity anomalies which are to be interpreted. The deviations from the ideal are, however, not large, indeed, if relative scales are considered.

The raw observations of gravity are not easily interpretable, if at all. They must first be reduced, i.e. referred to the reference normal gravity model, i.e., to the normal earth. The various ways of treating the normal earth and the visible deviations from it are subject of the various kinds of reductions and further data analysis (Chap. 4). In order to understand the gravity treatment better, a brief overview of the gravity variations or anomalies encountered on Earth will be given in the next Sect. 1.5.

Gravity anomalies are variations in space (and in time), and relative gravity meters can perfectly provide the wanted information; even absolute gravity observations are interesting in their variations for gravity interpretation. Variation implies an ensemble of points or a continuous field, and it has become customary to understand the term "anomaly" in the sense of "anomalous field". One isolated value of gravity is useless for interpretation as envisaged here (Sect. 1.1.3). An ensemble of discrete points of gravity values is not identical with a continuous anomaly field, indeed, generally field is an idea, and in this sense, defining an "anomaly" from discrete points is an act or part of interpretation. "Field" and interpretation thus mutually influence each other and the data points are but one part of this. Defining an anomaly from a limited set of points is thus not generally a trivial task. The theory chapter (2) deals with gravity effects usually in the form of continuous functions of coordinates, derivatives, relations in space and the possibilities of exploiting them for their interpretation. In the observation chapter (3) planning surveys (Sect. 3.4) is shown to be guided by expectations of anomalies. In the reduction chapter (4) the emphasis is on making anomalies "visible"; especially Sect. 4.7 on the analysis of anomalies, deals with the concrete construction of an anomaly from discrete points and with the notion of their errors (Sect. 4.7.1); and as a frequent task, Sect. 4.7.7 discusses the separation of regional and residual fields. The interpretation Chaps. 5, 6 and 7 are anyway always concerned with anomalies in space; in Sect. 5.1.5, in particular, the notions of anomalies and of gravity effects are confronted with each other and their mutual dependence is considered; they should be clearly kept apart.

1.5 Some Important Aspects of the Terrestrial Gravity Field and Internal Mass Distribution

1.5.1 General Considerations

Gravity interpretation does not happen in isolation, but in the world of shallow subsurface investigation, of mineral exploration, and of whole Earth geodynamics. Basic knowledge of the essential features of terrestrial gravity and mass or density distribution is therefore a precondition for a reasonable approach to the tasks at hand. Moreover, the fundamental ambiguity in gravity interpretation makes a priori knowledge mandatory for reducing this ambiguity to an acceptable level. However, a priori knowledge includes both basic ideas and high precision geological and geophysical data. Familiarity with, or a feeling for, the subject is essential for successful and efficient work, but thinking must go beyond the familiar limits. Questions, as to what kind of gravity and density variations are to be expected or what are their normal magnitudes, and hence what are the requirements of accuracy, will mutually influence measuring, modelling and interpreting different gravity effects.

In the 19th and 20th centuries knowledge about the Earth increased and recent progress has been fast. The dual role of gravity, as signalling density variations inside the earth, and generating them by driving dynamic processes becomes more and more relevant, and both are intimately interconnected. To interpret large-scale gravity anomalies one needs to know something about the processes and the material properties of the Earth's interior. To successfully apply gravity to the search for mineral resources, knowledge of the processes of mineral concentration and their geological associations is equally essential.

In thinking about gravity it is critical to distinguish between the different kinds of anomalies: the customary Bouguer anomaly (*BA*), the Free Air anomaly (*FA*) and the isostatic anomalies. The different reference models used in defining the various anomalies must be taken into account (see Chap. 4); otherwise gross misinterpretations are the result; the relations with topographical, geological and tectonic features is very different; for example, mountain ranges are usually accompanied by generally positive, but highly scattered *FA* values and at the same time by a strongly negative smooth *BA*; spreading ocean ridges have a similar gravity expression, except that the *BA* is positive, if referenced to sea level, but negative in comparison with the deep sea basins.

The following descriptions will necessarily be somewhat subjective. These will include: *the Earth's figure and constitution* (Sect. 1.5.2: ellipsoid, geoid, Earth's density and shells crust, mantle, and core), *continents and oceans* (Sect. 1.5.3: isostasy of large geological structures, fold mountain ranges, limits to lateral density variations), *plate tectonics and mantle flow* (Sect. 1.5.4: mantle dynamics: convection, ridges, subduction), *associated gravity anomalies* (Sect. 1.5.5: scale laws and kind and size of gravity variations or anomalies to be expected), *other large-scale gravity features* (Sect. 1.5.6: loading and unloading processes, postglacial rebound), *smaller-scale gravity anomalies relevant to exploration for economic minerals*

(Sect. 1.5.7: density anomalies inside the crust: objects of general geological research and mineral exploration), *harmonic spectrum of the gravity field* (Sect. 1.5.8: Kaula's rule, upward and downward continuation, mantle tomography).

This book is not an exhaustive treatise on geodynamics, geology, geochemistry and geophysics of the Earth. Only a brief outline is given here to emphasize the relations of gravity with Earth structures and processes. The reader is also referred to a number of historical and recent texts where many of these aspects are treated in one way or the other and help the reader to form an overall picture of the Earth (Wegener, 1915–1930, 1966, 1980; Holmes, 1944, 1993; Cox, 1973; Press & Siever, 1974; Press et al., 2003; Turcotte & Schubert, 1982, 2002; Skinner & Porter, 1989; Lowrie, 1997; Mussett and Khan, 2000; Schubert et al., 2001; Fowler, 2004).

1.5.2 The Earth's Figure and Constitution

As already mentioned, the Earth's gravity field and figure are intimately related to each other. Basically this follows from Newton's law of gravitation, in that a given arbitrary mass distribution generates a unique external gravity field which becomes smoother and more spherical with distance from the source. But the regularities of the Earth and its gravity field demonstrate that gravity played a major role in shaping and structuring the Earth. It is nearly a sphere, or more accurately, an ellipsoid of rotation and nearly exactly obeys Clairot's principle of the equilibrium figure of a rotating self-gravitating fluid body in space (A.C. Clairot, 1713–1765). Equilibrium and the deviations from it play an essential role in the whole field of gravity interpretation and geodynamics. However, the most voluminous part of the Earth, the mantle is not fluid; it is made of solid rock which transmits seismic transverse shear waves. Obviously this solid material has properties of a fluid if subjected to long-lasting forces such as gravitation and centrifugal acceleration.

The Earth's surface topography has a relief of about $\pm 10\,\mathrm{km}$, that is about $\pm 1/600$ of Earth's radius. The ellipsoidal major and minor axes differ by the same amount, and the flattening is about 1/300 (the flattening is defined as f = (a – c)/c with a = equator radius and c = polar radius). This leads to a difference between gravity at the poles and at the equator by about 0.5% or 1/200 ($\pm 1/400$). The gravity difference is relatively greater than the geometrical difference, because gravity reflects both the direct centrifugal force *and* the effect of the ellipsoidal shape. The exact value of flattening and gravity variation depends on the internal density structure, primarily the density depth distribution. Thus, by itself, gravity tells us about the density increase with depth, supported by mechanics and astronomical observations concerning the Earth's angular momentum and hence momentum of inertia.

Speculation about the Earth's internal structure and material properties began from hard surface rock and proceeded to hot molten rock to explain volcanoes and religious ideas about a burning hell. Iron meteorites suggested to scientists that the interior might be molten iron. Astronomical and geodetic mathematical theory and improving physical understanding led to the derivation of the general densification with depth, which could be explained by pressure and chemical stratification.

A more detailed picture arose as a result of seismic studies of the propagation of waves through the Earth's interior, and by the early 20th century a fairly accurate knowledge of a three-layered Earth had been gained. It became natural to imagine crust, mantle and core as the basic "onion model". Crust is a thin veneer of quartz-rich rocks. Mantle, to 2900 km depth, consists of ultramafic silicate rocks, olivine rich peridotite, transformed by pressure and temperature at depth through phase transitions (olivine→spinel→perovskite and magnesiowüstite). The resulting layer boundaries roughly conform to equipotential surfaces, but significant lateral deviations are expected in response to dynamic processes. The core consists of iron with impurities, the outer core is molten, and the inner core solid frozen; this somewhat surprising situation is due to the pressure effect on melting.

Equilibrium would mean perfect density stratification, varying exclusively with depth according to the principle of minimum potential energy. Density boundaries would then perfectly conform to internal equipotential surfaces, and the variation with depth would affect the Earth's ellipticity and the normal gravity field which varies only with latitude (see Chap. 4). The Earth would have become static and "dead". Non-equilibrium boundary undulations with associated gravity anomalies, that is deviations from the normal gravitational field, can be maintained either by internal elastic strength and/or generated by dynamic processes disturbing the equilibrium. Thermal convection provides such a process. The gravity effects of undulating density boundaries are indistinguishable by spectral methods from effects generated by voluminous lateral density variations, which themselves are also caused by convective currents. This process is most relevant to the mantle; however, the large mantle viscosity makes the convection currents move slowly, probably not exceeding a few decimetres per year, under normal circumstances.

1.5.3 Continents and Oceans

The Earth's surface obviously deviates from fluid-like equilibration. Topography is governed by continents and oceans; about 30% of the Earth' surface are continent, including continental shelf area submerged under shallow seas, and 70% are deep ocean basins. Only small portions are occupied by continental slopes, deep sea trenches and active high mountain belts. The rest is mainly in two plateaus above and below sea level. It was early realized (e.g. by Alfred Wegener, 1912; Jacoby, 2001) that this kind of frequency distribution of elevation, called the "hypsographic curve", calls for a fundamental explanation with two kinds of Earth crust. Now it is known from a multitude of seismic studies that continental crust is 20–80 km thick, 20 km in exceptional low elevation regions as some shelf areas or plains as the Pannonian Basin, and perhaps up to 80 km under the highest mountain ranges and plateaus, as the Himalaya and Tibet or the Altiplano of the Andes. Continental crust contains cores of material that solidified 4 Ga ago or even earlier. Oceanic crust is about 7 km thick, on average, it is much younger, 180 Ma at most in the north-western Pacific, and it is made of rocks of basaltic composition as products of mantle melting. All ocean basins are traversed by ocean ridges, the active, i.e. spreading ridges gently sloping towards the abyssal plains, see below. Passive ridges, active or extinct volcanic islands and seamounts are partly organized in some order, along chains, which was not understood before the advent of continental drift and plate tectonics.

The notion of crust and crustal thickness has played an essential role in understanding the Earth and especially its gravity field. Before detailed seismic studies had been carried out in large style, it was clear from mechanical and gravity arguments that ocean crust and mantle are in approximate isostatic equilibrium with continental crust and mantle. It was understood that continents and oceans differed significantly in rock density in the upper 100 km depth range, or so. Seismology then provided proxy information on crustal densities on the basis of density-related seismic velocities (see Chap. 3). Thus, crust and mantle were basically geophysical notions (seismic, gravity, isostasy). But as geodynamic and petrologic knowledge increased, particularly after the advent of plate tectonics, the notions of crust and mantle have somewhat shifted from geophysical to petrologic definitions involving the processes of their origin. One now speaks about differences between the seismic (or gravity) and petrologic crust or mantle. Crustal basaltic/gabbroic material at the base of the continental crust may suffer a phase change to eclogite which in seismic and density properties resembles high-velocity and high-density mantle material, such that the seismic and gravity crust may appear thinner than the petrologic crust which includes mantle-like, but crustal eclogite at its bottom. Under the ocean basins an opposite process seems to occur when water percolates through the basaltic crust into the topmost mantle, peridotite reacts with the water and is transformed into low-density and low-velocity serpentinite. Thus the seismic (and gravity) oceanic crust may look geophysically thicker than the basaltic, i.e. petrologic crust.

1.5.4 Plate Tectonics and Mantle Flow

The discovery of the plate movements and plate tectonics has completely changed our view of the Earth, some 50 years after Alfred Wegener proposed continental drift in 1912. Understanding the Earth and its gravity field is intrinsically linked to the processes of plate interaction and the underlying mantle flow. Only these ongoing endogenic processes explain Earth structure, topography, gravity and many more features. However, large-scale geology is shaped also by exogenic processes as erosion, sediment transport and sedimentation in a complex interaction with the endogenic processes. High mountain ranges are actively eroded, so they must be geologically young and rising to be and remain high for some time. Erosion disturbs the isostatic equilibrium and the response is a rise; endogenic push-up or pull down may occur simultaneously. “Tectonically active” means that these processes are at work and this nearly always shows up in gravity anomalies. Eroded material is transported toward the ocean basins were it is ultimately deposited as sediments.

Continental margins, and especially deltas of big rivers, become sediment deposits which form loads on the crust or, better, on the lithosphere, and depress it. By this mechanism of isostatic adjustment, very thick sedimentary sequences may be laid down to form what earlier had been called "geosynclines".

When studied by surface geology and deep geophysical methods, old peneplaned regions turn out to be orogenic roots of former mountain ranges. In geology, such structural and mineralogical characteristics define an orogeny or mountain belt; the present-day topography is not an essential feature of an orogen. In the cold rigid upper crust, the old orogenic structures are frozen in, the strength of the rocks prevents flow and equilibration on the scales of the structures; this again is expressed in gravity anomalies. Most continental regions have experienced a series of orogenies, the younger overprinting the older ones and often younger mountain belts were attached to older solidified structures, themselves having formed in a similar fashion earlier; thus, continents look like a complex mosaic of orogenic belts with the younger one surrounding older cores. However, an old core may directly abut an ocean basin, and some continents have evidently been torn apart such that older geological structures are cut abruptly just to reappear on the other side of an ocean, e.g., the Atlantic.

Basically, convergence and continental collision form new continental crust. Convergence of lithospheric plates implies subduction of one plate under the other, or collision of continental plates, i.e. plates carrying continental crust at the convergent margin, which inhibits subduction because of the low density and large buoyancy of continental crustal material.

The opposite of convergence is plate divergence at active ocean ridges and in continental rift zones which may initiate large-scale divergence, continental separation and ocean floor spreading which may ultimately reverse and lead to convergence and orogeny completing a "Wilson cycle". Or rifts may fail and will then be preserved in continents at some stage of development. In the upper crust, such structures also freeze in and generate gravitational signals.

The third type plate interaction is that of transform faults where two plates move horizontally past each other, as in the case of the San Andreas Fault of western North America or the North Anatolian Fault in Turkey. The movement juxtaposes different structures and deforms them by shearing. Active transform faults connect other types of plate boundaries, especially offset ridge segments in the oceans, and beyond them, they become inactive fracture zones where lithosphere of different age is juxtaposed.

These processes are more complex than a simple description can convey. The relative movements are rarely exactly normal or parallel to the plate boundaries but usually oblique and encompass aspects of transpression or transtension: boundaries, at closer look, are not clear-cut faults but complex sets of faults and wide belts of deformation in which, more or less locally, the sense of deformation may even reverse, involving, e.g., grabens and rifts in collision zones.

Active volcanoes occur preferentially in tectonically active zones, mostly in plate-marginal regions. These regions are generally also seismically active, i.e., they are belts of seismicity or earthquake occurrence. That plate divergence is accompanied by volcanism is not surprising as hot material must rise into the gap. When rising mantle melts it produces basalt (see above) often called "MORB" (mid ocean ridge basalt), hence the result is ocean crust. But volcanism is also dominant in convergence zones, exactly speaking: on the upper plate above the subducted one where its surface reaches about 100 km depth. The products are different, typically andesitic (the term being derived from "Andes") which is a rock type intermediate between acid or silica-rich and basic or silica-poor. Melting of wet, i.e. H_2O-rich subducted material is a source of this type of volcanic rocks. They play an important role in orogeny and the forming of new or recycled or mixed continental material.

Volcanism of importance also occurs far from plate boundaries. Such an anomalous occurrence of volcanism is called a "hot spot", as e.g. Hawaii. Hot spots may also occur near or on plate boundaries as in Iceland, lying on a divergent plate boundary. The volcanic products, called OIB (ocean island basalt), are similar to MORB, but significant differences especially in trace elements suggest different sources. Hot spot volcanism is interpreted by the model of heat advection from possibly great depth. The generally accepted model is called "mantle plume" envisioned as concentrated upwelling which begins to be seen by seismic tomography (see below).

The relations of plate motion with mantle convection are also not simple, in contrast to early ideas that large steady convection cells encompass the mantle and that plate divergence occurs above the upwellings and subduction occurs over the downwellings. Actually little is known about the flow pattern in the mantle, but seismic mantle tomography does provide 3D P and S velocity perturbations from standard radial velocity models, as PREM (Preliminary Reference Earth Model; Dziewonski and Anderson, 1981; for tomography see e.g. Masters et al., 1996; Grand et al., 1997; Kennett & van der Hilst, 1998; Kennett et al., 1998, to mention just a few). If it is assumed, as often has been done, that velocity and density are related, for example, through temperature and/or chemical composition of mantle rocks, flow patterns may be implied or can be derived and related to the surface anomalies of gravity and/or the geoid. One difficulty is that the velocity-density relations may vary in the mantle. Theoretical relations between the geopotential and gravity with density (and thus indirectly with tomography) are given in Schubert et al., 2001 (pp. 279–280), and an application is mentioned (King & Masters, 1992).

Plumes which are part of convection may rise from different depths. Vertical movements imply work in the gravity field and the question of mass balance and thus also observable gravity anomalies. A very simple isostatic "Airy plume" model is discussed in Sect. 5.6.9.3. Mantle plumes are predicted, among others, by high-Rayleigh number convection experiments and numerical modelling and hence dynamic plume models need to be explored (see e.g. Schubert et al., 2001, pp. 537–543); however, this goes beyond the present treatise. Other types of melting anomalies or heterogeneities in the mantle, for example, inherited from former plate subduction, may also play a role.

Especially when relating the geodynamic aspects to gravity, the notion of rheology or the laws governing material strength, deformation, fracture and flow becomes of paramount importance. How much stress can be sustained elastically? Are there limits of force and mass imbalance (in the gravity field) which the Earth can sustain for some time or for how long time? This is immediately related to the question of maximum possible elevation differences and slopes or maximum possible density contrasts and dimensions of such contrasts. It is the same question, in different terms, as that of isostasy and its possible modes. What we observe today is a geological snapshot and geological history can tell us something about the relevant time constants of the processes involved. Some appear static (as in “isostatic”) maintained for billions of years, some appear transient, as for example, glacial or postglacial isostasy or better: isostatic readjustment, lasting only thousands of years, in some hot regions as Iceland much shorter.

The above structures and processes are driven largely by gravity and thermal energy and they generate characteristic gravity anomalies or signals. Unfortunately for the study of Earth, the processes and signals are superimposed on each other in a complex fashion and the observed picture is very complicated. As emphasized in this treatise, however, gravity anomalies reflect horizontal or lateral density variations, such that the study of gravity is an essential aspect of regional geology. Below, a brief discussion follows of what may be expected.

1.5.5 Associated Gravity Anomalies

The reader is again reminded of the differences of Bouguer anomalies (*BA*) and Free Air anomalies (*FA*) as treated in Chap. 4. In the Bouguer model topography is but added to, or in the case of the oceans subtracted from, an otherwise idealized layered Earth. The Free Air earth model ignores the topography on the idealized earth which acknowledges its approximate isostatic compensation within the upper 100 km. The *BA* thus emphasizes such density variations inside the Earth while the *FA* is rather affected by mass excess or deficit along the vertical down to some depth.

Beside gravity as such, the gravitational potential or, as derived from it, the geoid undulations depict large-scale regional to global anomalies or the major features of the gravity field better than gravity itself does, because the potential as an integral quantity emphasizes the longer wavelengths. The geoid is the equipotential surface which coincides with the mean sea level and is, thus, the idealized shape of the Earth as defined by its gravity field. For geoid undulation we often briefly say “geoid”. What is meant is the geoidal height reduced by the best fitting axial ellipsoid of rotation. The geoid resembles the *FA* anomaly, but is much smoother.

The longest-wavelength *FA* gravity variations (apart from those related to rotation and ellipticity) have dimensions of 10^{3-4} km and show little or no obvious relations with the continent-ocean distribution. Shorter wavelengths of order 10^2 km closely image the continental margins, especially where they are steep and marked. Passive, i.e. non-convergent, margins are usually accompanied by a dipolar band of distinct positive anomalies above the shelf break and less distinct negative anomalies above the foot of the continental slope. The amplitudes are tens of milligals and the width corresponds to that of the continental margin. The steeper the continental slope, the more pronounced the gravity anomalies. This medium-scale feature is mostly suppressed by the Bouguer reduction by which the change from positive to negative *BA* values (from ocean to continent) is brought out. The broad-scale *BA* is generally negative in continents, especially in highly elevated areas, and positive in oceans, and the regional mean *BA* values approximately correspond to the effects of the Bouguer reduction, i.e. the gravity effect of the topographic mass mathematically removed or subtracted on land and added in the oceans (see Chap. 4); on the large scale, it looks like the reduction being wrong or superfluous. The conclusion from this is that the homogeneously layered reference earth with topography only added or subtracted is wrong; to the contrary, elevated excess mass is compensated by low density deeper roots and vice versa, as mentioned above. This is the mass equilibrium principle of isostasy.

All major plate tectonic margins are accompanied by relatively short-wavelength gravity anomalies (*FA* and *BA*), especially where elevation has significant slopes. "Short" here means typically one to several hundred kilometres, to a large portion similar to the width of the geological and morphological structures. However, some of the characteristic gravity anomalies extend beyond the immediate structural limits. The relation with plate boundaries or margins is not simply one-to one but varies along the boundaries. Nevertheless, some general trends exist.

There is some obvious relation of the longest gravity wavelengths with plate tectonics. A belt of relatively positive *FA* anomalies accompanies the belt of plate convergence surrounding the Pacific and extending also to the Mediterranean-Himalayan-Sunda belt of convergence. In the Sunda region north of Australia exist the largest positive *FA* anomalies and the highest geoid undulation of order 100 m; it is the region with the largest concentration of plate convergence on Earth. The positive circum-Pacific belt is surrounded by a less clear belt of broad negative *FA* anomalies with the deepest minimum (order –100 m) on Earth south of India (near Sri Lanka). The gravity high accompanying convergent plate margins is a broad *FA*, up to several thousand kilometres wide accompanied by a narrow deep *FA* low over ocean trenches following approximately the crest of the broad high. In continental mountainous collision zones the deep *FA* low is missing. In the *BA* the relations with the deep sea trench or mountain belt are just reversed as the Bouguer mass reduction mostly outweighs the *FA* lows or highs. Topography and the Bouguer reductions vary with the broad *FA* gravity high, therefore strong variations occur along convergence zones and from zone to zone.

Active ocean ridges, i.e. the diverging plate boundaries, too, have a tendency of slightly positive *FA* values (order 10 mGal) broadly correlated with ridge topography. The ratio of the ridge related *FA* over topography, relative, say, to adjacent deep sea basins, is low for the broad ridges but much larger for short wavelength of, say, ridge crest rift valleys, sea mounts (and trenches). This reflects Newton's $1/r^2$ law: shallower, nearer masses have stronger gravity effects than the deeper compensating, more distant masses; moreover, different isostatic mechanisms may support this trend. The gravity over topography amplitude ratio, especially when systematically measured versus wavelength λ (or wave number $1/\lambda$ or $2\pi/\lambda$), is called admittance and its study constrains density and dynamical models more tightly than gravity can do alone, because the ambiguity of gravity modelling is reduced by including topography information.

The dominant gravity anomalies in the vast ocean areas, however, seem to bear little relation to the plate motions or ocean depth and are not those related to plate divergence. Geoid and *FA* highs occur also far from plate convergence as a large positive feature or broad anomaly belt extending from the north Atlantic, centred on Iceland, south-eastward across Africa to the southern Indian Ocean roughly marked by the Kerguelen hotspot. A somewhat similar, less distinct feature occupies the Southeast Central Pacific. Analysis reveals that these positive regions are correlated with a high spatial frequency (or density) of hotspots. It suggests some relation with dominant mantle upwelling.

That high *FA* and geoid anomalies accompany mantle upwelling, on the one hand, and plate convergence and downwelling, on the other hand, is surprising. Obviously, the relations of gravity with plate tectonics and mantle flow are not so simple and are probably related to the interaction between the rheological mantle structure and the convective flow.

Transform faults have not a very consistent gravity signature as they have also a varied morphological expression. Both depend on the local relative normal motion which varies in space and time because the faults are not straight, i.e. great circle lines. In zones under present convergence and compression with a transpressive character, ridges or transverse ranges are being pushed up; in zones under present divergence and tension with a transtensional character, pull-apart basins are opening which are filled with sediments in continents of form deep chasms in distal ocean areas (as the 7000 m deep Romanche Deep in the equatorial Atlantic). The associated gravity anomalies (*FA*) very much reflect the morphology with dimensions of the order of 10^{1-2} km (and more in length).

Hotspots have already been mentioned to preferably occur in high geoid and *FA* regions. There seems also to exist a typical shorter-wavelength signal consisting of a positive *FA* core surrounded by a negative rim, however, the anomalies are relatively weak in comparison to the regional anomaly variations so that they are not easily detected.

1.5.6 Other Large-Scale Gravity Features

Some broad gravity anomalies are associated and caused by transient external processes as build-up and disappearance of large ice sheets presently experienced 10 000 a after the latest ice age. Both northern North America and Fennoscandia are characterized by negative *FA* anomalies of up to several tens of milligals which roughly outline the former ice cover. Here it seems evident that isostatic equilibrium after melting of the ice has not yet been achieved. The observations can be used to estimate the viscosity of the mantle material flowing back towards the rising areas; the gross viscosity estimate is about 10^{21} Pa s, but the subject is more complex and not treated here. Although the basic interpretation has been debated, the general view is supported by many additional observations as, for example, the present uplift rates of the order of 1 cm/a in the central regions of former glaciation.

Transient features are also related to rapid erosion and sedimentation in limited regions as high standing young mountain belts or big river deltas. However, the rates of vertical change are generally much slower, typically one order of magnitude or more, than glacially driven changes, and so are the gravity effects.

1.5.7 Smaller-Scale Gravity Anomalies Relevant to Exploration for Economic Minerals

Gravity anomalies are often instrumental in guiding the exploration geophysicist and geologist to objects of interest. The tasks are varied, a complete account of all possibilities is not intended. Often gravity variations give the first overview of a previously little studied region, be it a whole country or an area, a kilometre or less in dimension. Correspondingly anomalies of interest range from the sub-milligal to tens of milligal amplitudes and wavelengths from meters to tens or hundreds of kilometres.

Generalisations of the targets of exploration are as difficult. They may be, from small to large scales: cavities, man-made construction features, faults, ore concentrations, synclines and anticlines to whole sedimentary basins and other large scale promising features. In very many cases, it is not the economic mineral as such which gives a significant gravity signal, but the geological structures which are the targets of study and which, from experience, are loci of oil or gas accumulation. Within a sedimentary basin, faults and anticlines or synclines may be prospective sites of oil, gas or mineral accumulations. Anticlines sometimes have dense cores or, in the case of salt structures, the opposite. Obviously it is essential that broad geologic and tectonic knowledge is coupled with geophysical understanding.

Technical applications of gravity in buildings are varied, and no general rule is evident, but modern gravity meters are accurate enough for detecting structural aspects as, for example, deformation when large weights are installed, or unknown inhomogeneities under the building.

As gravity interpretation is highly ambiguous, it is the combination with other data, for example, from seismic refraction or reflection, which will narrow down the spectrum of possible models. In some cases, gravity is used to fill in gaps of information; structural interpolation between seismic lines or between drill holes can gain considerably from gravity modelling, and in special cases “blind spots” of seismic models can be filled in this way.

1.5.8 Harmonic Spectrum of the Gravity Field

Beside the variation in space, spectral aspects of the gravity field are interesting for interpretation. In many cases the spectrum is more revealing and may disclose some facets of the sources. Furthermore, certain features of harmonic fields or field components are most attractive in their properties in space and since harmonic analysis is separation of individual harmonic components it has many advantages for gravity interpretation. Moreover, numerical treatment in the spectral domain has become very efficient. Global analysis is done by spherical harmonic expansion of the field. In small regions as in exploration geophysics, expansion in one or two-dimensional Fourier series serves the same purpose.

The global spatial spectrum is described in spherical harmonics, i.e. a series of Legendre polynomials to degree n in latitude φ multiplied by a Fourier series in longitude λ of orders $m = 0$ to n (see Sect. 2.10). The complete picture includes all terms of the series which describe superimposed waves in two coordinates, φ and λ, of minimum wavelength $2r\pi/n$(r = earth's radius, $2\pi r = 40000\,\text{km}$), and thus n and m play the role of the wave numbers in the Fourier spectrum. The complete set of coefficients (C_{nm}, S_{nm}) of all series terms corresponds to the amplitude and phase spectrum of the Fourier expansion. Often only the amplitude spectrum or the power spectrum, is considered; its dimensionless coefficients are $S_{\mathrm{n}}{}^2 =_{\mathrm{o}} \Sigma^{\mathrm{n}}(C_{\mathrm{nm}}{}^2 + S_{\mathrm{nm}}{}^2)$. The power spectrum has been defined in different ways in terms of the normalisation. The coefficients are transformed to dimensional values through multiplication with GM/r (disturbing potential in $\mathrm{m}^2/\mathrm{s}^2$), r (geoid heights in m), $GM(n+1)/r^2$ (gravity disturbance in $\mathrm{m/s}^2$), $GM(n-1)/r^2$ (gravity anomaly in $\mathrm{m/s}^2$). Kaula (1966) suggested a decrease of power in the form

$$S_n \approx 10^{-5}(2n+1)^{1/2}/n^2,$$

called "Kaula's rule of thumb".

Hipkin (2001), on the other hand, who corrected the normalisation of the (logarithmic) power spectrum found that it shows at least three straight-line sections versus n which can be related to three depth levels where mass concentrations occur preferentially (which, at those depths, would have the white spectra of delta functions or effective point masses). The interpretation is that anomalous masses (volume times density contrast) move buoyantly and thus interact with the rheological mantle structure (e.g. layering). The argument is based on the upward or downward continuation of the field (see Sect. 2.10) leading to two competitive effects: decay of gravity effect amplitude with depth and inhibition of sinking or rising. Since dominant wavelengths of anomalies increase with distance from the source or harmonic waves of defined wavelength decay in amplitude the more rapidly the smaller the wavelength, one may associate probable depths to the spectrum. However, one must not forget that long wavelength sources may exist at shallow depths.

Another aspect is the relations with the spectra of other geophysical or geological features. Relations exist, for example, between plate sizes and related large-scale features (expanded in harmonic series) and the low end of the gravity spectrum. Tomographic velocity variations at different depth levels in the mantle may have spectra similar to those of gravity and guide the associations of velocity and density. The approach is to compare the spectra, but whether or not relations are genetic is generally quite open; relations may have common causes or be but accidental.

In any case, ideas of possible or even probable interpretations may be suggested by spectral relationships between data sets, though it seems unlikely that under the circumstances probabilities can ever be reliably quantified. The principal ambiguity of the inverse problem of finding the source from the gravity anomalies is the same in the spectral domain as in the space domain.

On the small scales Fourier spectra of gravity, magnetics, geological structures and related data sets may reveal interesting relationships of exploration interest.

References

Blakely, R.J.: Potential Theory in Gravity and Magnetic Applications. *Cambridge Univ. Press*, 441pp., 1995

Cox, A.: Plate Tectonics and Geomagnetic Reversals. *Freeman, San Francisco*, 702pp., 1973

Dziewonski, A.M., Anderson, D.L.: Preliminary reference earth model. *Phys. Earth Planet. Int.*, 25, 297–365, 1981

Fowler, C.M.R.: The Solid Earth, 2nd ed. *Cambridge Univ. Press*, 685pp., 2004

Grand, S.P., van der Hilst, R.D., Widiyantoro, S.: Global seismic tomography: A snapshot of convection in the earth. *Geol. Soc. Amer. Today*, 7, 1–7, 1997

Grant, F.S., West, G.F.: Interpretation Theory in Applied Geophysics. *McGraw-Hill, New York, N.Y.*, 584pp., 1965 [**GW65]**

Hipkin, R.G.: The statistics of pink noise on a sphere: applications to mantle density anomalies. *Geophys. J. Internat.*, 144, 259–270, 2001

Holmes, A.H.: Principles of Physical Geology. Nelson & Sons, Edinburgh, 1288pp., 1944; 4th ed., edited by P.M.D. *Duff, Trans-Atlantic Publications, Philadelphia*, 807pp. 1993

Jacoby, W.R.: Origin of continents, English translation of A. Wegener, 1912: Die Entstehung der Kontinente. *J. Geodynamics* 32, 29–63, 2001

Jung, K.: Schwerkraftverfahren in der Angewandten Geophysik. *Akademischer Verlag Geest & Portig*, 348pp., 1961 [**KJ61]**

Kaula, W.M.: Theory of Satellite geodesy. *Blaisdell, Waltham*, 124pp., 1966

Kennett, B.L.N., van der Hilst, R.D.: Seismic structure of the mantle: From subduction zone to craton. In “The Earth’s Mantle: Composition, Structure, and Evolution”, ed. I. Jackson, 381–404,*Cambridge Univ. Press, Cambridge, England*, 1998

Kennett, B.L.N., Widiyantoro, S., van der Hilst, R.D.: Joint seismic tomography for bulk sound and shear wave speed in the Earth’s mantle. *J. Geophys. Res.*, 103, 12469–124693, 1998

King, S.D., Masters, G.: An inversion for radial viscosity structure using seismic tomography. *Geophys. Res. Lett.*, 19, 1551–1554, 1992

Lowrie, W.: Fundamentals of Geophysics. *Cambridge Univ. Press*, 354pp., 1997

Masters, G., Johnson, S., Laske, G., Bolton, H.: A shear velocity model of the mantle. *Phil. Trans. Roy. Soc. London*, 354, 1385–1411, 1996

Mussett, A.E., Khan, M.A.: Looking into the Earth, An Introduction to Geological Geophysics. *Cambridge Univ. Press*, 470pp., 2000

Press, F., Siever, R.: Earth. *Freeman, San Francisco*, 945pp., 1974

Press, F., Siever, R., Grotzinger, J., Jordan, T.: Understanding Earth, 4th ed. *Freeman, New York*, 568pp., 2003

Schubert, G., Turcotte, D.L., Olsen, P.: Mantle Convection in the Earth and Planets. *Cambridge Univ. Press*, 940pp., 2001

Skinner, B.J., Porter, S.C.: The Dynamic Earth, an Introduction to Physical Geology [with Study Guide]. *Wiley, New York*, 541pp., 1989

Telford, W.M., Geldart, L.P., Sheriff, R.E.: Applied Geophysics, 2nd ed. *Cambridge Univ. Press, Cambridge, New York, N.Y.*, 770pp., 1990

Turcotte, D.L., Schubert, G.: Geodynamics: Applications of Continuum Physics to Geological Problems. *Wiley, New York*, 450pp., 1982

Turcotte, D.L., Schubert, G.: Geodynamics: Applications of Continuum Physics to Geological Problems, 2nd ed. *Cambridge Univ. Press, Cambridge, England*, 456pp., 2002

Wegener, A.: Die Entstehung der Kontinente. *Petermanns Geographische Mitteilungen, 581, 185–195, 253–256, 305–309, 1912*

Wegener, A.: Die Entstehung der Kontinente und Ozeane. *Vieweg, Braunschweig, 1915, 1920, 1922, 1930* (first and fourth edition reprinted, *Vieweg, 1980*)

Wegener, A.: The Origin of Continents and Oceans. *Methuen, London*, 1924*; Dover, New York*, 1966

List of some great classical scientists: mathematicians, astronomers, geodesists and geophysicists who advanced the theoretical basis of gravity analysis and interpretation

Airy, George Biddell, 1801–1892
Bessel, Friedrich Wilhelm, 1784–1846
Bouguer, Pierre, 1698–1758
Bruns, E. Heinrich, 1838–1919
Clairot, Alexis Claude, 1713–1765
Eötvös, Roland (Lorand), 1848–1919
Galileo Galilee, 1564–1642
Gauß (Gauss), Johann Carl Friedrich, 1777–1855
Hayford, John, 1868–1925
Heiskanen, Weikko, Aleksanteri, 1895–1971
Helmert, Friedrich Robert, 1843–1917
Jung, Karl, 1902–1972
Kepler, Johannes, 1571–1630
Laplace, Pierre Siméon, maquis de, 1749–1827
Legendre, Adrien-Marie, 1752–1833
Leonardo da Vinci, 1452–1519
Moritz, Helmut, 1923–
Newton, Sir Isaac, 1643–1727
Poisson, Simon Denis, 1781–1840
Pratt, John Henry, 1809–1871
Stokes, George Gabriel, 1819–1903

Springer
http://www.springer.com/978-3-540-85328-2

Gravity Interpretation
Fundamentals and Application of Gravity Inversion and Geological Interpretation
Jacoby, W.; Smilde, P.L.
2009, XX, 395 p. With CD-ROM., Hardcover
ISBN: 978-3-540-85328-2