Whole Earth Geophysics

An Introductory Textbook for Geologists and Geophysicists

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To my parents and grandmother,
for their inspiration and example.
To my son, Ben,
for his inspiration and example.
The Earth is a circle.

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CHAPTER 1

Introduction

geology *(jē äl′ ə jē)* ***n.***, [< *Gr.* geō, *the Earth;* < *Gr.* logos, *science*], *the study of the Earth.*
physics *(fiz′ iks)* ***n.***, [< *L.* physica, *physics*], *the study of matter and energy and their interactions.*
geophysics *(jē′ ō fiz′ iks)* ***n.,*** *the application of the principles of physics to study the Earth.*

Geology is visual. We are attracted to features on Earth's surface because we see them; our imagination helps us visualize processes within the Earth that form mountains, continents, and oceans. Students of geology commonly develop skills based on visualization; the first impulse of a geologist is often to "make a sketch," much like plays diagramed in the dirt during sandlot ball games.

The movement of objects or the passage of energy as waves occurs in predictable ways; physics lends itself to the formulation of mathematical expressions that describe these phenomena. The first impulse of a physicist might be to write a formula that portrays, concisely, a pattern or process.

Geophysics, as the hybrid of geology and physics, requires the ability to view the same problem from both visualization and mathematical formulation (Fig. 1.1). Most geophysics textbooks rely heavily on the latter approach, explaining concepts mainly through mathematics. That style can lead to two problems in introductory geophysics courses: 1) students with geology backgrounds may be lost in the abstract world of mathematical equations, without visualization of how the equations explain things about the Earth; 2) physics students may understand the equations, but without a feel for aspects of the Earth modeled by the equations.

Whole Earth Geophysics is the outgrowth of a two-term course consisting of undergraduate and graduate geology students, along with a few physics and geophysics majors. While having a qualitative feel for the Earth, geology students often lack advanced-level courses in math and physics. This book explains concepts through numerous graphic illustrations; equations, where necessary, are developed with mathematics that most geology students have mastered. The book presents geophysical techniques, but the focus is on how each technique provides information on the internal structure and tectonic development of the Earth.

Geophysics students may not have been exposed to their subject in a graphic and systematic way; concepts in many geophysics courses are revealed through equations and illustrations from the literature intended for advanced-level researchers. The visual approach employed in this book may help geophysics students see how ideas developed mathematically in other courses relate to the "real world."

The book presents plate tectonic theory in an early chapter, explaining the development of continental rifts, ocean basins, continental margins and various types of mountain ranges. Illustrations in later chapters portray the expressions of geophysical data in different tectonic settings. Simple models predict the appearance of geologic structures on seismic reflection profiles, and show the form of gravity anomalies developed during stages of opening and closing of ocean basins.

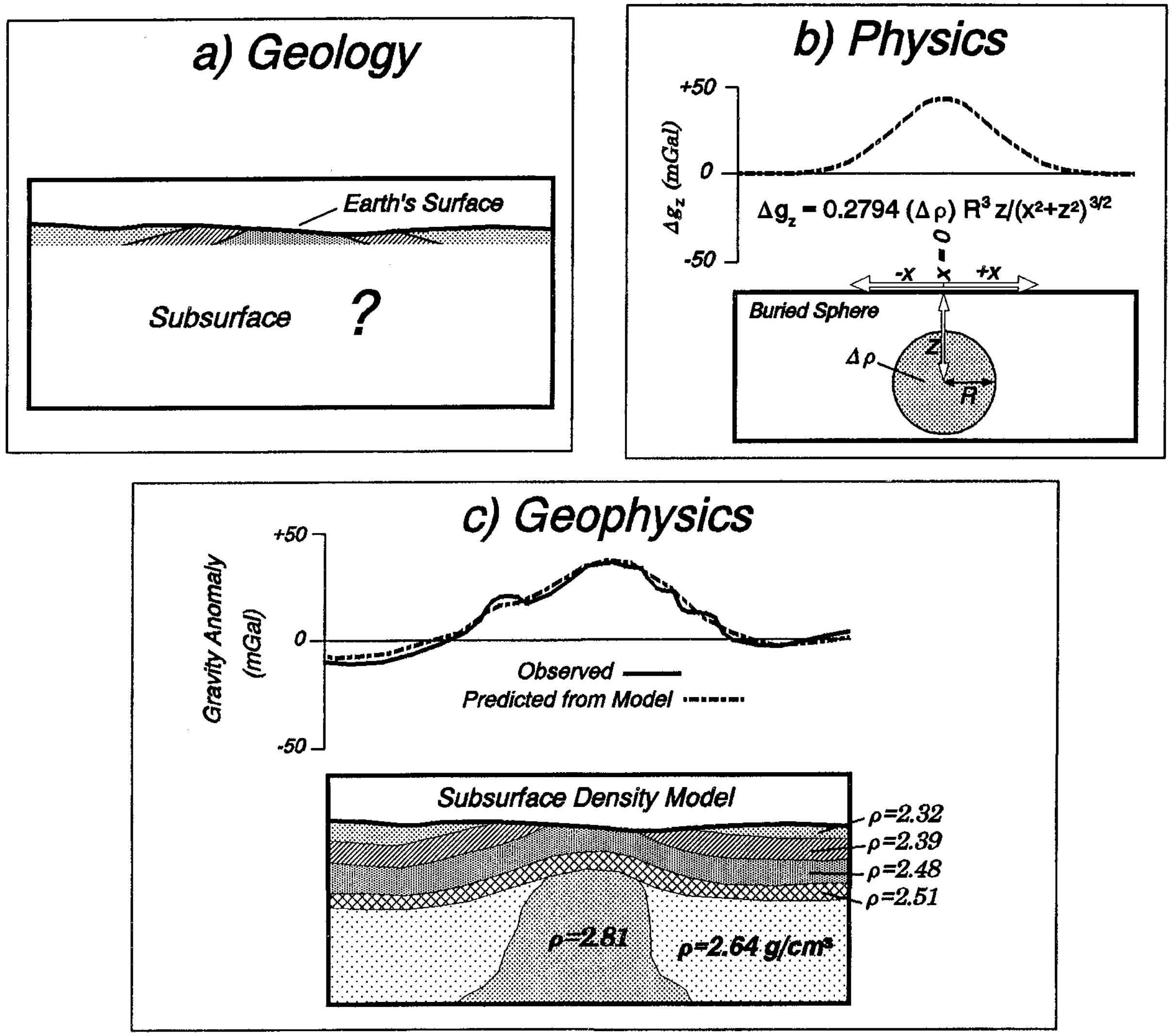

FIGURE 1.1 Geophysics aims to interpret the subsurface by combining observations of Earth materials (geology) with observations of physical phenomena (physics). a) Cross-section illustrating surface geology, with no subsurface information. b) Model of a physical parameter, the change in Earth's gravity field (Δg_z) that would result from a sphere of radius (R) and density contrast ($\Delta\rho$). The mathematical equation predicts the change in gravity caused by such a mass buried depth (z) below the surface. c) Observed change in gravity field, along with a model of subsurface density distribution (ρ) that might cause such a change. The model agrees with the observed surface geology and shows density distributions that result in a predicted gravity anomaly close to that observed.

A primary focus is the relationship between topography, the crust/mantle boundary, and the lithosphere/asthenosphere transition; these three features balance through *isostasy,* whereby pressure equalizes at a certain depth within the Earth. Students thus appreciate the utility of geophysical measurements to constrain interpretations of the crust and lithosphere/asthenosphere system in different portions of the Earth.

The geophysical methods covered in this book (refraction, reflection, earthquake, gravity, magnetics, and heat flow) are basic to the education of geology students, particularly in helping them appreciate Earth's gross structure and plate tectonics. Other methods (for example, geochronology, radioactivity, well logging, electrical methods) are important, but they may be addressed better in geochemistry or more advanced geophysics courses.

OVERVIEW OF GEOPHYSICAL TECHNIQUES

Measurements of natural or induced properties are commonly made at the surface of the Earth (for example, gravitational acceleration). Applied geophysics interprets those observations in terms of properties within the Earth (for example, density distributions that locally change the gravitational acceleration). Geophysical techniques employed at or near Earth's surface include *seismic, potential field* and *heat flow* measurements (Fig. 1.2).

Seismic

Relatively small and rapid, up-and-down or sideways movements of Earth's surface, measured by a seismometer, relate to the passage of seismic waves through the Earth. The "ground motion" (*displacement, velocity,* or *acceleration* of the

Geophysical Technique		Property Measured at Earth's Surface	Property Investigated within Earth
SEISMIC	Natural Source: Earthquake	Ground Motion (Displacement, Velocity or Acceleration)	Seismic Velocity (V) and Attenuation (Q)
	Controlled Source: Refraction		Seismic Velocity (V)
	Controlled Source: Reflection		Acoustic Impedance (Seismic Velocity, V, and Density, ρ)
POTENTIAL FIELD	Gravity	Gravitational Acceleration ($\vec{g}$)	Density (ρ)
	Magnetics	Strength and Direction of Magnetic Field ($\vec{F}$)	Magnetic Susceptibility (χ) and Remanent Magnetization ($\vec{J}_{rem}$)
HEAT FLOW		Geothermal Gradient ($\partial T/\partial z$)	Thermal Conductivity (k) and Heat Flow (q)

FIGURE 1.2 Geophysical techniques measure properties at Earth's surface. Interpretation of the measurements suggests properties within the Earth.

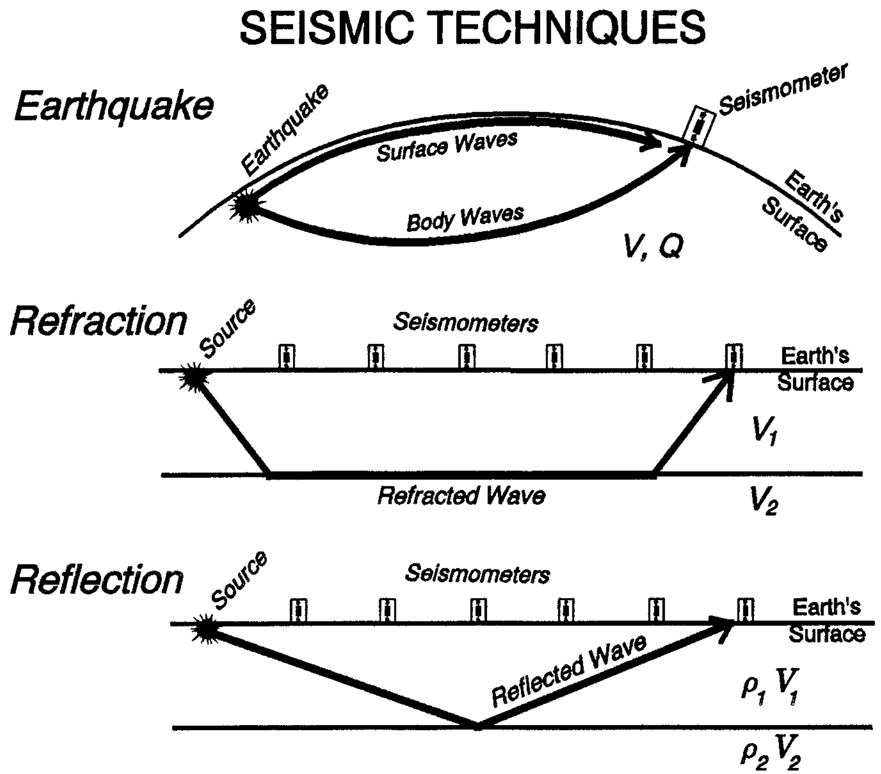

FIGURE 1.3 Seismic techniques employ seismometers to measure movement of the ground resulting from waves generated by an earthquake or artificial source. The time of travel from the source to a receiver is a function of the seismic velocity (V) of the material along the wave's path. The amount and type of ground motion may reveal other properties within the Earth, such as seismic attenuation (Q) and acoustic impedance (the product of density, ρ, and seismic velocity).

seismometer) reveals properties of the materials that the waves encountered (Fig. 1.3). The time it takes for the waves to get from their source to a seismometer (*travel time*) is a function of the speed the waves passed through a region of the Earth (*seismic velocity, V*). The amount and type of ground motion reveals how readily the region absorbed or scattered wave energy (*attenuation,* or "quality factor," Q).

Seismic waves are generated naturally by *earthquakes.* They travel through the Earth as *body waves,* or follow Earth's outermost regions as *surface waves.* Seismic waves can also be generated from explosions or other controlled sources, facilitating techniques to measure the *refraction* of waves as they encounter regions of changing *velocity* (V), or *reflections* due to changes in *acoustic impedance* (density, ρ, times velocity, V).

Potential Field

Potential fields, like those due to Earth's *gravitational attraction* and *magnetism,* change strength and direction depending on the position of observation within the field. The strength of a potential field generally decreases with distance from the source of the field. When the broad effects of Earth's rotation, equatorial bulge, and topography are subtracted, observations of *gravitational acceleration* ($\vec{g}$) relate to nearby mass distributions (that is, subsurface *density* changes, $\Delta\rho$; Fig. 1.4). Earth's *magnetic field* ($\vec{F}$) is changed locally by the ability of nearby rocks to be magnetized

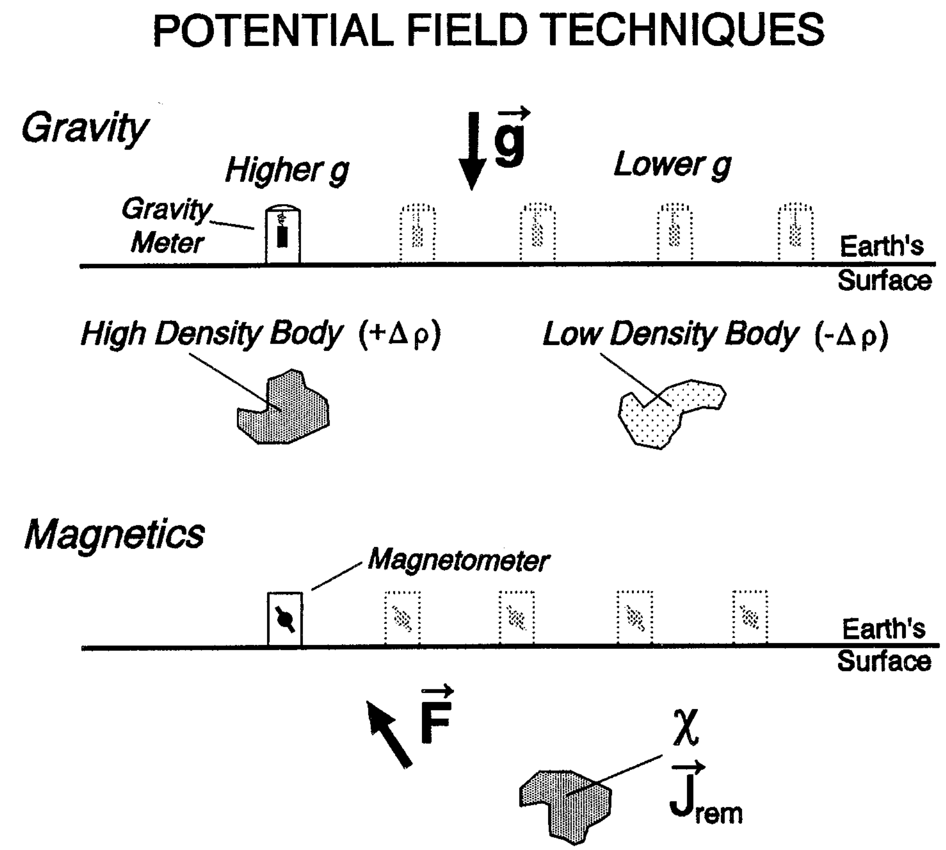

FIGURE 1.4 *Potential field techniques.* A gravity meter measures gravitational acceleration ($\vec{g}$), sensitive to local density changes ($\Delta\rho$). Magnetometers reveal the Earth's total magnetic field ($\vec{F}$), influenced by the magnetic susceptibility (χ) and remanent magnetization ($\vec{J}_{rem}$) of subsurface materials.

(*magnetic susceptibility,* χ) or by the rocks having been magnetized as they formed (*remanent magnetization,* $\vec{J}_{rem}$).

Heat Flow

Heat constantly flows outward, from hotter regions to Earth's surface. The change in temperature (T) can be measured from the surface downward in drillholes (Fig. 1.5). Knowing the *thermal conductivity* (k) of the rocks in the area, the *geothermal gradient* ($\partial T/\partial z$) can be used to calculate the rate at which heat escapes from that region of the Earth (*heat flow*, q). Without heat, Earth's interior would be completely solid and motionless. Heat softens up a portion of the upper mantle (asthenosphere); movement of rigid plates (lithosphere) over this softer zone is a product of the flow of heat from Earth's interior.

INTERPRETATION: METHODS AND CONSTRAINTS

Various methods are used to interpret aspects of the Earth from geophysical data. The quality of interpretations depends on how well the problem is constrained by other criteria, such as additional geological and geophysical observations, or assumptions based on models.

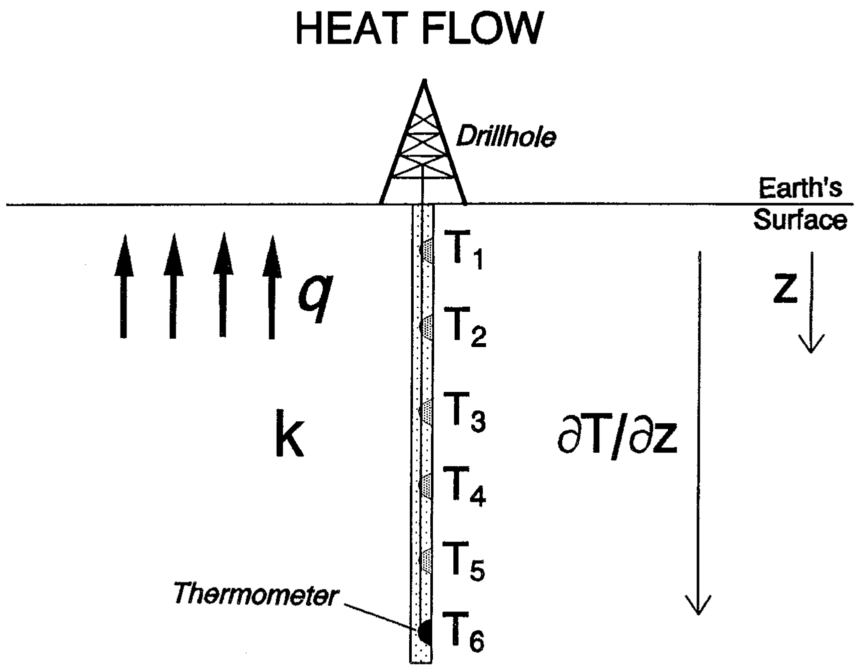

FIGURE 1.5 *Heat flow technique.* Temperatures (T_1, T_2, etc.) are measured at various depths in a drillhole. The change in temperature (T) with depth (z), or geothermal gradient ($\partial T/\partial z$), is a function of the thermal conductivity (k) and the flux of heat through the surface (heat flow, q).

Methods

Both inverse and forward methods are used to interpret geophysical observations. In each case we ask, "What caused what we observed?" *Inversion* uses mathematical equations to calculate a subsurface model from observed data; *forward modeling* assumes a subsurface model and calculates observations that would result.

Fig. 1.6 shows an interpretation (model) that results from the inversion of seismic refraction observations. Observed parameters are inserted into mathematical equations that yield a model of the seismic velocities and thicknesses of layers. We are accustomed to using inversion in math and physics courses, when we "plug into" formulas to yield results.

The forward modeling of an observed gravity profile is illustrated in Fig. 1.7. Layers with different densities are assumed. Calculations from the subsurface model predict the gravity profile that would result. Thicknesses and densities of layers are then adjusted until the predicted ("calculated," or "computed") profile matches the observations; we might consider the adjusted model as one potential interpretation of the observed data.

Constraints

No matter what methods are used to interpret geophysical data, we should not lose sight of the objective: *We make observations of certain properties of the Earth in order to interpret the nature of the Earth.* Geologists often use rock hammers to crack open the Earth, to see what's there and analyze how it got to be that way. In many respects, *geophysical techniques are just another type of rock hammer;* we bang on the Earth and listen to what the Earth tells us about itself.

Alone, a geophysical technique may not tell us much about the Earth. When that technique is combined with other observations, however, we may learn a great deal about a region's subsurface geology and evolution. Those other observations, in the form of geological and other geophysical data, are *constraints.* The more con-

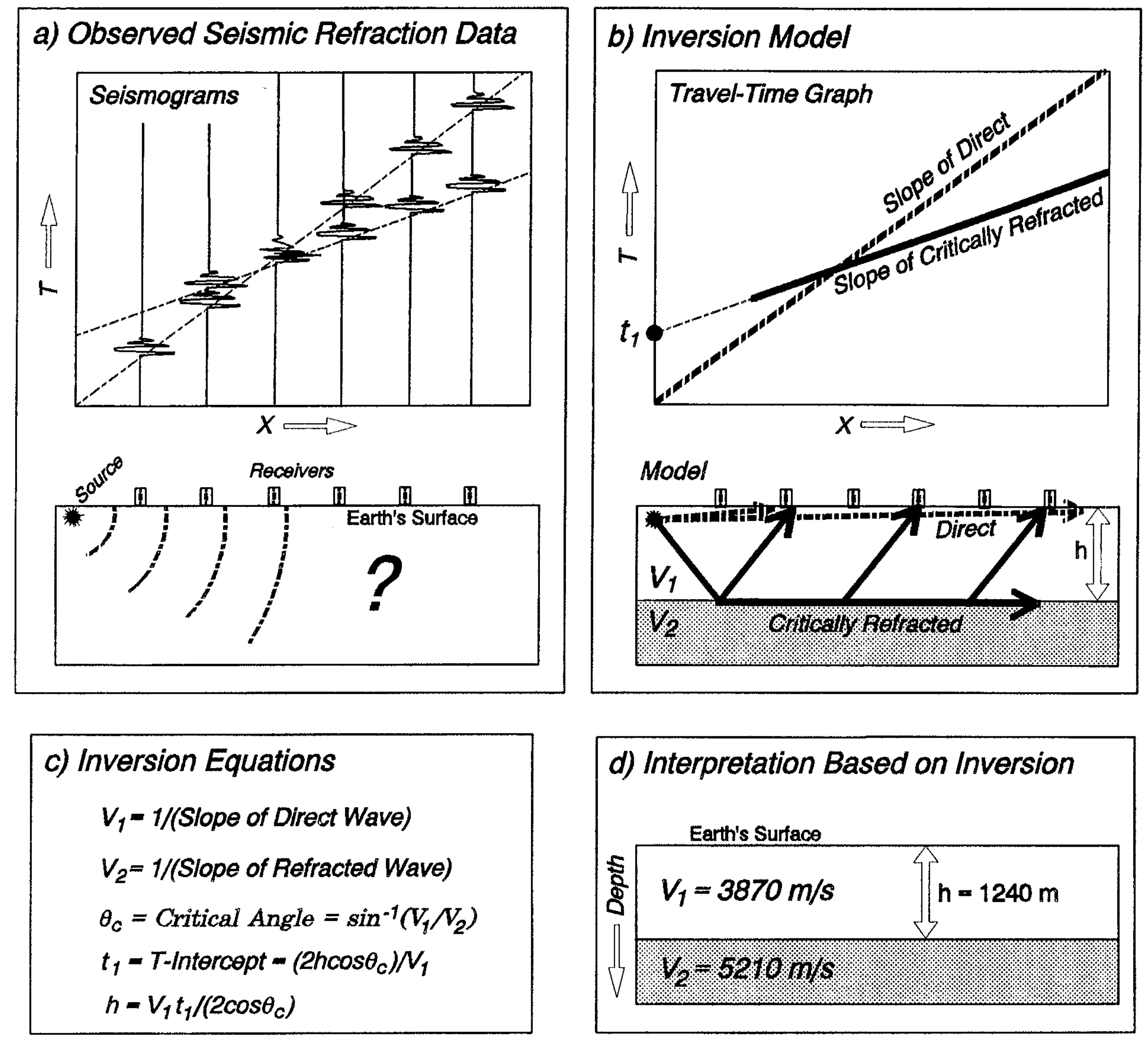

FIGURE 1.6 *Inversion example.* a) Observed seismograms showing times of arrival (T) of direct and critically refracted waves at seismometers placed increasing distance (X) from the source. b) Two-layer model showing parameters that can be read from the observed data: slope of the direct arrival; T-axis intercept time (t_1); and slope of the critically refracted arrival. c) Equations that can be used to invert observations of slopes and T-axis intercept time (see Chapter 4). d) Model of seismic velocities for two layers (V_1, V_2), and the thickness of the upper layer (h), that result from inserting the slopes and intercept time into the inversion equations.

straints we have on a problem, the more likely we are to come to a unique solution. Rarely is a region so well constrained that we can perceive of only one possibility for its subsurface interpretation; we therefore say that most interpretations of geophysical data are "nonunique."

Nonuniqueness means that it is possible to offer more than one interpretation that agrees with all available information. The problem is like that of the "blind men and the elephant;" the interpretation depends largely on our sample locations and the overall density of sampling. In approaching a problem, it is wise to keep in mind a *hierarchy of constraints* (Fig. 1.8).

Level 1: (*Firm Constraints*):
Direct observations of the Earth that you can put in your hand:
a) Outcrop samples.
b) Drill cores.

Level 2: (*Softer Constraints*):
Indirect or inferred observations about the Earth.
a) Map interpretations based on scattered direct observations.
b) Geophysical observations.

Level 3: (*Reasonable Assumptions*):
Theoretical considerations, based on logic and common sense (for example, "modeling").

Thinking should flow from higher (1) to lower (2, 3) levels. For example, surface geological mapping of a region (Level 1) can constrain interpretations of geophysical data (Level 2); the geophysical interpretations further suggest models (Level 3) for overall structure or processes in the region. Thinking in the other

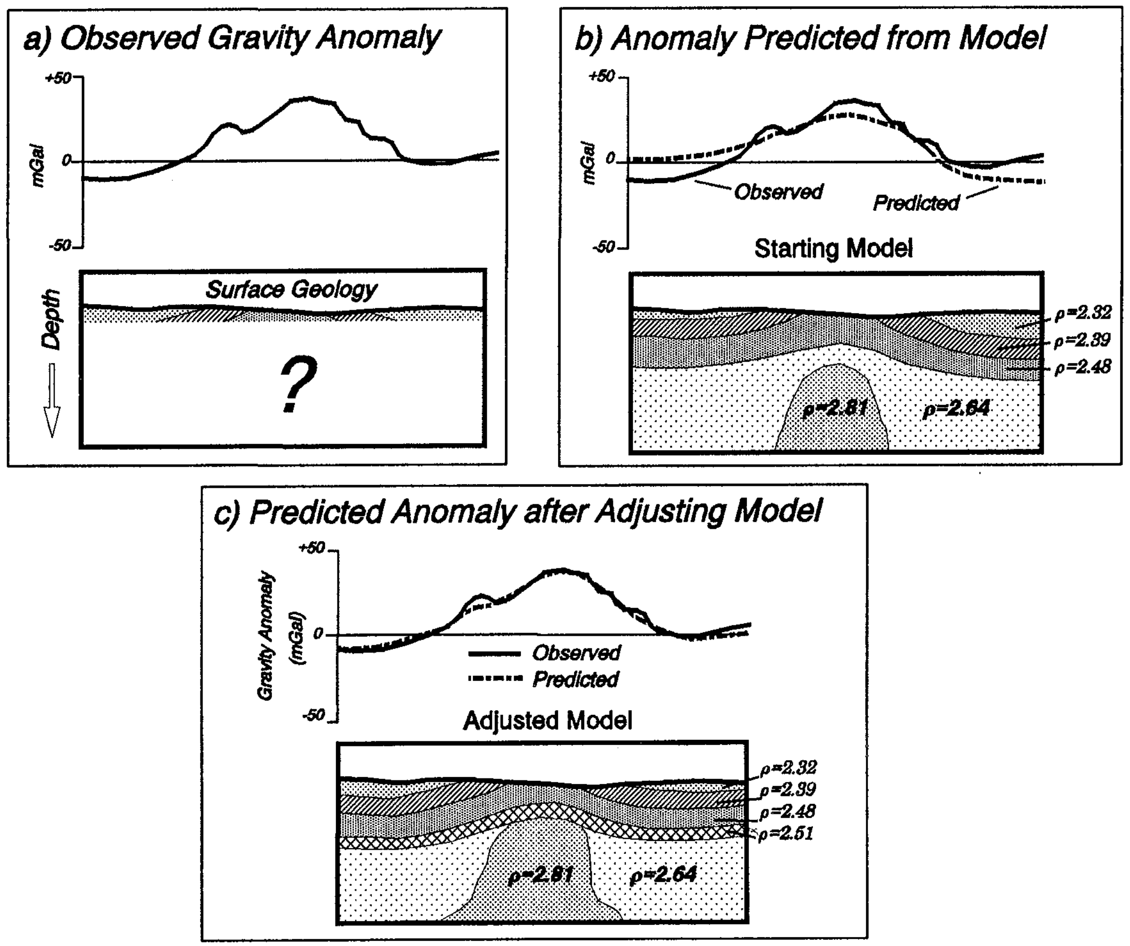

FIGURE 1.7 *Forward modeling example.* a) Gravity anomaly measured at several stations on the surface. Surface outcrop and dips serve as constraints on interpretation. b) Preliminary model testing subsurface densities and geometries, resulting in a predicted gravity anomaly (see Chapter 8). ρ = density (g/cm^3). c) Densities and geometries adjusted to achieve closer agreement between observed and predicted anomalies. Note that the constraints offered by surface geology are not changed.

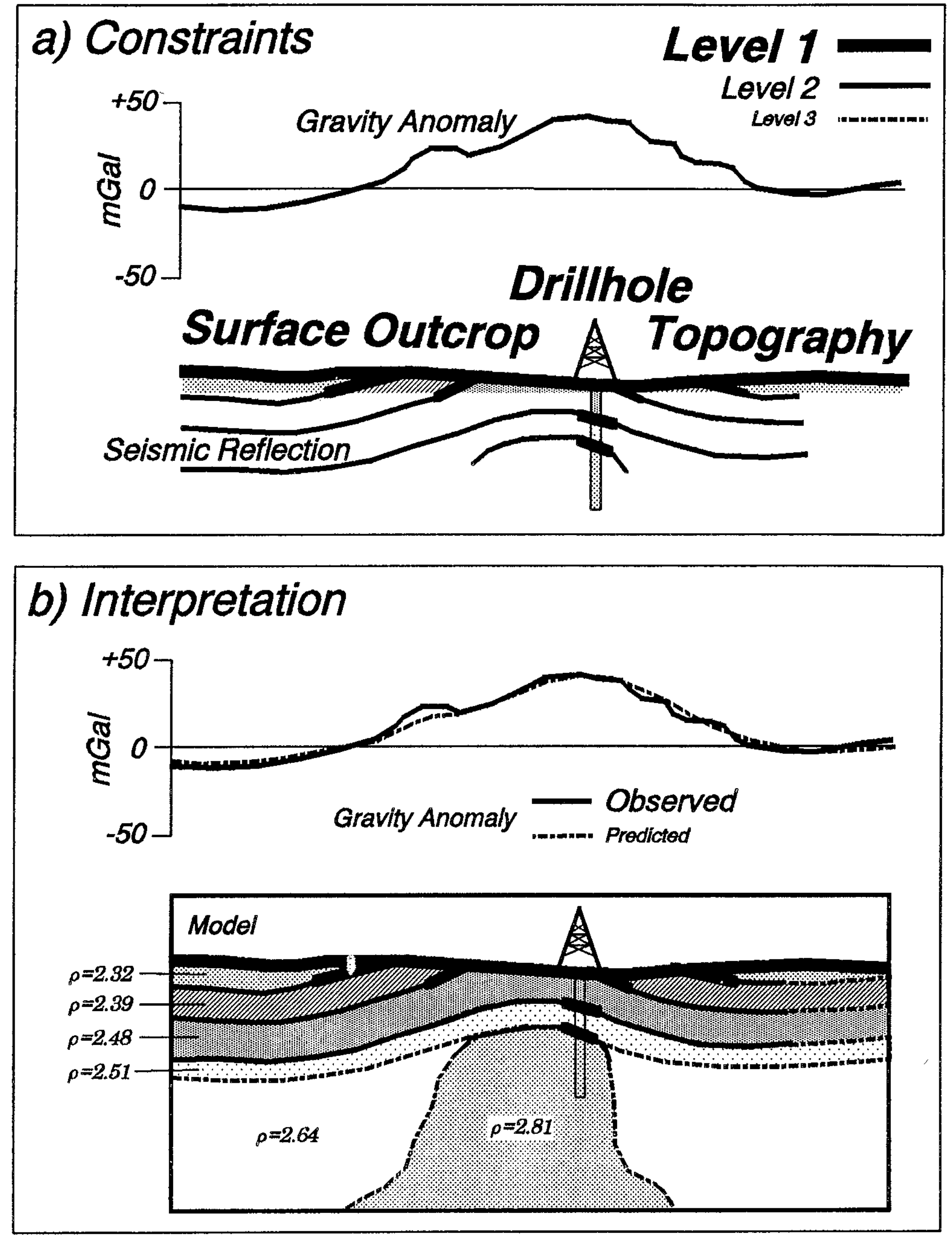

FIGURE 1.8 *Constraints and interpreted cross section.* a) The firm (Level 1) constraints include topography, types of rocks, and dips observed at the surface and in the drillhole. Less firm (Level 2) constraints come from the orientations of reflectors interpreted from seismic reflection profiles, and from the observed gravity anomaly. b) An interpreted cross section places strict value on the Level 1 constraints, less on those from Level 2. Level 3 constraints (shown by the dashed lines) result from a model of density configurations that brings the predicted gravity anomaly close to the observed.

GEOLOGIC TIME	THE EARTH	RESOLUTION (What We Know)
Our Lifetime	*Earth's Surface*	*Great Detail*
Recorded History (0 - 5,000 years)	*Crust* (0 - 30 km)	*Quite a Bit*
Phanerozoic (0 - 600,000,000 years)	*Lithosphere - Asthenosphere System* (0 - 700 km)	*Some*
Precambrian (600,000,000 - 4,600,000,000 years)	*Lower Mantle and Core* (700 - 6300 km)	*Not Much*

FIGURE 1.9 Analogy showing diminishing resolution going back in time and going deeper into the Earth.

direction is not wise (for example, models or geophysical observations do not give us better information about surface geology than we could get from a detailed geologic mapping project).

WHOLE EARTH KNOWLEDGE

Our knowledge of Earth's interior is analogous to looking back in time (Fig. 1.9). We know a lot about events that happened in our lifetimes, far less about things from our parents' and grandparents' time. As we look farther back in time or deeper within the Earth, the quality of observation deteriorates; not only do we have less information, but the detail of the information diminishes. The concept of *resolution* is therefore important in appreciating what is known about the Earth, both temporally and spatially. In our own lifetimes, we know about events that shaped history (the fall of the Berlin Wall), but also great details of some less important observations (the route from our homes to school or work). We know of some important events that shaped our parents and grandparents lives (landing on the moon; World War II), but far less about what daily life was like for them. As we continue back through recorded history, some events stand out (Europeans coming to America; development of Roman, Greek, and Egyptian civilizations), but the time between "important" events becomes longer and vague. Likewise, the scale of features we can interpret becomes larger as we probe deeper and deeper into the Earth. We know a great deal about Earth's surface and upper crust, a fair amount about its lower crust and uppermost mantle. Going deeper, we have only general appreciation of the composition and boundaries of the lower mantle and core.

Knowledge of the Earth comes almost entirely from observations made at or near Earth's surface (Fig. 1.10). Direct observations, in the form of actual rock or magma, sample only the upper 200 or so km, about 1/30th of Earth's 6300 km radius. Surface exposures are almost entirely rocks formed within Earth's crust, with occasional pieces of uppermost mantle brought to the surface during deformation; those

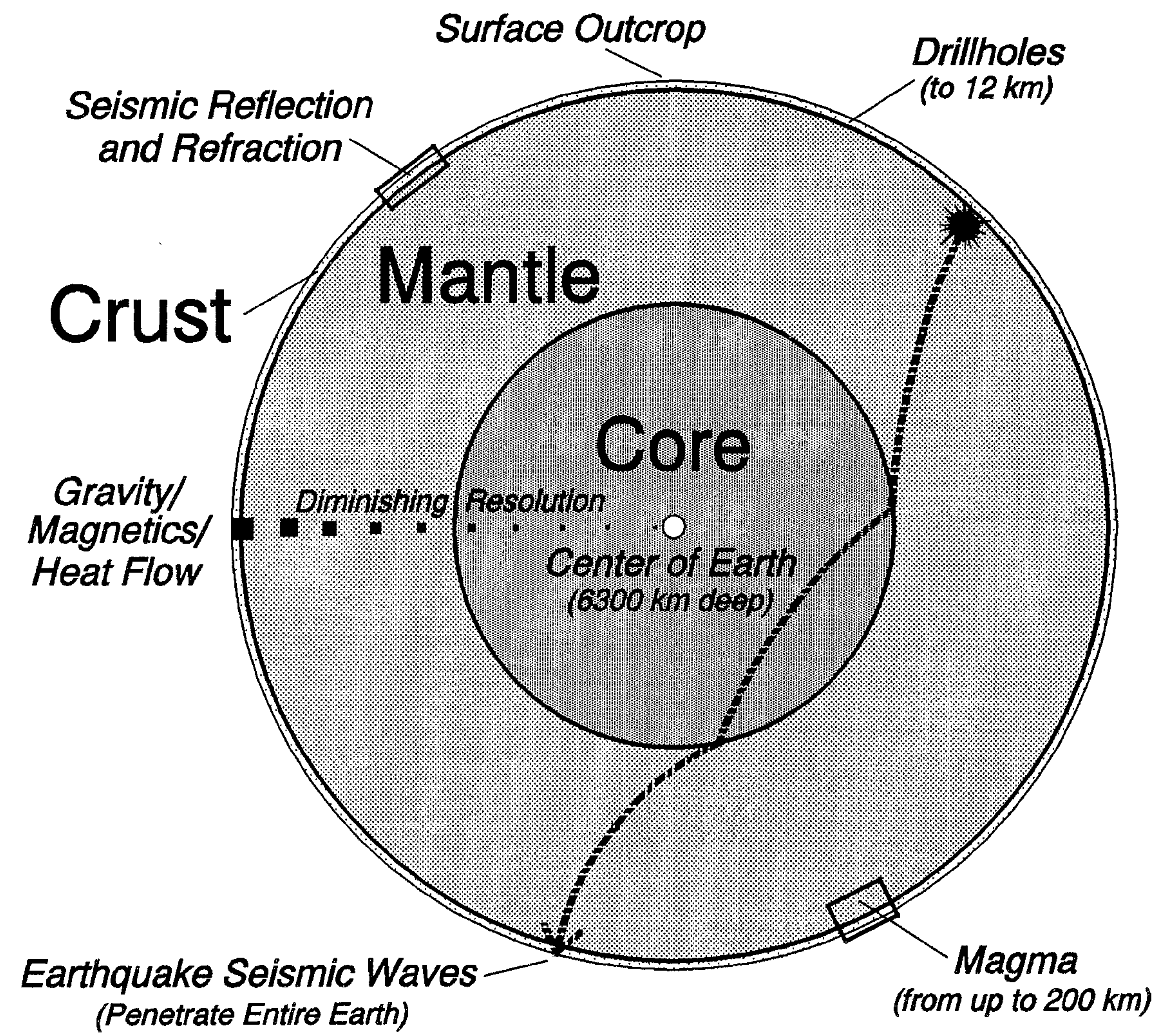

FIGURE 1.10 *Constraints on nature of Earth's interior.* Direct observations (surface outcrops, drillholes, magma reaching surface) generally sample only the crust and uppermost mantle. Geophysical observations (controlled-source seismic, potential field, heat flow) provide further constraints on the outer shells; earthquake seismic waves give most of the information on the lower mantle and core.

materials generally formed in the uppermost 50 km. The deepest drillhole penetrates to about 12 km depth, less than half the thickness of typical continental crust. Volcanic eruptions and igneous intrusions (with the exception of deep-seated kimberlites) come from magma that originated at lower crustal or upper mantle depths, generally within the upper 200 km.

Geophysical data allow us to look deeper into the Earth and sample more widely, but with varying degrees of resolution (Fig. 1.10). Our knowledge is limited by the maximum depth that particular techniques can probe, effectively, within the Earth. Seismic reflection data show details within sedimentary basins (upper 10 km) and, in recent years, provide information about the lower crust and the crust/mantle transition ("Moho"). Seismic refraction data provide constraints on crustal thickness changes and, in some cases, seismic velocities within the crust and uppermost mantle.

Most of our constraints on the deep interior of the Earth are due to the fact that seismic waves from large earthquakes travel through the entire Earth, where they are recorded on the other side. Changes in seismic wave velocity with depth are derived from analysis of the travel times and paths of various earthquake waves. The seismic velocities in turn give constraints on the composition and physical state of portions of the Earth.

Gravity and magnetic measurements constrain the size and positions of anomalous bodies within the Earth, but their resolution decreases with the depth of the bodies (potential field strength lessens with increasing distance from the source). Similarly, heat flow pinpoints shallow intrusions and suggests changes in the depth to the lithosphere/asthenosphere transition zone. For the Earth as a whole, gravity, magnetic, and heat flow data provide constraints on gross properties (density, magnetism, and thermal state, respectively), though not at the detail given by earthquake seismic studies.

This book first presents a general framework for study of gross features of the Earth (plate tectonics), then examines how each geophysical technique contributes to whole Earth knowledge.

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