Tutorial: Gravity anomalies for nonspecialists

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> *Nature and Nature's laws lay hid in night:*
> *God said, Let Newton be! and all was light.*
> —Alexander Pope

Pope's tribute to Isaac Newton remains as true today as when written during the life of the brilliant English astronomer, physicist, and mathematician. Indeed, Newton's inverse square law of universal gravitation is at the heart of all modern gravity modeling algorithms. Hence, an adequate theory of gravitation existed long before the advent of an adequate technology for gravity prospecting.

Today, gravity prospecting remains a viable exploration tool after over half a century of continuous use by the oil and gas industry. Given this fact, it is almost paradoxical that the fundamental principles regarding gravity anomalies are often unclear to many oil company geologists and geophysicists. For many explorationists within this group, a little bit of exposure to this generally unfamiliar subject has led to some dangerous misconceptions.

Two misconceptions seem particularly rampant among the ranks of geologists, seismic interpreters, and exploration managers. So apparently universal are these two misconceptions that each is worthy of distinction:

- Misconception 1: A gravity anomaly high signifies a structural high.
- Misconception 2: A gravity anomaly low signifies a structural low.

This tutorial will make it evident that the two misconceptions arise from a lack of appreciation for the nature of gravitational fields and of the diversity of geologic sources that can contribute to the creation of gravity anomalies.

That the gravitational attracting force of a volume of material is proportional to the quantity of material (or mass) present is a concept first grasped to an unprecedented extent about 400 years ago by the German astronomer Johannes Kepler. This physical property of matter forms the basis of the gravity prospecting method in that different geologic features have different internal distributions of mass and thus produce different strength gravitational fields.

As an example, the density of limestone is typically higher than that of sandstone. Consequently, the mass in a structure comprised mainly of carbonate rocks is distributed differently from that in one comprised chiefly of clastic rocks, whether or not the two structures are the same geometrically. Hence, mass distribution differences between geologic features exist as a result of density and/or geometric differences between the features.

The Earth's gravity field may be characterized as an acceleration field, the acceleration g at any point P being that which a body would experience if placed within the field at P. About 400 years ago, Galileo Galilei dealt a blow to the Aristotelian physics popular at the time when he proved by experiment that the acceleration g experienced by a body at an arbitrary point P in the earth's gravitational field is the same regardless of the mass of the body placed at P (e.g., a small lead weight falls at the same rate as a large lead weight if air resistance is ignored).

Differences in gravitational acceleration observed on or above the surface of the Earth are related to differences in the subsurface mass distribution. Since such variations reflect geologic changes, observed differences in gravitational acceleration can be used to interpret the geology of the subsurface.

Geophysical units of gravitational acceleration. Geologic features give rise to anomalous gravitational accelerations that are quite small relative to the average gravitational acceleration at the Earth's surface (approximately 980 cm/s^2). Consequently, the unit of gravitational acceleration used in geophysical prospecting, the milligal (abbreviated mGal) is also quite small:

$$1 \text{ mGal} = 0.001 \text{ Gal} = 0.001 \text{ cm/s}^2 .$$

The Gal and the milligal are named in honor of Galileo. To place the magnitude of the milligal in better perspective, it need merely be noted that geologic features give rise to measurable anomalous gravity effects typically between 0.01 and 100 mGal in size.

Newtonian formulation of gravitational acceleration. The basic equation for the gravitational acceleration dg observed at a point P due to an infinitesimally small volume dV of attracting material of density ρ and mass dm (where $dm = \rho\, dV$) was derived over 300 years ago by Newton. He ultimately published his theory of universal gravitation in 1687 in the famous *Philosophiae Naturalis Principia Mathematica.* Newton derived the inverse square law of universal gravitation

$$dg = \gamma\, dm/r^2$$

in which γ is a proportionality constant (known today as the universal constant of gravitation) and r is the distance between the observation point P and the infinitesimal volume element dV of attracting material. These quantities are illustrated in Figure 1.

Carrying the inverse square law a step further, the acceleration g observed at a point P due to an extended body of attracting material can be obtained merely by summing the gravitational contributions of all of the

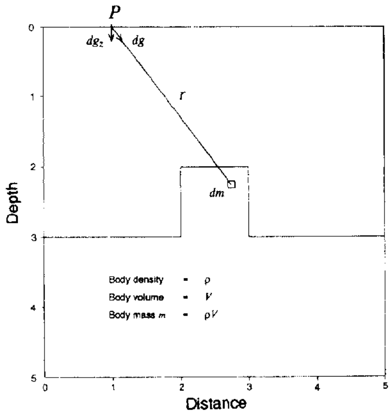

Figure 1. Gravitational acceleration dg observed at a point P due to an infinitesimal element of mass dm within an attracting body (or mass distribution) of mass m and density ρ at a distance r from P. The vertical component of the acceleration dg_z is also indicated. The net gravitational acceleration g observed at P due to the entire body is simply the vector sum of accelerations due to all mass elements composing the body.

infinitesimal mass elements *dm* which compose the extended body. Mathematically, this summation is equivalent to an integration over the volume of the body of the gravity effects of all the infinitesimal mass elements:

$$g = \int_v \gamma \frac{dm}{r^2} = \int_v \gamma \frac{\rho \, dV}{r^2} .$$

Indeed, all computer gravity modeling algorithms solve for the gravity effect of a geologic source (or feature) by effecting this integration.

This integral makes it obvious that, when considering two cases of similar geometry and volume at arbitrary measurement point P, the gravitational acceleration will be different if the bodies have different densities.

This dependence of anomalous gravitational acceleration on density differences between the attracting bodies is fundamental to the gravity prospecting method, in the same sense as the presence of an acoustic impedance contrast is fundamental to the seismic reflection method. Lateral density differences (or contrasts) between geologic features are necessary for creating anomalous gravitational accelerations. Figure 2 illustrates this key concept. The anomalous gravitational acceleration produced by the geologic features in Figure 2a is equivalent to that produced by a single body (Figure 2b) whose spatial extent and density are merely that of the lateral density contrast between the geologic features in Figure 2a.

The vertical component of gravitational acceleration, g_z. Most present gravity exploration makes use of gravity meters that measure the vertical component g_z of the gravitational acceleration g. This practice is now so common that the distinction between g and g_z is usually not acknowledged but rather is something that is assumed to be understood. The vertical component g_z is the component of g that is normal to a horizontal observation datum. By way of illustration, the vertical component dg_z of dg is shown in Figure 1. Unless otherwise noted, references to gravity anomalies in the remainder of this tutorial will be with respect to anomalous variations in the vertical component of the gravitational attraction. Note that an anomalous mass will cause a deviation in what is called "vertical" (the plumb line), compared to its direction in the absence of that mass.

Principle of superposition for gravitational accelerations. A geologic sequence or section, in terms of its gravitational effect, may be conceived of comprising differing density bodies, the gravitational attraction of each body contributing vectorially to the net gravitational acceleration g observed at some arbitrary point P on the observation datum. This cumulative property of gravity effects is embodied in the principle of superposition for gravity fields. Hence, the gravitational acceleration observed at P is quite literally the superposition of gravity effects from "the grass roots down."

The net vertical component g_z of the gravitational acceleration g at P due to the entire geologic sequence is simply the algebraic sum of the vertical acceleration components contributed by each of the discrete bodies.

Lateral density contrast—prerequisite for a gravity anomaly. The essential point to grasp when considering the analysis of a gravity map or profile is that a gravity anomaly cannot arise from a geologic feature if no lateral density contrast is associated with that feature. Regardless of whether an actual geologic structure or feature is present, its presence will be undetectable by gravity prospecting in the absence of a lateral density contrast.

The criticalness of a lateral density contrast to the development of a gravity anomaly can be demonstrated by considering the basic equation and invoking an argument of symmetry. However, a mathematical proof will be skipped, and the importance of a lateral density contrast will be demonstrated by some calculated model examples. The examples, while geologically oversimplified, adequately illustrate the point.

In Figure 3a, granitic basement (density 2.65 g/cm^3) is overlain by a carbonate sedimentary section (2.65 g/cm^3) truncated at the surface by an unconformity. Although a well developed basement structure is present, no lateral density contrast exists between the granitic basement and the adjacent sedimentary section. Thus no gravity anomaly is produced.

The case illustrated in Figure 3b is similar to the previous example except that a structural low is present instead of a structural high. Once again, no gravity anomaly is produced since no lateral density contrast exists between the carbonate material filling the structural low and the adjacent granitic basement. As in the former case, the pres-

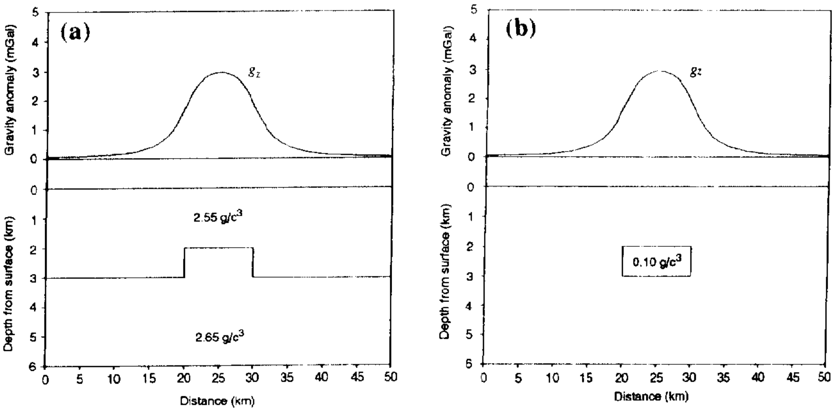

Figure 2. Lateral geologic density contrasts are responsible for the formation of gravity anomalies. For instance, the gravity anomaly due to the geologic structure in (a) is equivalent to that arising from a body (b) whose spatial extent and density are equal to the lateral density contrast that is present.

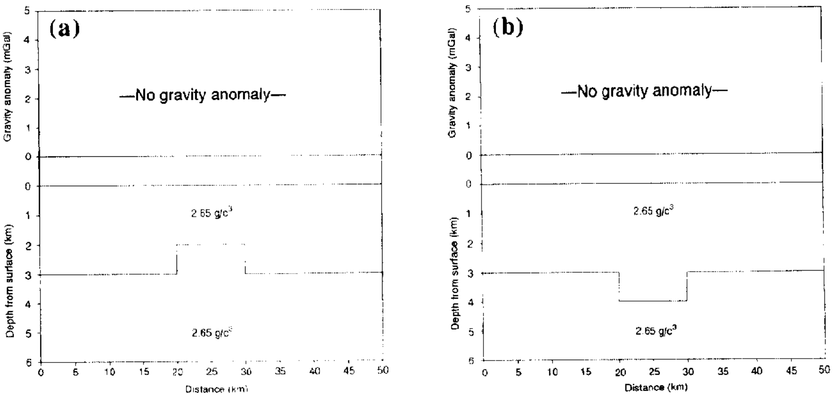

Figure 3. Illustration that even though a geologic structure may be present (a and b), no gravity anomaly is produced if no lateral density contrast exists.

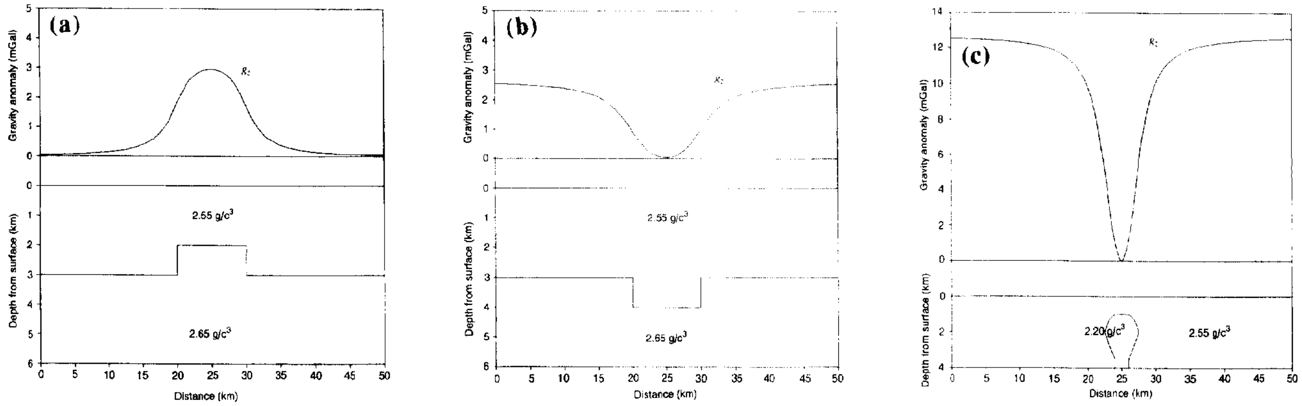

Figure 4. Illustration that a gravity anomaly is produced by a geologic structure (a, b, and c) if a lateral density contrast exists. Note that the production of a gravity anomaly low or a gravity anomaly high depends on the relative density contrast and not on the structure.

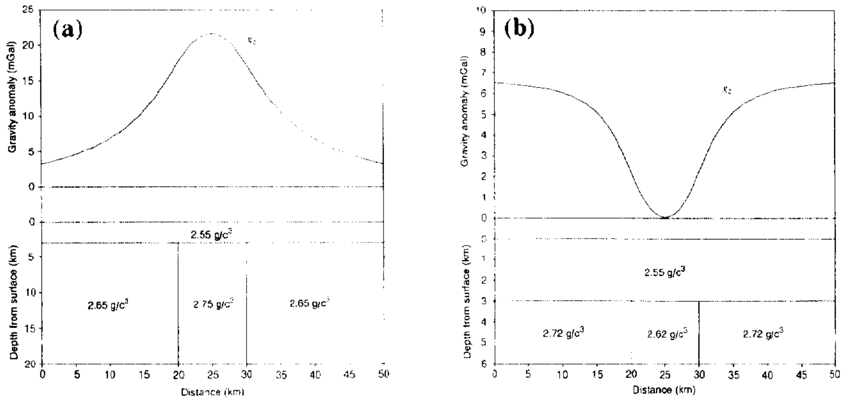

Figure 5. Illustration that a gravity anomaly may arise from a geologic compositional change (a and b) without geologic structure being present, provided that a lateral density contrast is associated with the compositional change.

ence of a structure does not in itself guarantee the existence of an associated gravity anomaly.

Figure 4a is similar to Figure 3a except that the carbonate sedimentary section has been replaced with a section of lower density (2.55 g/cm³) clastic material. The positive density contrast of 0.10 g/cm³ which now exists between the granitic basement structure and the adjacent clastic sequence gives rise to a local gravity anomaly high.

Figure 4b is similar to Figure 3b except that the carbonate sedimentary section has been replaced with a section of lower density (2.55 g/cm³) clastic material. The negative density contrast of -0.10 g/cm³, which now exists between the clastic material filling the structural low and the adjacent granitic basement, gives rise to a local gravity anomaly low.

The salt dome in Figure 4c illustrates the case of a diapiric structure. The salt dome's density of 2.20 g/cm³ creates a negative density contrast of -0.35 g/cm³ with the adjacent clastic section (2.55 g/cm³), resulting in the creation of a local gravity anomaly low over the dome. Hence, a gravity anomaly low does not by itself imply the presence of a structural low—thus disproving Misconception 2. One must clearly consider the geologic features likely to be present in a given area before interpreting gravity anomalies.

The previous examples have focused on gravity anomalies associated with geologic structures. It is also possible for lateral density contrasts to arise from facies changes in sedimentary rock or from compositional changes within crystalline rock. Figure 5a shows a clastic sedimentary section (2.55 g/cm³) overlying crystalline basement. The basement surface is a peneplain, devoid of any structural relief. The "normal" granitic basement (2.65 g/cm³) has emplaced within it a mafic instrusive (2.75 g/cm³). The positive density contrast of 0.10 g/cm³ between the mafic intrusive and the adjacent granitic basement gives rise to a local gravity anomaly high. Obviously then, a gravity anomaly high does not by itself imply the presence of a structural high, thus disproving Misconception 1.

The final example, Figure 5b, is similar to the previous case except that the "normal" crystalline basement consists of relatively high density (2.72 g/cm³) Paleozoic metasediments intruded by a lower density (2.62 g/cm³) granite stock. The negative density contrast of -0.10 g/cm³ between the granite intrusive and the adjacent Paleozoic basement gives rise to a local gravity anomaly low. As in Figure 4c, it is again seen that a gravity anomaly low does not by itself imply the existence of a structural low, disproving Misconception 2 once more.

Conclusion. This tutorial has attempted to convey to the gravity nonspecialist the importance of an awareness for the great diversity of geologic gravity anomaly sources. An appreciation of this natural diversity makes obvious the fallacy of the misconceptions discussed at the beginning of this article. Thus, when contemplating a gravity map or profile or when weighing a gravity interpretation, one should pose the question: "What geologic sources of lateral density contrasts are likely?" LE

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