CRC

HANDBOOK of PHYSICAL PROPERTIES of ROCKS

Volume I

Robert S. Carmichael

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Handbook of Physical Properties of Rocks

Volume I

Editor

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PREFACE

The objective of this handbook is to provide an organized compilation of data on rocks and minerals.

"Science is organized knowledge."

Herbert Spencer
(1820—1903)
English philosopher

The handbook is a current guide to physical properties, for easy reference to and comparison of various properties or various types of materials. Its function is to present a reliable data base that has been selected and evaluated, and as comprehensively as reasonable size limitations will permit. The intent is to bridge the gap between individual reports with only specific limited data, and massive assemblies of data which are uncritically presented.

Individual chapters have been prepared by recognized authorities who are among the leaders of their respective specialties. These authors are drawn from leading university, industrial, and government and scientific establishments. An Advisory Board of nationally prominent geoscientists has helped to oversee the handbook development.

The handbook is interdisciplinary in content and approach. A purpose is to provide data for persons in geology, geophysics, geochemistry, petrophysics materials science, or geotechnical engineering, who might be expert in one special topic but who seek information on materials and properties in another topic. This might be for purposes of evaluation, estimates, modelling, prospecting, assessment of hazards, subsurface character, prediction of properties, beginning new projects, and so on. The expert may have sources of reference as a guide in his area, but needs assistance to get started on something new or on a topic in an allied field.

The format is primarily tabular for easy reference and comparability. In addition to tables and listings, there are graphs and descriptions where appropriate. Graphical trends, e. g., how a property varies with a parameter such as mineral composition or temperature or pressure, can be particularly useful when studying rocks. This is because, for some rock properties, the trend may be more reliable and useful than the absolute value of the property at one particular condition.

Rocks are the foundation of our physical world, both literally and figuratively. The importance of them, and of their physical properties, derives from such applications as:

1. They are the material on or in which geotechnical engineers install buildings, dams, tunnels, bridges, underground storage or waste disposal facilities, and a variety of other structures.
2. They contain the natural resources needed by modern industrial society, including oil and gas, coal, groundwater, geothermal energy, and ore deposits of such metals as iron, copper, lead, zinc, and nickel.
3. Their variations in physical properties such as density, magnetization, elastic-wave velocity, and electrical resistivity provide means for remotely determining subsurface geology and structure by the methods of exploration geophysics.
4. They rupture on fault zones to produce earthquakes and transmit the resulting seismic waves for long distances.
5. Laboratory study of them can often reveal the age, origin, and geologic history of rocks and events.

Physical properties of rocks and of their constituent minerals are of concern to geologists, geophysicists, petrophysicists, and geotechnical engineers. Over the past 20 years or so, there has been a great increase in the amount and variety of data available. This was because of the development of new measuring equipment and analytical techniques, the rise of new applications requiring new or more refined data, and the acquisition of rocks from habitats that had been previously inaccessible. The latter include great depths in the continents (down over 10,000 m in sedimentary basins), the continental shelves and seafloors to depths of several hundred meters below the deep seafloor, and the Moon.

Rock properties are of interest for recently developing topics such as deeper drilling for petroleum and other resources, including deep minerals and geothermal energy development; understanding earthquakes and their prospective prediction based on precursory physical changes occurring in the epicentral area; engineering geology; more refined geophysical prospecting of the subsurface using inherent rock properties as well as rock structure; and study of surface geology from satellite remote sensing.

There is also ever-increasing interest in the properties of rocks and minerals because of new or expanded applications in allied fields. For example, materials scientists and solid-state physicists are interested in such physical properties as the magnetic, electrical, and optical character of mineral crystals. Such information has use for magnetic memory devices for computers, for permanent magnets, and for electronics. Construction engineers need better information on rock properties in unconventional sites, e.g., for installing oil-storage tanks on the seafloor, for burying pipelines in permafrost terrain, and for siting major structures in areas of seismic risk.

"Human knowledge is but an accumulation of small facts made by successive generations of (investigators) — the little bits of knowledge and experience carefully treasured up by them growing at length into a mighty pyramid."

Samuel Smiles
(1812—1904)
Scottish writer

Chapters in Volume I include:

Mineral composition of rocks — Chemical composition and physical characteristics of igneous, sedimentary, and metamorphic rocks, and of pore fluids (including geothermal fluids), economic ores and fuels (including coal, petroleum, oil shale and tar sands, radioactive minerals), and marine sediments. Properties of minerals and crystals, including petrographic characteristics. Composition of the Earth's crust and mantle, and of meteorites and Moon rock.

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Electrical properties of rocks and minerals — Conductivity/resistivity and dielectric constants of minerals and dry rocks. Variation of electrical properties with temperature, pressure, frequency at which measurement is made, and ithology and porosity. Induced polarization. Resistivity of brine and water-bearing rocks. Electrical properties and electric logs of sedimentary rocks, in situ sequences of rocks, and coal, permafrost, and the Earth's interior.

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Spectroscopic properties of rocks and minerals — Interaction of matter with electromagnetic radiation, in the visible and infrared range. Properties of absorption/transmission, reflection and emission, and spectral characteristics of minerals and rocks.

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Volume II will include:

Seismic velocities — Compressional and shear wave velocities for rocks, minerals, marine sediments and water, aggregates and glasses, the Earth's crust and supper mantle (continental and oceanic), glaciers and permafrost. Laboratory and in situ measurements. Variation of velocity with degree of fluid saturation, pressure and temperature.

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Professor of Geological Sciences
and Graduate Program in Geophysics
University of Washington
Seattle, Washington

Magnetic properties of minerals and rocks — Magnetic and crystalline properties of magnetic minerals. Types of remanent magnetizations. Magnetic properties of rocks: susceptibility, coercive field, Curie temperature, anisotropy, saturation magnetization. Variation with chemical composition, grain size and shape, temperature and pressure.

Robert S. Carmichael, Ph.D.
Professor of Geology
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Engineering properties of rock — Factors and tests relating to rock appraisal, characterization, and assessment of properties such as strength, hardness, elastic constants, and deformation. Engineering properties, including the effects of pore water pressure.

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Volume III will include:

Mechanical properties (inelastic) — Inelastic mechanical properties of rocks and minerals, emphasizing strength and rheology. Laboratory tests in rock mechanics, stress-strain relations, and effects of pore fluids, time and stress rate, and temperature. Rock friction. Compilation of experimental data.

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Elastic Constants
Thermal Properties
Seismic Attenuation
Radioactivity Properties

Data have been gathered, transcribed, and reproduced here with as much care as possible; in the event of any apparent uncertainty, one should check with the original references as given.

My thanks are extended to all who have contributed to the formulation and execution of this Handbook series. The editorial function at CRC Press was performed by Susan Cubar, Pamela Woodcock, and Cathy Walker. The University of Iowa provided partial summer support in the form of an Old Gold Fellowship to the Editor. Appreciation is due Dr. Richard Moppin, Chairman of Geology at Iowa, for fostering the supportive environment conducive to professional labors of love such as this.

Robert S. Carmichael
1981

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Robert S. Carmichael, Ph.D., is professor of Geophysics and Geology in the Department of Geology, University of Iowa, Iowa City. He graduated from the University of Toronto with a B.A. Sc. degree in geophysics/engineering physics, and then earned M.S. and Ph.D. degrees in Earth and Planetary Science from the University of Pittsburgh. His thesis specialties were in seismology and rock magnetism, and while there, he was an Andrew Mellon university Fellow.

After graduation in 1967, he spent a year at Osaka University in Japan, as a post-doctoral Research Fellow of the Japan Society for Promotion of Science and working in high-pressure geophysics. Upon return, he joined Shell Oil's Research Center in Houston as a research geophysicist in petroleum exploration. Now at the University of Iowa, Dr. Carmichael has research interests in rock properties, exploration geophysics, high-pressure geophysics and magnetics, and earthquakes in the central Mid-continent region.

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* Deceased 1980

** Relinguished position upon assumption of duties as President's Science Advisor and Director of Office of Science and Technology Policy, Washington, D.C.

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Graham R. Hunt, Ph.D., D. Sc., earned degrees from the University of Sydney in Australia and worked in spectroscopy at Tufts University, M. I. T., and the Air Force Cambridge Research Labs. As of 1981 he was a Senior Research Scientist with the U.S. Geological Survey as Chief of the Petrophysics and Remote Sensing Branch in Denver. Dr. Hunt's research has been in spectroscopy and physical chemistry, molecular structure, and the remote sensing of the composition of terrestrial and extraterrestrial surfaces. He passed away in 1981 after a brief illness.

George V. Keller, Ph.D., graduated from Pennsylvania State University and then worked for the U.S. Geological Survey. He is now Professor of Geophysics at the Colorado School of Mines and former Head of the Department. He is co-author of the book, *Electrical Methods in Geophysical Prospecting*. Dr. Keller's research includes electrical prospecting, geothermal resources, physical rock properties, and the Earth's crust.

George A. Kiersch, Ph.D., graduated from the Colorado School of Mines and the University of Arizona. He worked as a geologist with the Army Corps of Engineers and directed exploration programs for the University of Arizona and Southern Pacific Company before joining Cornell University in 1960 as Professor of Engineering Geology. He served as Chairman of Geological Sciences there from 1965 to 1971. Dr. Kiersch's interests have been in engineering geology, mineral deposits, and geomechanics. He is now Emeritus Professor from Cornell and practices as a geologic consultant with offices in Arizona and New York.

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Chapter 1

MINERAL COMPOSITION OF ROCKS

Kenneth F. Clark

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INTRODUCTION

The composition of naturally occurring assemblages of minerals has a fundamental bearing on the physical properties of rocks of which they are constituents. Considerations of rock density, elasticity, seismic, thermal, electrical, magnetic, and radioactive properties, for example, are largely dictated by aggregate properties of individual minerals. Thus, any fundamental consideration of the physical properties of rocks must be prefaced by a scrutiny of the chemical and physical properties of minerals. This leads to a consideration of crystal structures, which in turn is governed by atomic characteristics and chemical bonding.[278]

In the following pages, the properties of minerals and rocks of the Earth have been compiled, taking into account their terrestrial distribution that is governed by geologic processes. Relevant data on extraterrestrial materials is indicated, as are naturally occurring substances that do not strictly fit the definition of mineral or rock. Included here are several chemically and physically contrasting fluids located on and below the surface of the Earth. Last, the mineral compositions of earth materials that have historically proved to be useful to man are surveyed, including organic and radioactive substances.

COSMIC ABUNDANCES

Earth materials are considered to be a sample of cosmic matter. Extraterrestrial matter (solid, liquid, gaseous) has been grouped[301] into stellar matter, interstellar matter, and matter of our solar system. Our own solar system including sun, planets, matter of comets and meteorites, and gaseous atmosphere of the sun and planets is assumed to have a common origin. Knowledge of the chemical composition of cosmic matter allows recognition of relationships between solar systems and the origin and development of terrestrial matter.

As noted earlier,[301] the chemical composition of extraterrestrial matter can be studied by spectral analyses of luminous matter, by examining meteorites, or by examining lunar rock samples. Table 1 compares several compilations of elemental cosmic abundances. Tables 2 to 9 show the classification of meteorites plus their mean chemical composition and mineralogy. Tables 10 to 12 provide data on averages of major elemental analyses of basaltic lunar rocks. In Figure 1, weight percent CaO is plotted against weight percent Al_2O_3 in glasses from the Apollo 14 landing site and compared to typical values in meteorites. Major elemental compositions of some ANT-Suite (anorthositic-noritic-troctolitic) rocks[281] are given in Table 12 and their compositional fields and nomenclature are plotted on the Ol-An-SiO_2 pseudoternary diagram in Figure 2.

EARTH'S CRUST

Several theories suggest that the Earth was formed by the cold accretion of particles of metal, troilite, and silicates with bulk composition approximated by chondrites.[397] The chondritic meteorites are made up of three different phases or groups of phases: nickel-iron, iron sulfide, and silicate minerals. Within the Earth, elements are distributed between phases that can be formed according to their relative affinity for metal or for silicate. While gravity controls the relative positions of the phases, the distribution of elements within these phases depends upon chemical potentials.[221] Whatever the origin and chemical differentiation that took place in the history of the Earth, a plausible hypothesis about the chemistry of the interior can be made by distributing the metal and silicates of meteorites so that they satisfy the density and elastic proper-

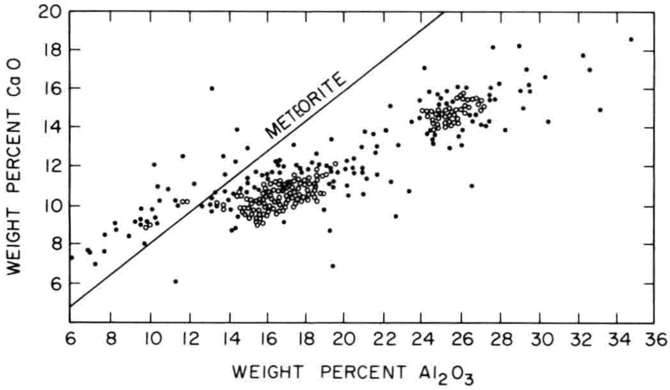

FIGURE 1. Plot of weight percent CaO versus weight percent Al_2O_3 in glasses from Apollo 14 landing site regolith.

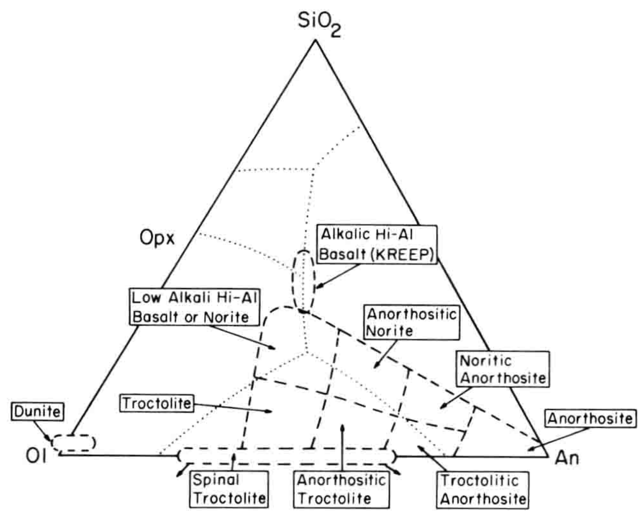

FIGURE 2. Compositional fields and nomenclature of ANT-Suite Rocks plotted on the 01-An-SiO_2 pseudoternary diagram. (High alumina (KREEP) basal fields are also included for reference.)

ties deduced from geophysical measurements. This gives rise to a generally accepted model of a core consisting largely of molten iron surrounded by a mantle made up mostly of silicates of iron and magnesium[188] and a surficial crust. This differentiation may be the most significant event in the Earth's history; it led to the formation of the crust and eventually to continents and probably initiated escape of gases from the interior that resulted in formation of the atmosphere and oceans.[278]

The distribution of rock types in large structural units of the crust and crustal layers is given in Tables 13 and 14. Elemental data for types of crust are given in Tables 15 to 17.

MANTLE AND CORE

The core and mantle together essentially determine the bulk composition of the Earth. The mantle constitutes 67.2% of the Earth's total mass and 90% of its volume.[397] The composition of the upper mantle may be obtained directly by the study of rocks that have been directly derived from the mantle and emplaced in the crust by tectonic processes.[294] Some of these ultramafic intrusions are documented in Table 18, whereas xenoliths of mantle origin are shown by mineralogy and/or major element analysis in Tables 19 to 21. The term pyrolite, as shown in Table 22, is the inferrred parental material that gave rise to mantle-derived ultramafic rocks that remained after a basaltic component had been extracted,[294] and is consistent with an Earth model derived from material resembling carbonaceous chondrites.

CRYSTALS AND MINERALS

A crystal is a solid body bounded by plane natural surfaces that are an expression of the regular internal arrangement of constituent atoms or ions.[222] The classification of crystals based on planes, axes, and centers of symmetry using the Hermann-Maugin symbols is shown in Table 23. Ionic radii, electronegativities, and coordination of ions are displayed in Tables 24 and 25. Chemical classification of minerals, isomorphism, and structural classification of silicates are identified in Tables 26 to 28. The predominant rare earth elements as fixed in minerals are listed in Table 29. For X-ray powder diffraction identification of minerals, see Reference 28.

PETROGRAPHIC CHARACTERISTICS

Petrography is the systematic description and classification of rocks.[243] The polarizing microscope is specifically designed for the study of minerals and rocks whereby distinctive optical properties can be detected. Some minerals are opaque (Table 30) and can only be evaluated in reflected light, whereas others are transparent or translucent and can be viewed in transmitted light. Typical aggregates and/or crystal forms, cleavage, and color are shown in Tables 31 to 33. Other parameters that aid in mineral identification include isotropism; minerals that are dark under crossed polarizers. Included here are minerals of the isometric system and amorphous substances.

Anisotropic minerals (Table 39), consisting of those in the hexagonal and tetragonal systems, possess one optic axis, whereas those that crystallize in the orthorhombic monoclinic and triclinic systems are biaxial and contain two optic axes. Dependent on the optic sign, uniaxial and biaxial minerals are shown in Tables 34 to 38. The optic angle (2V) separating the optic axes of biaxial minerals is listed in Table 40. Birefringence, based on differences in indices of refraction for various minerals, is shown in Table 41.

MINERALOGY OF ROCK KINDREDS

The main groups of rocks are termed igneous and sedimentary and their metamorphic equivalents. Igneous rocks are the products of crystallization of naturally occurring silicate melts, whereas sedimentary rocks result from accumulation of materials at the surface of the earth by various processes under the influence of agents such as wind, water, and ice. Metamorphic rocks result from recrystallization of igneous and sedimentary rocks at relatively high temperatures and pressures. The various mineralogic associations that constitute igneous, sedimentary, and metamorphic rocks are shown in Table 42.

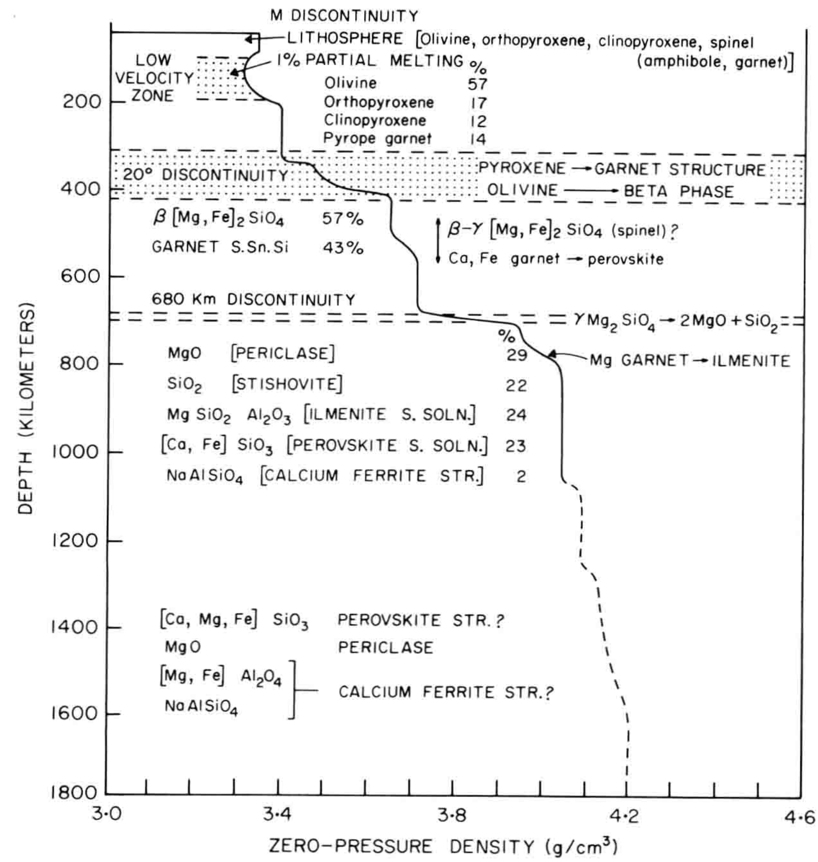

FIGURE 3. Possible mineral assemblages and corresponding zero-pressure densities for a model mantle of pyrolite composition.

IGNEOUS ROCKS

A classification of igneous rocks based on relative mineral abundances is portrayed in Figure 6. Included here are volcanic and plutonic rocks whose essential and accessory minerals are shown in Table 43. Compositions of average igneous rock are given by several investigators in Table 44 and norms of granitic, intermediate, gabbroic-basaltic, peridotitic, anorthositic, and alkalic rocks are included in Tables 45 to 49. In the calculation of the norm the various oxides, determined by chemical analysis, are combined sequentially to form the normative mineral components.[52] The Cross, Iddings, Pirsson, and Washington method (CIPW) is shown for several igneous rocks and is described in standard works.[177]

Chemical analyses of igneous rock suites that characterize particular segments of the earth, for example, oceanic basins, continental crust, or tectonic belts, or that evolved through various evolutionary processes are given in Tables 50 to 85. In addition to major rock-forming elements and corresponding normative mineralogy, trace elemental and isotopic data are included in several instances. Additionally, rare earth element (REE) contents of various rock kindreds[124] are cited in Tables 81 to 83. Finally analyses of gases from fumaroles and volcanoes are shown in Tables 84[52] and 85.[327]

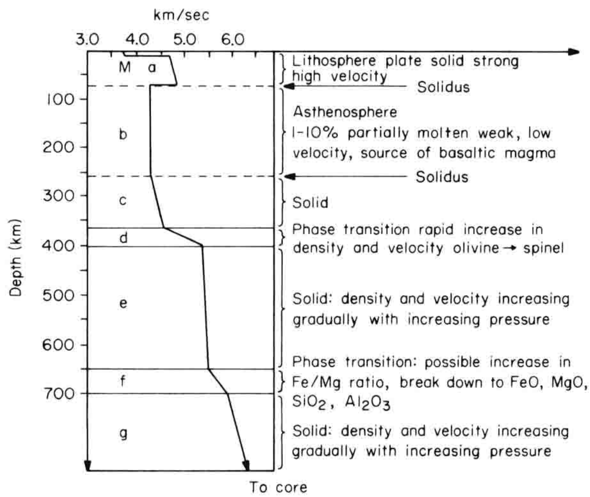

FIGURE 4. A modern view of the structure outermost 700 km of the Earth is illustrated by a plot of S-wave velocity against depth.

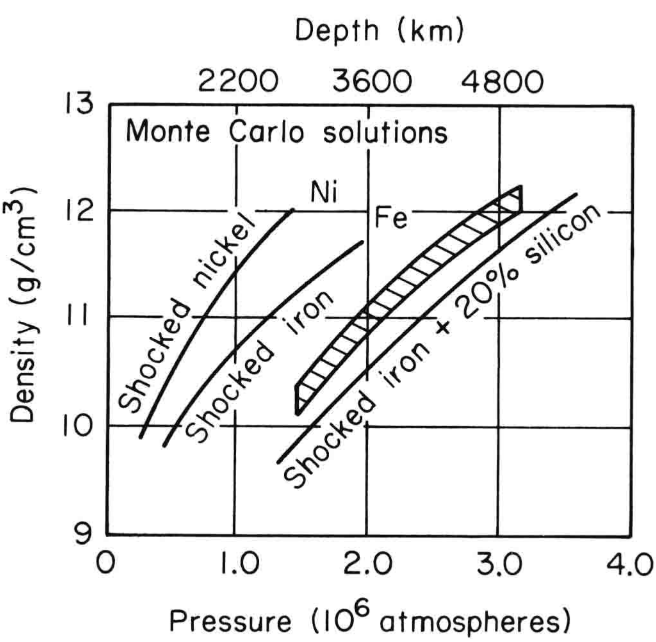

FIGURE 5. Density in the Earth's fluid core plotted against depth below the surface and against pressure.