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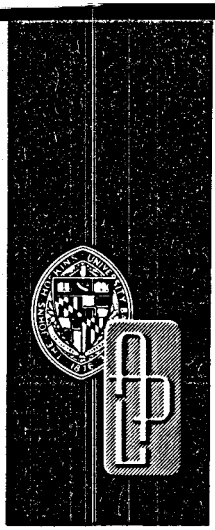

GEOTHERMAL HANDBOOK

C. S. LEFFEL, JR. and R. A. EISENBERG

THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20810

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ABSTRACT

This handbook is intended to assist the physicist, chemist, engineer, and geologist engaged in discovering and developing geothermal energy resources. The first section contains a glossary of the approximately 500 most frequently occurring geological, physical, and engineering terms, chosen from the geothermal literature. Sections 2 through 8 are fact sheets that discuss such subjects as geothermal gradients, rock classification, and geological time scales. Section 9 contains conversion tables for the physical quantities of interest for energy research in general and for geothermal research in particular.

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PREFACE

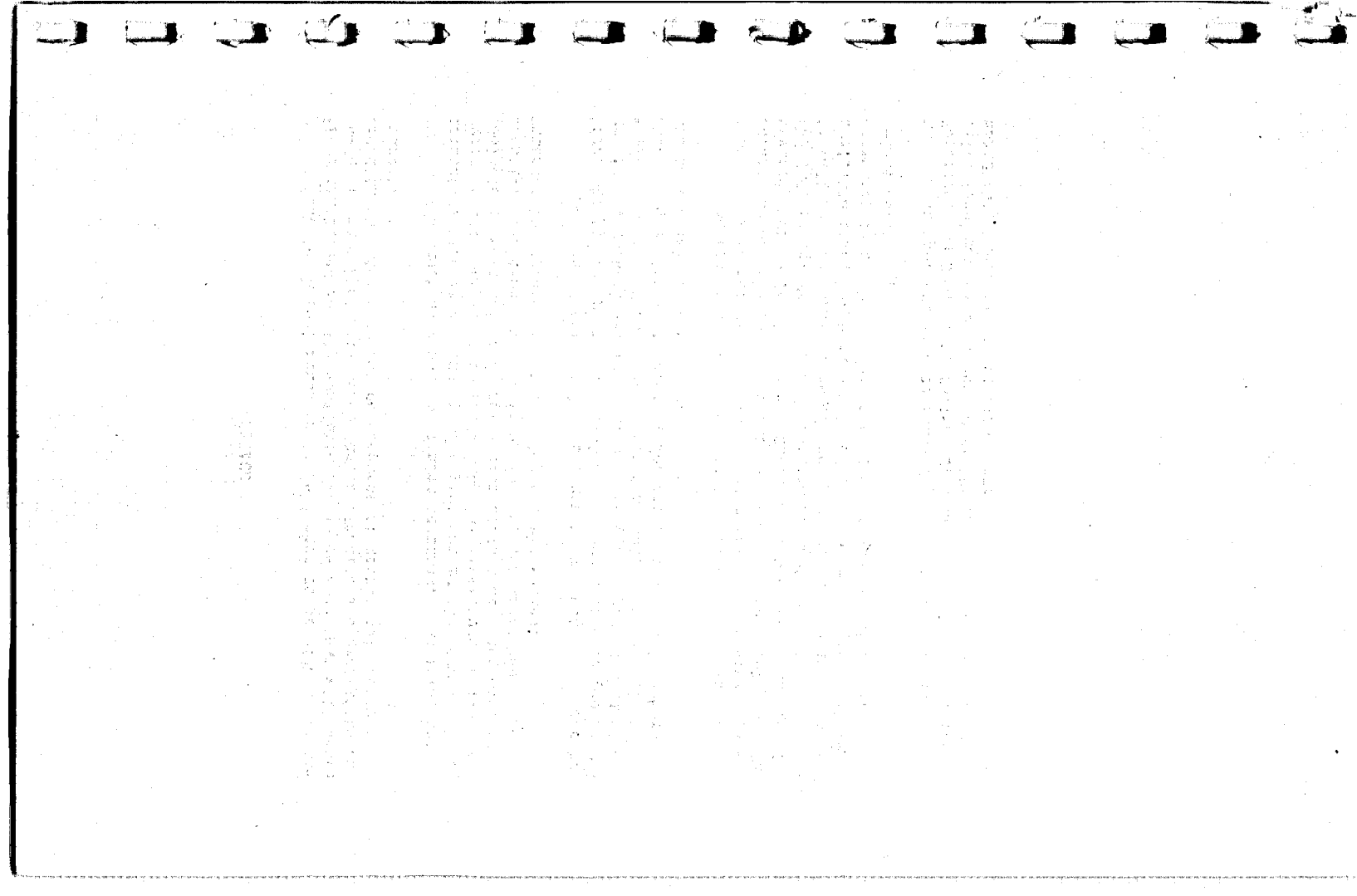
The Geothermal Handbook is published to provide a simplified, small, and readily available reference work that will prove useful to the physicists, chemists, engineers, and geologists engaged in the discovery and development of geothermal energy resources.

The Handbook consists of nine sections. The first and largest section is a glossary of approximately 500 terms. These terms, chosen largely from the geothermal literature, define the geological, physical, and engineering terms that occur most frequently. The glossary is written for the nonexpert and is not intended to replace standard geological glossaries.

Sections 2 through 8 of the Handbook consist of a set of "fact sheets" containing discussions of such topics as geothermal gradients, rock classification, and geological periods and time scales. Section 9 contains conversion tables for many of the physical quantities of interest for energy research in general and geothermal research in particular.

The Handbook had its origin in self-education in the course of work performed by The Johns Hopkins University Applied Physics Laboratory as the Operations Research and Development Contractor, DGE Region 5, for the Division of Geothermal Energy of the U.S. Energy Research and Development Administration. Although it reflects the limitations of the authors, both in expertise and available time, the Handbook is offered to the larger geothermal community in the hope that it will provide a useful desk-top reference.

The authors wish to thank Dr. A. M. Stone, Mr. F. C. Paddison, and Drs. J. W. Follin, Jr., and R. J. Taylor for their criticisms and corrections and Mr. R. Kroll who edited and composed this Handbook in its final form.



1. GEOTHERMAL GLOSSARY

ABSOLUTE TEMPERATURE Temperature measured in degrees Celsius from absolute zero (-273.18°C). Absolute temperatures are given as "degrees absolute" or as "degrees Kelvin."

$$°K = °C + 273.18$$
$$°K = 5/9\ (°F - 32) + 273.18$$

ABYSSAL PLAINS Flat, nearly level areas that occupy the deepest portions of many ocean basins

ACOUSTIC LOG A generic term for well logs that display any of several aspects of acoustic-wave propagation. In some acoustic logs the travel time of the compressional wave between two points is measured. In others, the amplitude of part of the wave train is measured. Other acoustic logs display part of the wave train in wiggle or variable-density form. Still others are characterized by the objective of the measurements rather than their form.

ADIABATIC The relationship of pressure and volume when a gas or other fluid is compressed or expanded without either giving out or receiving heat, see Isothermal Process

ADIT A nearly horizontal passage from the surface by which a mine is entered and water is removed. In the United States an adit is usually called a tunnel, though the latter, strictly speaking, passes entirely through a hill and is open at both ends.

AGATE A multicolored variety of quartz that is waxy in appearance, in which the colors are in bands, clouds, or distinct groups

AGGLOMERATE Accumulations of angular fragments of rock thrown up by volcanic eruptions and showered around the volcanic cone or crater of eruption

ALBITE One of the plagioclase feldspars in which the diagnostic positive ion is Na^+. Essentially a sodium-aluminum silicate

ALKALI METAL Any metal of the alkali group, as lithium, sodium, potassium, rubidium, or cesium

ALKALINE 1: Having the properties of a base 2: Containing sodium and/or potassium in excess of the amount needed to form feldspar with the available silica, e.g., an alkaline rock – in this sense sometimes written alkalic 3: Containing ions of one or more alkali metals 4: Waters containing more than average amounts of carbonates of sodium, potassium, magnesium, or calcium

ALLUVIUM A general term for all detrital deposits resulting from the operations of modern rivers. Included are the sediments laid down in river beds, flood-plains, lakes, and estuaries.

AMORPHOUS Without form; a term applied to rocks and minerals having no definite crystalline structure

ANDESITE A fine-grained igneous rock with no quartz or orthoclase, composed of about 75% plagioclase feldspars and 25% ferromagnesium silicates. Important as lavas, possibly derived by fractional crystallization from basaltic magma; widely characteristic of mountain-making processes around the Pacific Ocean

ANION A negatively charged ion

ANISOTROPIC Exhibiting properties with different values when measured along axes in different directions

ANTICLINE Rock beds or strata that bend in opposite directions from a common ridge or axis, like the roof of a house; a fold that is concave downwards

ANTICLINORIUM A series of anticlines and synclines arranged structurally so that they form a general arch or anticline

APPARENT RESISTIVITY 1: The ground resistivity calculated from measurements and a geometric factor derived for the case where the ground is homogeneous and isotropic 2: Also the resistivity recorded by an electrical log that differs from the true resistivity of the formation because of the presence of mud column, invaded zone, and influence of adjacent beds

AQUIFER A water-bearing stratum of permeable rock, sand, or gravel

AQUICLUDE An impermeable strata that acts as a barrier to the flow of ground water

ARENACEOUS Rocks that have been derived from sand or that contain sand

ARGILLACEOUS Rocks or substances composed of clay minerals, or having notable proportion of clay in their composition such as shale and slate

ARKOSE A sandstone containing 25% or more of feldspars usually derived from silicic igneous rocks

ARRAY STATION Earthquake-detection station that uses an array of seismometers. Twenty seismometers spread over about 20 km may be employed so that spatial filtering can be used to improve the detectability of weak signals.

ARTESIAN Ground water that has sufficient hydrostatic head to rise above its aquifer

ARTESIAN WATER Ground water that is under sufficient pressure to rise above the level at which it is encountered (by a well), but which does not necessarily rise to or above the surface of the ground

ARTESIAN WELL A well that penetrates an aquifer containing water with sufficient pressure to rise above the local ground level

ASEISMIC REGION A region relatively free of earthquakes

ASTHENOSPHERE A shell tens of kilometers below the surface of the earth of undefined thickness. The formation is a shell of weakness where plastic movements take place to permit isostatic adjustments. Plates of the lithosphere move over the asthenosphere.

AUGER A drilling tool designed so that, during the drilling operation, the cuttings are carried continuously to the top of the hole by helical grooves on a rotating drill pipe

AXIAL PLANE A plane through a rock fold that includes the axis and divides the fold as symmetrically as possible

AZIMUTH As used in surveying, the azimuth of a body is the arc measured from due north to the right (clockwise).

BALNEOLOGY Science of the healing qualities of baths, especially natural mineral waters; the therapeutic use of natural warm or mineral waters

BASALT A fine-grained igneous rock dominated by dark-colored minerals, consisting of plagioclase feldspars (a calcium-sodium-aluminum-silicate, usually present in amounts over 50%), and ferromagnesium silicates. Basalts and andesites represent about 98% of all extrusive igneous rocks.

BASEMENT Geologic basement is the highest surface beneath which sedimentary rocks are not found; i.e., igneous or metamorphic rock underlying sedimentary rocks. In many places, they are Precambrian, but may be much younger. In terms of petroleum exploration, basement is the surface below which there is no current exploration interest.

BASEMENT COMPLEX A series of rocks found beneath dominantly sedimentary rocks. These rocks generally have a complex structure; in many places they are igneous and metamorphic of either early or late Precambrian although they can be much younger.

BASE TEMPERATURE The maximum temperature attained by geothermal water during convective circulation

BATHOLITH A great irregular mass of coarse-grained igneous rock with a surface exposure of more than 40 mi^2 (100 km^2), that has either intruded the country rock, cutting across the layering, or is derived from the country rock through metamorphism

BEDDING PLANES In sedimentary or stratified rocks, the division planes that separate the individual layers, beds, or strata

BED ROCK A general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material

BENIOFF ZONE Subduction zone; a dipping zone containing earthquake foci

BENTONITE A highly plastic, colloidal clay that increases its volume upon addition of water; a component of drilling mud

BIPOLE-DIPOLE MAPPING Electrical method of geophysical exploration. Current flow is established in the earth by using a pair of source electrodes; the electric field is determined by observing the voltage drop between two pairs of electrodes oriented approximately at right angles.

BLACK BODY An ideal body, the surface of which absorbs all the radiation that falls upon it; i.e., it neither reflects nor transmits any of the incident radiation

BLIND HOLE A borehole characterized by lost circulation of the drilling fluid

BLOWOUT PREVENTER A device used to prevent the escape of oil, water, or gas when a pressurized pocket is penetrated by a drill

BOILING POINT The temperature at which the vapor pressure of a liquid is equal to the pressure of the atmosphere on the liquid

BOREHOLE A hole drilled into the earth, often to a great depth, as a prospective oil well or for exploratory purposes

BOREHOLE EFFECT A distortion of a well log because of the size and influence of the borehole or the invading zone

BOUGUER ANOMALY The gravity value existing after the Bouguer corrections to a level datum have been applied

BOUGUER CORRECTION A correction made in gravity survey data to take into account the elevation of the station and the rock between the station and some level datum, usually sea level

BRECCIA 1: Fragmental rock whose components are angular and therefore, as distinguished from conglomerates, are not waterworn 2. Rock made up of highly angular coarse fragments that may be sedimentary or formed by the action of crushing or grinding along faults 3: Volcanic breccia is a more-or-less indurated pyroclastic rock consisting chiefly of accessory and accidental angular ejecta 32 mm or more in diameter lying in a fine tuft matrix.

BRINES A highly saline solution. A solution containing appreciable amounts of NaCl and other salts

BRITISH THERMAL UNIT The quantity of heat required to raise the temperature of 1 lb of water 1°F at or near its point of maximum density (equivalent to 252 cal)

CALDERA A large basin-shaped volcanic depression, circular in form, with a diameter many times greater than the included volcanic vent. The steepness of the walls or form of the floor does not matter.

CALORIE The quantity of heat needed to raise 1 g of water 1°C at or close to 16°C

CAMBRIAN The oldest of the periods of the Paleozoic era; also the system of strata deposited during that period

CANADIAN SHIELD Nucleus of Precambrian rocks around which the North American continent has grown

CAP ROCK A comparatively impervious stratum that prevents the circulation of heat or fluids

CARBONATE A compound containing the radical CO_3^{+2} or rock composed of carbonate minerals

CARNOT CYCLE A thermodynamic cycle in which the working substance is compressed and expanded along the adiabatic and isothermal lines of a P-V diagram in such a manner as to complete a closed reversible cycle. If heat is absorbed from a warm reservoir and injected into a cooler reservoir, the cycle represents an engine with work as the output; if work is applied to the cycle, heat is transformed from one reservoir to another and the cycle represents a Carnot refrigerator (or a heat pump).

CARNOT EFFICIENCY For a Carnot engine working between high temperature T_2 and low temperature T_1, the efficiency (work-out/heat removed from T_2) is given by $(T_2 - T_1)/T_2$; all temperatures measured on an absolute scale. For a refrigerator, the desired product is the removal of heat from T_1 and the coefficient of performance is $T_1/(T_2 - T_1)$. For a heat pump, the desired product is the addition of heat to T_2, and the coefficient of performance is $T_2/(T_2 - T_1)$. The second law of thermodynamics states that Carnot efficiencies, or coefficients of performance, cannot be exceeded by any realizable machine.

CATION Positively charged ion

CENOZOIC The latest of the four eras into which geologic time, as recorded by the stratified rocks of the earth's crust, is divided. The Cenozoic era includes the periods called Tertiary and Quaternary in the nomenclature of the U.S. Geological Survey.

CHALCEDONY A transparent, or more generally, a translucent cryptocrystalline quartz; the material of agate

CHEMICAL GEOTHERMOMETER The technique of predrilling assessment of temperature characteristics of the geothermal reservoir. Most widely used geothermometers are the SiO_2 content and Na, Ca, and K ratios measured in water samples.

CHERT Cryptocrystalline varieties of quartz regardless of color

CINDERS Primarily uncemented, volcanic ejecta ranging from 3 to 4 mm in diameter

CLARKE The average percentage of an element in the earth's crust

CLASTIC Sedimentary rock formed from mineral particles that are mechanically transported

CLAY MINERALS Finely crystalline, hydrous silicates that form as a result of the weathering of such silicate minerals as feldspar, pyroxene, and amphibole

CLEAVAGE 1: Mineral cleavage – a property possessed by many minerals of breaking in certain preferred directions along smooth plane surfaces. The planes of cleavage are governed by the atomic pattern and represent directions in which atomic bonds are relatively weak 2: Rock cleavage – a property possessed by certain rocks of breaking with relative ease along parallel planes or nearly parallel surfaces

CONCORDANT PLUTON An intrusive igneous body, the contacts of which are parallel to the bedding of the country rock

CONDENSER A device for reducing gases or vapors to liquid or solid form

CONDUCTION In thermodynamics, the transference of heat through a medium or body driven by a temperature gradient and involving no macroscopic particle motion

CONDUCTION DOMINATED REGION Any region within the earth where the heat flow is dominated by conduction

CONGLOMERATE Rounded water-worn fragments of rock or pebbles, cemented together by another mineral substance; also a consolidated gravel

CONNATE WATER Water trapped in the interstices of sediments at the time of deposition

CONTACT The place or surface where two different kinds of rocks come together. Although used for sedimentary rocks as the contact between a limestone and sandstone, it is more generally used to indicate the interface between igneous intrusions and their walls.

CONTACT METAMORPHISM Metamorphism genetically related to the intrusion (or extrusion) of magmas, taking place in rocks at or near their contact with a body of igneous rock

CONTINENTAL RISE The submarine surface beyond the base of the continental slope, generally with a gradient of less than 1 in 1000, occurring at depths from about 1373 to 5185 m and leading down to abyssal plains

CONTINENTAL SHELF A gently sloping, shallowly submerged marginal zone of a continent, extending from the shore to an abrupt increase in bottom inclination; the greatest average depth is less than 183 m, the slope generally less than 1 in 1000, a local relief less than 18.3 m, and a width ranging from very narrow to more than 321.8 km.

CONTINENTAL SLOPE The continuously sloping portion of the continental margin with a gradient of more than 1 in 40, beginning at the outer edge of the continental shelf and bounded on the outside by a rather abrupt decrease in slope where the continental rise begins at depths ranging from about 1373 to 3050 m

CONTOUR MAP A map showing the configuration of the surface by means of lines connecting the points that have the same elevation

CONVECTION A process of mass movements of portions of any fluid medium (liquid or gas) in a gravitational field as a consequence of different temperatures in the medium and hence different densities. The process thus moves both the medium and the heat and the term is used to signify either or both.

COUNTRY ROCK A general term applied to the rock surrounding and penetrated by mineral veins; in a wider sense applied to the rocks invaded by and surrounding an igneous intrusion

CRATON A stable relatively immobile area of the earth's crust that forms the nuclear mass of a continent or the central basin of an ocean

CRETACEOUS The third and latest of the periods included in the Mesozoic era; also the system of strata deposited in the Cretaceous period

CRISTOBALITE A type of quartz formed at high temperatures

CRITICAL DISTANCE The distance from a seismic disturbance at which the refracted and reflected wave arrive at the same time; that is, the reflection from a lower medium, characterized by a greater sound velocity, occurs at the critical angle (angle of total reflection)

CRITICAL POINT The temperature and pressure at which the properties of a liquid and its vapor become indistinguishable

CRUST The lithosphere, or solid exterior portion of the earth; that portion of the earth above the Mohorovicic discontinuity

CRYSTALLINE Having regular molecular structure; contrasted with amorphous

CURIE TEMPERATURE The temperature at which ferromagnetic effects are destroyed by thermal agitation in ferromagnetic substances. In common iron alloys, the curie temperature (or curie point) is typically 500 to 700°C.

CYCLE A sequence of changes at the end of which the initial situation has been re-established

DARCY A unit of permeability. The unit of the Darcy is g-cm/atm-s^2 since in Darcy's equation, length is in cm, pressure in atmospheres, mass in grams, fluid flow in cm^3/s, and viscosity in centipoise = 0.01 dyne-s/cm^2 = 0.01 g/cm-s.

DARCY'S EQUATION A relationship for the fluid flow rate q through a medium:

$$q = \frac{kA}{u} \frac{\Delta p}{\Delta x}$$ where

k = permeability, A = cross-sectional area, u = viscosity, and Δp = pressure difference across the thickness Δx.

DEBYE TEMPERATURE A parameter with the dimensions of temperature in the Debye equation for the specific heat of a solid at constant volume. Above the Debye temperature, the specific heat for all solids approaches the value of about 6 cal/g mole-deg, the Dulong and Petit value. For many common metals and simple compounds, the Debye temperature lies between 100 and 300°K and the specific heat at constant volume is very nearly constant at room temperatures and above. The Debye equation for specific heat is a quantum mechanical calculation, and in practice, the Debye temperature is an experimentally determined parameter for a given solid.

DENSITY LOG A well log that records the formation density. The logging tool consists of a gamma-ray source and a detector shielded so that it records backscattered gamma rays from the formation.

DETRITAL SEDIMENT Sediment formed from accumulations of minerals and rocks derived either from mechanical erosion of previously existing rock or from the mechanically weathered products of these sediments

DEVONIAN In the ordinarily accepted classification, the fourth in order of age of the periods comprising the Paleozoic era, following the Silurian and preceding the Mississippian; also the system of strata deposited at that time. Sometimes called the Age of Fishes

DIAMOND PIPES Intrusive bodies that are roughly circular with a pipelike shape, usually an altered ultramafic rock containing diamonds

DIATOMITE A siliceous sediment consisting of the hard parts (skeletons) of diatoms

DIATOMS A microscopic, single-celled plant growing in marine or fresh water. Diatoms have siliceous skeletons of a great variety of forms that may accumulate in sediments in enormous numbers.

DIKE A tubular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rock. Although most dikes result from the intrusion of magma, some are the result of metamorphic processes.

DIORITE A plutonic rock composed essentially of sodic plagioclase (usually andesite) and mafic (dark) minerals. Small amounts of quartz and orthoclase (potassium-sodium-aluminum-silicate) may be present.

DIPOLE-DIPOLE ARRAY An electrode array used in induced polarization, electrical, and electromagnetic surveying

DISCORDANT PLUTON An intrusion that cuts across the bedding or foliation of adjacent rock

DOLOMITE 1: A mineral composed of the carbonate of calcium and magnesium $CaMg(CO_3)_2$ 2: A rock name for formations composed largely of dolomite

DOME A roughly symmetrical upfold, the beds dipping in all directions more or less equally from a point

DRILLING MUD A suspension, generally aqueous, used in rotary drilling. It is pumped downward through drill pipe to seal off porous zones and to counterbalance the pressure of oil, gas, and water.

DRILL PIPE Pipe to which the bit is attached and which is rotated by a drill. Drilling fluid circulates through the pipe.

DRY ROCK Rocks beneath the earth's surface that do not have meteoric or juvenile water supplied to them by an aquifer or any other source

EFFICIENCY The ratio of the useful energy output of a machine or other energy-converting plant to the energy input

EFFLUENT 1: Something that flows out, as an outflowing branch of a main stream or lake 2: Waste material (as smoke, liquid industrial refuse, or sewage) discharged into the environment, especially when serving as a pollutant

ELECTRICAL SURVEY Measurements made at or near the earth's surface of natural or induced electrical fields; used for mapping mineral concentrations or basement formations

ELECTROMAGNETIC PROSPECTING A geophysical method that uses the generation of electromagnetic waves at the earth's surface to penetrate the earth and impinge on conducting formations or ore bodies. Currents are induced in the conductors which provide the source of new waves that radiate from the conductors and are detected by instruments at the surface.

EMISSIVITY The relative ability of a surface to emit radiant energy compared to an ideal black body at the same temperature with the same area

ENDOTHERMIC Characterized by or formed with absorption of heat

ENTHALPY In thermodynamics, enthalpy, H, is defined for a reversible process as $dH = dQ + Vdp$ where Q is heat, V = volume, and p = pressure. For reversible isobaric processes, the difference in enthalpy is the heat transferred; $H_f - H_i = Q$. Enthalpy is usually tabulated as specific enthalpy; as J/kg or Btu/lb. It is a function of the state of the system and at constant pressure, $H_f - H_i = Q_t$ is true for phase changes, where Q_t is the heat of transformation.

ENTROPY In thermodynamics, entropy, S, is a function of the state of a system, defined by $S_2 - S_1 = \int_1^2 \frac{dQ}{T}$. For irreversible processes, the entropy of any isolated system always increases, and entropy is a measure of the thermal energy in a system that is not available for conversion into work.

EOCENE Second epoch of the Tertiary period; also the series of strata deposited during that epoch

EPEIROGENY The broad movements of uplift and subsidence that affect large portions of continental areas or the oceanic basins

EPICENTER The point on the earth's surface directly above the origin of an earthquake

EPIPALEOZOIC Rocks above the paleozoic (less than 225 million years old)

EPITHERMAL A deposit formed from low-temperature hydrothermal solutions in rocks at shallow depths

EPIZONE The "upper zone" of metamorphism. In this zone the physical conditions of metamorphism, which the rocks characteristically show, are a result of a moderate temperature, lower hydrostatic pressure, and great stress.

EPOCH A division of geologic time; when capitalized it is a formal division of geologic time corresponding to a series of rock or a subdivision of a geologic period.

EQUATION OF STATE A mathematical formula that expresses the relationship of pressure, volume, and temperature of a substance in any state of aggregation

EQUILIBRIUM Equilibrium exists in any system when the phases of the system do not undergo any change of properties with the passage of time, provided that the phases have the same properties when the same conditions, with respect to the variants, are again reached by a different procedure.

EUGEOSYNCLINE The seaward part of a geosyncline in which volcanism is associated with sediments derived by mechanical weathering

EXOTHERMIC Designating, or pertaining to a reaction that occurs with a liberation of heat

EXTRUSIVE A term applied to those igneous rocks that have cooled and solidified after reaching the earth's surface

FAHRENHEIT A thermometric scale in which the melting point of ice is 32 degrees above zero and the boiling point of water is 212 degrees above zero ($°F \approx 9/5\ °C + 32$)

FAULT A fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture

FAULT BLOCKS A mass bounded on at least two opposite sides by faults. It may be elevated or depressed relative to the adjoining regions, or it may be elevated relative to the region on one side and depressed relative to that on the other.

FAULT SCARP A cliff formed by a fault; most fault scarps have been modified by erosion since the faulting

FELDSPAR A group of abundant rock-forming minerals of the general formula, M Al $(Al,Si)_3O_8$ where M can be K, Na, Ca, Ba, Rb, Sr, and Fe. Most widespread of any mineral group, feldspar may constitute 60% of the earth's crust, occurring in all types of rock. When the positive ion is K^+, the mineral is orthoclase; when it is Na^+, it is albite; when it is Ca^{+2}, it is anosthite.

FELDSPATHOIDS (FOIDITES) A group of comparatively rare rock-forming minerals consisting of aluminosilicates of sodium, potassium, or calcium and having too little silica to form feldspar

FELSIC A mnemonic term derived from "fe" for feldspar, "l" for lenads or feldspathoids, and "s" for silica. The term is applied to light-colored rocks containing an abundance of one or all of these constituents. Also applied to the minerals themselves, the chief felsic minerals being quartz, feldspars, feldspathoids, and muscovite.

FIELD RELATIONS The total pattern of contacts, faults, intrusions, unconformities, and other surfaces where rock formations meet; the field geologist reconstructs the chronology and history of an area from these patterns

FIRST LAW OF THERMODYNAMICS The first law of thermodynamics introduces the concept of internal energy of a system and expresses the fact that the change of energy of a system is equal to the amount of energy received from the external world. The energy received from the external world is equal to the heat taken in by the system and the work done on the system.

FISSURE An extensive crack, break, or fracture in rock. A mere joint or crack persisting only for a few inches or even a few feet is not usually termed a fissure by geologists or miners, although in a strict physical sense it is.

FLASH STEAM The steam generated when the pressure on hot water (usually above 100°C) is reduced

FLUX 1: Passage across a physical boundary such as CO_2 from atmosphere to hydrosphere, or across a chemical boundary as CO_2 from atmosphere to organic matter 2: The rate of flow of a fluid, heat, or the like

FOCUS 1: The source of a given set of elastic waves 2: The true center of an earthquake, within which strain energy is first converted to elastic wave energy

FOLIATION The laminated structure resulting from segregation of different minerals into layers. Foliation is considered synonymous with "flow cleavage," "slaty cleavage," and schistosity by many writers to describe parallel fabrics in metamorphic rocks.

FOOT WALL The side that lies below an inclined fault

FOREDEEPS A long, narrow, crustal depression or furrow bordering a folded orogenic belt or island arc on the convex side, commonly on the oceanward side

FORMATION 1: Something naturally formed, commonly differing conspicuously from adjacent objects or material, or being noteworthy for some other reason 2: In stratigraphy the primary unit of formal mapping or description. Most formations exhibit distinctive rock compositions. Boundaries are not based on time criteria. Formations may be combined into groups or subdivided into members.

FORMATION FACTOR The electrical resistance of a rock saturated with an electrolyte, divided by the resistivity of the electrolyte. There is an inverse linear relationship between the formation factor and the porosity and permeability of the rock.

FOSSIL FUEL A deposit of organic material containing stored solar energy that can be used as fuel. The most important are coal, natural gas, and petroleum.

FOURIERS LAW Relates temperature gradient with conductivity and heat flow; written: $dt/dr = q/k$, where dt/dr = temperature gradient, q = heat flow, and k = conductivity

FRACTIONAL CRYSTALLIZATION Separation of a magma into two phases, crystal and liquid, possibly followed by a gross separation of the two phases from each other by other processes

FRACTURE POROSITY Porosity resulting from the presence of openings produced by the breaking or shattering of an otherwise less pervious rock

FREE ENERGY That portion of the energy of a system that is the maximum available for doing work

FUMAROLE A hole or vent from which fumes or vapors issue; a spring or geyser that emits steam or gaseous vapor; usually found in volcanic areas

FUSION 1: Isotope. The combination of two light nuclei to form a heavier nucleus. The reaction is accompanied by the release of a large amount of energy as in the hydrogen bomb 2: Petrology. The process whereby a solid becomes liquid by the application of heat; melting; also, the unification or mixing of two or more substances as by melting together

GABBRO A coarse-grained (intrusive) igneous rock composed essentially of the more calcic plagioclase feldspars and one or more mafic minerals

GAMMA A unit of magnetic-field intensity; a gamma is 10^{-5} oersteds or $(1/4\ \pi)\ 10^{-2}$ ampere-turns/m

GAMMA-GAMMA LOG See Density Log

GAMMA-RAY LOG A well log that records natural radioactivity; in sediments the log mainly reflects shale content because minerals containing radioactive isotopes tend to concentrate in shales and clays

GAMMA-RAY WELL LOGGING A method of logging boreholes by observing the natural radioactivity of rocks through which the hole passes. Developed for logging holes that cannot be logged electrically

GAS CONSTANT In the ideal gas law, $PV = N\ RT$, where R is the universal gas constant, P is the pressure, V is volume, N the number of moles of gas, and T the temperature. The value of R depends upon the units in which the quantities are measured; for the

mks system of units $R = 8.31 \times 10^3$ J/kg-mole-deg. For more sophisticated equations of state, where correction terms are added to the ideal gas law (such as the van der Walls equation of state), the constant R is usually retained with the same dimensions and magnitude.

GAUSS The cgs-emu unit of magnetic induction or flux density, 1 gauss = 10^{-4} webers/m^2 in the mks system. The earth's magnetic field is 0.25 to 0.5 gauss.

GEOCHEMICAL ANOMALY A concentration of one or more elements in rock, soil, sediment, vegetation, or water markedly different from the normal concentration in the surroundings

GEOCHRONOLOGY The science of absolute and relative dating of geologic events and formations, primarily through the measurement of daughter elements produced by radioactive decay in minerals

GEOLOGIC MAP A map showing surface distribution of rock varieties, age relationships, and structural features

GEOMAGNETIC VARIOMETER An instrument used to measure variations in the earth's magnetic field

GEOPHYSICAL PROSPECTING The mapping of rock structures by methods of experimental physics; included are the measurements of: magnetic fields, the force of gravity, electrical properties, seismic wave paths and velocities, radioactivity, and heat flow

GEOPRESSURIZED Zones below depths of 6000 to 10 000 ft, in which sediments in basins are commonly characterized by abnormally high pressure, high temperature, and low salinity

GEOSYNCLINES 1: Large, generally linear troughs that subsided deeply throughout a long period of time in which a thick succession of stratified sediments and possibly extrusive volcanic rocks commonly accumulated. The strata of many geosynclines have been folded into mountains. Many different kinds have been differentiated and named 2: The area of such a trough 3: A stratigraphic surface that subsided in such a trough

GEOTHERM (GEOISOTHERM) A curving surface within the earth along which the temperature is constant

GEOTHERMAL ENERGY The internal energy of the earth, available to man as heat from heated rocks or water

GEOTHERMAL FLUX A vector quantity that measures the heat flow from the interior of the earth toward the surface. The global average for this quantity is about 1.5×10^{-2} cal/m^2-s.

GEOTHERMAL GRADIENT The rate of increase of temperature in the earth with depth. The gradient near the surface of the earth varies from place to place depending on the heat flow in the region and on the thermal conductivity of the rock. Approximate average geothermal gradient in the earth's crust is about 25°C/km.

GEOTHERMAL RESOURCE BASE All of the stored heat above 15°C to a depth of 10 km

GEOTHERMAL RESOURCES Stored heat that is recoverable using current or near-current technology

GEOTHERMIC; GEOTHERMAL The heat of the earth's interior

GEYSER A spring that throws forth intermittent jets of heated water or steam. The heat is thought to result from the contact of ground water with hot rock.

GIBBS FUNCTION A thermodynamic function defined as $G = H-TS$, where H is enthalpy, T is temperature, and S is entropy. For reversible isothermal and isobaric processes, G is a constant and is a useful function in the analysis of phase changes and chemical reactions.

GNEISS A coarse-grained regional metamorphic rock that shows compositional banding and parallel alignment of minerals

GRABEN An elongated, trenchlike structural form bounded by parallel faults created when the block that forms the trench moves downward relative to the blocks that form the sides

GRANITE 1: In a wide sense a coarse-grained acidic igneous rock consisting essentially of quartz, feldspar, and mafic minerals, by far the most abundant of all plutonic rocks 2: In seismology, a rock in which velocity of compressional waves lies between 5.5 and 6.2 km/s

GRANODIORITE A granite, in the wide sense, in which plagioclase feldspar considerably exceeds alkali feldspar; intermediate in composition between a granite and a diorite

GRAVIMETER An instrument for measuring variations in the magnitude for the earth's gravitational field

GRAVITY ANOMALY Difference between theoretical calculated and observed terrestrial gravity; excess observed gravity is positive and deficiency is negatively anomalous

GRAVITY SURVEY Measurements of the gravitational field at a series of different locations over an area of interest. The objective in exploration work is to associate variations with differences in the densities and hence of rock types.

GRAYWACKE A variety of sandstone generally characterized by its hardness, dark color, and angular grains of quartz, feldspar, and small rock fragments set in a matrix of clay-sized particles

HALITE Native salt; sodium chloride; a common mineral of evaporites

HALOGEN In chemistry, any one of the elements bromine, chlorine, fluorine, and iodine, which, with the metals, form compounds analogous in some respects to common salt

HALOID Denoting any halogen derivative

HANGING WALL An inclined fault plane where one of the displaced parts lies above another. Its surface along the fault plane is called the hanging wall.

HEAT That form of energy that is transferred between two bodies as a result of the difference in temperature and governed by the laws of thermodynamics.

In thermodynamics, heat is defined in terms of the first law:

$$U_2 - U_1 = Q - W, \text{ i.e.,}$$

the change is the internal energy of a system, $U_2 - U_2$, is equal to the heat Q flowing into the system minus the mechanical work done by the system.

HEAT CONTENT Although this term is seldom used in thermodynamics, its meaning is essentially the same as "enthalpy." Enthalpy is a function of the state of the system but it is meaningless to specify the "heat" of a system since heat, as defined by the first law of thermodynamics is not a function of the state of the system.

HEAT EXCHANGER A device for transferring heat from one fluid to another. The fluids are usually (but not necessarily) separated by conducting walls.

HEAT FLOW Dissipation of heat coming from within the earth by conduction (e.g., heat flow from a magma into its surroundings) or radiation (radiation from breakdown of radioactive elements) measured at the earth's surface; the average is about 1.5×10^{-6} cal/cm^2-s.

HEAT FLOW UNIT One heat flow unit is equal to 1×10^{-6} cal/cm^2-s

HEAT PIPE A closed system (usually in the form of a closed pipe) in which heat is transferred from one end to the other by a transfer of the working medium within the pipe accompanied by a change of phase at each end. Because of the large amounts of heat involved in the phase changes, large amounts of heat can be transferred, relative to metallic conduction, provided the circulation of the working medium can be effected.

HEAT PUMP A device which, by the consumption of work or heat, effects the transport of heat between a lower temperature and a higher temperature. In conventional usage, the term is usually limited to a device whose useful output is heat. A device whose useful output is the removal of heat is called a refrigerator.

HIGH-RESOLUTION THERMOMETER A small-diameter thermometer that has a fast response used for logging open or cased bore holes with a temperature resolution of 0.5°F

HIGH-TEMPERATURE RESERVOIRS Reservoirs with base temperatures greater than 150°F as defined by the U.S. Geological Survey Circular 726

HORIZON A plane or level of stratification, which at the time of deposition, is assumed to have been horizontal and continuous. Thus the strata, over the en-

tire earth that were formed at the same time belong to the same geological horizons. In paleontology, a stratum or strata characterized by a particular fossil or group of fossils. In seismology, the surface dividing two layers of rock that can be detected by seismic methods. In the soil sciences, the topsoil, subsoil, and parent material form distinct horizons.

HORST 1: A mass of earth-crust that is limited by faults and which stands in relief with respect to its surroundings 2: A block of the earth's crust separated by faults from adjacent relatively depressed blocks

HOT IGNEOUS SYSTEM A system in which the thermal anomaly is derived from igneous formations in the upper 10 km of the crust

HOT ROCK Pertains to any rock that is volcanically or radiogenically heated

HOT SPRING A thermal spring whose water has a higher temperature than that of the human body (98.6°F)

HOT-WATER SYSTEM A system that is dominated by a circulating liquid that transfers most of the heat and largely controls subsurface pressures. Characterized by hot springs that discharge at the surface

HYBRIDIZATION Derived from heterogeneous sources or composed of elements of different or incongruous kinds

HYDRAULIC CONDUCTIVITY Ratio of flow velocity to driving force for viscous flow under saturated conditions of a specific liquid in a porous medium

HYDRAULIC DISCHARGE Discharge of liquid ground water directly from the zone of saturation onto the land or into a body of surface water through springs or artificial openings

HYDRAULIC GRADIENT (PRESSURE GRADIENT) 1: As applied to an aquifer, the rate of change of pressure head per unit of distance of flow past a given point and in a given direction 2: A vector point function equal to the decrease in hydraulic head per unit distance in direction of greatest decrease in rate

HYDROFRACTURE Process of increasing the permeability of strata near a well by pumping in a mixture of water and sand under high pressure. The hydraulic pressure opens cracks and bedding planes, and introduced sand serves to keep them open after the pressure is reduced.

HYDROLOGIC CYCLE The complete cycle through which water passes, beginning as an atmospheric vapor, passing into liquid or solid form as precipitation, thence into the ground, and finally returning to atmospheric vapor by evaporation and transpiration

HYDROLOGY The science that deals with the properties, distribution, and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere

HYDROSTATIC HEAD The height of a vertical column of water, the weight of which, if of unit cross section, is equal to the hydrostatic pressure at a point

HYDROSTATIC LEVEL (STATIC LEVEL) That level, which for a given point in an aquifer, passes through the top of a column of water that can be supported by the hydrostatic pressure of the water at that point

HYDROSTATIC PRESSURE The pressure exerted by the water at any given point in a body of water at rest

HYDROTHERMAL An adjective applied to heated or hot aqueous-rich solutions, to the processes in which they are concerned, and to the rocks, ore deposits, and alterations products produced by them. Hydrothermal solutions are of diverse sources, including magmatic, meteoric, and connate waters.

HYDROTHERMAL ALTERATION The phase changes resulting from the interaction of hydrothermal fluids with pre-existing solid phases. Included are the chemical and mineralogical changes in rocks brought about by the addition or removal of materials through the medium of hydrothermal fluids.

HYDROTHERMAL CONVECTION SYSTEMS In such a system most of the heat is transferred by the convective circulation of water or steam rather than by thermal conduction through solid rock.

HYPERGENIC 1: Used by Sir Charles Lyell and intended as a group name for plutonic and metamorphic classes of rocks 2: Applied to mineral or ore deposits formed by generally ascending water

HYPERSALINE Water containing more salts than ocean water; i.e., greater than 3.5% by weight

HYPOTHERMAL Pertaining to hydrothermal ore veins deposited at relatively high temperatures (300° to 500°C)

IDEAL GAS A gas that obeys the general gas law perfectly (PV = NRT). The term implies: (a) atomic-sized gas particles, (b) the molecules are in random motion and obey Newton's laws of motion, (c) the total number of molecules is large, (d) the volume of the molecules is a negligibly small fraction of the volume occupied by the gas, (e) no appreciable forces act on the molecules except during a collision, and (f) collisions are elastic and are of negligible duration.

IGNEOUS ROCK Rock formed from a melt or magma by cooling and solidification. If the solidification occurred at depth, the rock is called "plutonic;" if formed from magma erupted onto the surface, called "volcanic".

INTERMEDIATE ROCK An igneous rock containing between 52 and 66% SiO_2

INTERMEDIATE TEMPERATURE RESERVOIR A reservoir in which the fluid temperature is between 90 and 150°C

INTERMONTANE Lying between mountains. Structural and topographic basin enclosed by diverging and converging mountain ranges

INTERNAL ENERGY In the first law of thermodynamics, $U_2 - U_1 = Q - W$, the difference in the internal energy, $U_2 - U_1$, is equal to the heat supplied to the system minus the work done by the system. For an ideal gas, the internal energy is a function of the temperature alone; kinetic theory shows that the internal energy for systems in general is equal to the sum of the kinetic and potential energies of the molecules.

INTRUSIVE Having been forced while in a fluid state into or between other rocks, but solidifying before reaching the surface. Said of plutonic igneous rocks and contrasted with extrusive

IRREVERSIBILITY The property of any process that proceeds in one direction spontaneously, without external interference, and cannot be returned to its original state without a change in the state of its surroundings

IRREVERSIBLE PROCESS In thermodynamics, any process that is not reversible (see reversible). All physical processes in nature are irreversible, which means that the entropy of any system increases and that the realizable efficiency of any real system is always less than the Carnot efficiency.

ISENTHALPIC A process that takes place without any change of enthalpy; i.e., the internal energy plus the product of pressure and volume remains constant.

ISENTROPIC A process that occurs with no change in entropy

ISLAND ARC A curved chain of islands generally convex toward the open ocean, margined by a deep submarine trench and enclosing a deep sea basin

ISOBARIC PROCESS A process in which the pressure is constant

ISOCLINAL FOLD In geology, a fold whose sides have parallel dips; it may be an anticline or a syncline.

ISOMETRIC CHANGE A change in a gas that takes place at constant volume

ISOTHERMAL PROCESS A process that takes place at a constant temperature. Isothermal relationships between pressure and volume of a gas or other fluid result when the temperature is constant and when heat is added or subtracted by an outside substance or body.

JOULE The SI unit for all forms of energy or work. The joule is equal to 1 newton-meter, 1 W-s, or 1 $kg\text{-}m^2/s^2$. The calorie is defined as 4.1868 J.

JOULE-KELVIN COEFFICIENT The partial derivative of temperature with respect to pressure, measured at constant enthalpy, $(\partial T/\partial P)_H$. For an ideal gas, this coefficient is zero; for real gases, it can be negative or positive. Applied to a throttling process, cooling is produced when the Joule-Kelvin coefficient is negative.

JOULE-KELVIN EFFECT A change in temperature observed when a gas undergoes an adiabatic expansion without doing external work

JOULE-THOMPSON EFFECT See Joule-Kelvin effect

JURASSIC The middle of three periods that comprise the Mesozoic era; also the system of strata deposited during that period

JUVENILE WATER Water that is derived from the interior of the earth and has not previously existed as atmospheric or surface water

KARST TOPOGRAPHY Topography that is formed over limestone, dolomite, or gypsum by dissolving; characterized by closed depressions, sinkholes, caves, and underground drainage

KELVIN-TEMPERATURE SCALE A scale of temperature based on thermodynamic principles, in which zero is equivalent to -459.4°F or -273.2°C

KIMBERLITE An ultra mafic rock, found in volcanic pipes, believed to have come from the mantle. Some examples, such as those in South Africa, are diamond bearing.

LACCOLITH A concordant, intrusive body that has domed up the overlying rocks generally with a horizontal floor but may be convex downward

LACUSTRINE Pertaining to, produced by, or formed in a lake

LAPILLI Volcanic ejecta consisting of fragments of lava of rounded or irregular shape, varying in size from that of a pea to that of a walnut

LATENT HEAT The quantity of heat absorbed or released in an isothermal transformation of phase

LATERITIC Red or reddish soil leached of soluble minerals, alumina, and silica, but retaining oxides and hydroxides of iron

LAVA Fluid rock that issues from a volcano or a fissure in the earth's surface; also the same material solidified by cooling

LEACHING The washing or draining by percolation; to dissolve minerals or metals from ore by using acid or water

LEUCOCRATIC Light-colored rocks, especially igneous rocks, containing between 0 and 30% dark minerals

LIMB One of the two parts of an anticline or syncline on either side of the axis

LIMESTONE A bedded sedimentary deposit consisting chiefly of calcium carbonate ($CaCO_3$) yielding lime when burned. Limestone is the most important and widely distributed of carbonate rocks and is the consolidated equivalent of limey mud, calcareous sand, or shell fragments.

LITHOLOGY The physical character of a rock; generally determined megascopically or with the aid of a low-power magnifier

LITHOSPHERE 1: In plate tectonics, a layer of strength relative to the underlying asthenosphere for deformations at geologic rates, which includes the crust and part of the upper mantle and is of the order of 100 km thick 2: In geochemistry and general geology, the silicate shell of the earth, including mantle and crust

LITHOSTATIC The equal, all-sided pressure in the crust of the earth caused by the weight of overlying rock

LOPOLITH A large floored intrusion sunken centrally into the form of a basin

LOW-TEMPERATURE RESERVOIR Geothermal reservoirs with base temperatures less than 90°C

MAFIC Pertaining to or composed dominantly of the magnesian rock-forming silicates; said of some igneous rocks and their constituent minerals. Contrasted with felsic. In general, synonymous with "dark minerals"

MAGMA Molten rock material within the earth from which an igneous rock results by cooling

MAGMA ASSIMILATION The incorporation into a magma of material originally present in the wall rock

MAGMA DIFFERENTIATION The process by which different types of igneous rocks are derived from a single parent magma, or by which different parts of a single molten mass assume different compositions and textures as it solidifies

MAGMATIC WATER Water that exists in or is derived from molten igneous rock or magma

MAGNETIC ANOMALY Any departure from the normal magnetic field of the earth

MAGNETIC VARIOMETER An instrument used to measure variations in a magnetic field

MAGNETOTELLURIC METHOD A method in which orthogonal components of the horizontal electric and magnetic fields induced by natural primary sources are mea-

sured simultaneously as a function of frequency to determine the resistivity of earth strata

MANTLE "PLUMES" Rising, columnar currents of solid hot material from the mantle; thought to be the source of "hot-spot volcanos," i.e., volcanism not associated with plate margins

MECHANICAL EQUIVALENT OF HEAT Number of units of work that are equivalent to one calorie of heat, its value being $(4.1855 \pm 0.0004) \times 10^7$ ergs/cal at 15°C or 4.1855 J/cal

MESOTHERMAL Of, having, or pertaining to an intermediate temperature

MESOZOIC One of the divisions or eras of geologic time, following the Paleozoic and succeeded by the Cenozoic; comprises the Triassic, Jurassic, and Cretaceous periods; also the strata of rocks formed during that era

METAMORPHIC ROCK An igneous or sedimentary rock that has partially or completely recrystallized in response to elevated temperature and pressure

METASEDIMENTARY Partly metamorphosed sedimentary rock

METAVOLCANIC Partly metamorphosed volcanic rock

METEORIC WATER Water that occurs in or is derived from the atmosphere

MICROCLINE A mineral that is a member of the feldspar group ($K AlSi_3O_8$)

MICROSEISMICS More-or-less persistent feeble earth tremors due to natural causes such as winds or strong ocean wave motion or hot brines

MIOCENE The fourth of the five epochs into which the Tertiary period is divided; also the series of strata deposited during that epoch

MIOGEOSYNCLINE A geosyncline in which volcanism is not associated with sedimentation. The nonvolcanic aspect of an orthogeosyncline (a geosyncline between continental and oceanic cratons), located near the continental craton.

MKS Meter, kilogram, solar second system of fundamental standards

MOHOROVICIC DISCONTINUITY (MOHO) Seismic discontinuity situated about 35 km below the continents and about 10 km below the oceans that separates the earth's crust and mantle

MONZONITE A granular plutonic rock containing approximately equal amounts of orthoclase and plagioclase and is intermediate between syenite and diorite. Quartz is usually present, but if it exceeds 2% by volume, it is classified as quartz monzonite.

MUD POT A type of hot spring consisting of a shallow pit or cavity filled with hot, boiling mud which carries very little water and a large amount of fine-grained mineral matter

MUD VOLCANO A cone-shaped mound with a maximum height of 250 ft built around a spring by mud brought to the surface by slowly escaping natural gas

MYLONITE A fine-grained laminated rock formed by extreme crushing and milling of rocks during movement on fault surfaces

NAPPES 1: Faulted overturned folds 2: A large body of rock that has moved forward more than 1 mi from its original position, either by overthrusting or by recumbent folding

NECK A lava-filled conduit of an extinct volcano that is exposed by erosion

NONCONFORMITY Where the older rocks were metamorphosed and exposed by profound erosion before the strata were laid down on them, there is a major unconformity, representing a hiatus of great duration. To distinguish unconformities of this significance, the term "nonconformity" is used.

NORMAL FAULT A fault where the hanging wall has been depressed relative to the foot wall

NOVACULITE A light-colored cryptocrystalline siliceous rock that is very dense and even-grained

OERSTED A unit of magnetic-field intensity in free space; the field which would exert a force of 1 dyne on a unit magnetic pole

OIL SHALE A fine-grained laminated sedimentary rock containing kerogen (i.e., material from which petroleum can be obtained by distillation)

OLIGOCENE The third of the epochs into which the Tertiary period is ordinarily divided; also the series of strata deposited during that epoch

OLIGOCLASE A mineral of the plagioclase feldspar series with more sodium than calcium in its composition

OPAQUES Minerals that transmit no light through a thin section under a microscope

ORDOVICIAN The second of seven Paleozoic periods generally used in North America; also the strata of the system of rocks deposited during that period

ORE A mineral of sufficient value, quality, and quantity so that it may be profitably mined. A mineral, or mineral aggregate, containing precious or useful metals or metalloids, that occurs in such quantity, grade, and chemical combinations as to make extraction commercially profitable.

OROGENIC The process of forming mountains, particularly by folding and thrusting

OROGENIC CYCLE The geotectonic cycle in which a mobile belt (geosyncline) is folded and deformed into a stable orogenic belt, having passed through preorogenic, orogenic, and post-orogenic phases

ORTHOCLASE A mineral, a member of the feldspar group ($KAlSi_3O_8$)

OVERDRAFT For a geothermal source, when the ratio of heat removed by a fluid (water or steam) to the normal heat flow into the volume of the fluid exceeds unity, the ratio is called the overdraft.

PALEOZOIC One of the eras of geologic time, between the Precambrian and Mesozoic, comprising the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian systems.

PARAMARGINAL GEOTHERMAL RESOURCES The resources that are recoverable at a cost between one and two times the current price of competitive energy

PASSIVE MICROWAVE TECHNIQUE Radiometry conducted in the microwave region of the electromagnetic spectrum

PEGMATITE An exceptionally coarse-grained rock (most grains are 1 cm or more in diameter) of igneous origin, with interlocking crystals

PENEPLAIN A land surface worn by erosion to a nearly flat or broadly undulating plain

PERAKLALINE In the Shand classification of igneous rock, a division embracing those rocks in which the molecular proportion of alumina is less than that of soda and potash combined

PERMEABILITY The permeability of a rock is its capacity for transmitting a fluid. Degree of permeability depends upon the size and shape of the pores, the size and shape of their interconnections, and the extent of the latter. It is measured by the rate at which a fluid of standard viscosity can move a given distance through a given interval of time. The unit of permeability is the darcy.

PERMEABLE ROCK Having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water. A permeable rock has communicating interstices of capillary or supercapillary size.

PERMIAN The last (youngest) of seven periods of the Paleozoic era

PERTHITE A variety of feldspar consisting of an intergrowth of plagioclase and alkali feldspar

PETROGENESIS A branch of geology that deals with the origin of rocks, and more particularly with the origin of igneous rocks

PETROLOGY The branch of geology dealing with the origin, occurrence, structure, and history of rock. Petrology is broader in scope than petrography, which is concerned with the description and classification of rock.

PHASE 1: A variety differing in some minor respect from the dominant or normal type; a facies, ordinarily used in the detailed description of igneous rock masses 2: A homogeneous, physically distinct portion of matter in a nonhomogeneous sys-

tem 3: An event on a seismogram marking the arrival of an impulse or a group of waves at a detecting instrument and indicated by a change of period or amplitude, or both

PHENOCRYSTS Isolated or individual crystals, usually visible to the naked eye, that are embedded in a finer grained groundmass of igneous rocks

PHREATIC WATER A term originally applied only to water that occurs in the upper part of the zone of saturation under water-table conditions. Now it is applied to all water in the zone of saturation; thus making it an exact synonym of ground water.

PIEDMONT Lying or formed at the base of mountains

PLAGIOCLASE 1: A mineral series ranging from the composition $NaAlSi_3O_8$ to $CaAl_2Si_2O_8$ 2: A convenient designation for the feldspars consisting chiefly of silicates of sodium, calcium, and aluminum as opposed to those consisting chiefly of potassium and aluminum silicates (i.e., alkali feldspars)

PLEISTOCENE The earlier of the two epochs comprising the Quaternary period

PLEOCHROIC The property of differentially absorbing light of different polarizations as it passes through a crystal, i.e., the crystal is optically anisotropic.

PLIOCENE The last of the five epochs of the Tertiary period; also the series of rocks deposited during that epoch

PLUTON In the strictest sense, a body of igneous rock that has formed beneath the surface of the earth by consolidation from magma

PLUTONIC Rocks, usually igneous, formed at great depth. These rocks are usually medium grained (1 to 5 mm) to coarse grained (5 to 30 mm).

PNEUMATOLITIC Contact metamorphism in which the composition of rock has been altered by introducing magmatic material

POROSITY The ratio of the aggregate volume of interstices in a rock or soil to its total volume; usually stated as a percent

PORPHYRITIC A textural term for those igneous rocks in which larger crystals (phenocrysts) are set in a finer ground mass which may be crystalline, glassy, or both.

PRECAMBRIAN All rocks formed before the Cambrian era

PRECAMBRIAN SHIELD A continental block of the earth's crust composed of Precambrian rock that has been relatively stable over a long period of time and has undergone only gentle warping.

PYROCLASTICS Detrital volcanic materials that have been explosively or aerially ejected from a volcanic vent; also a general term for the class of rock made up of these materials

PYROMETER An instrument for measuring temperatures, especially those beyond the range of mercurial thermometers, as by means of the change of electric resistance, the production of thermo-electric current, the expansion of gases, the specific heat of solids, or the intensity of the heat or light radiated

QUARTZ A mineral (SiO_2) composed exclusively of silicon oxygen tetrahedra with all oxygens joined together in a three dimensional network

QUARTZITE Metamorphic rock commonly formed by metamorphism of sandstone and composed of quartz

QUATERNARY The younger of the two glacial periods or systems in the Cenozoic era. Quaternary is subdivided into Pleistocene and Holocene (recent) epochs or series.

RADIATION Any form of energy propagated as rays, waves, or streams of particles; especially light and other electromagnetic waves, sound waves, and the emissions from radioactive substances

RADIOACTIVITY The spontaneous disintegration of the nuclei of some of the isotopes of certain elements with the emission of alpha or beta particles, sometimes accompanied by a gamma ray. Alpha and beta emission change the chemical nature of the element involved; pure gamma emission is limited to energy changes within a given isotope.

RADIOGENIC Formed as a consequence of radioactive decay, as radiogenic heat or radiogenic helium

RAPAKIVI TEXTURE A texture originally described from Finnish granites. In typical specimens large flesh-colored potassic feldspars occur as rounded crystals a few centimeters in diameter and are mantled with white sodic plagioclase.

REGRESSIVE BOILING Boiling that occurs in a liquid during a decrease in temperature

REINJECTION The process of pumping waste water back into a well or aquifer

RESERVOIR A natural underground container of liquids, such as oil, water, or gases. In general such reservoirs were formed by local deformation of strata, changes of porosity, or intrusions.

RESISTIVITY The resistance to electrical current of a three-dimensional, unbounded medium, as opposed to resistance that refers to electrical impedance of confined conductors. It is the reciprocal of conductivity and is usually expressed in ohm-meters.

RESISTIVITY LOG Well logs that determine the resistivity of earth material about the sampling device, or sonde, lowered into the well. Resistivity may be measured by DC probes in contact with the earth or by induction coils carrying and measuring AC currents.

RESISTIVITY METHOD Observation of electric potential and current distribution at the earth's surface intended to detect subsurface variations in resistivity that may be related to geology, ground-water quality, or porosity

RETROGRESSIVE METAMORPHISM The mineralogical adjustment of relatively high-grade metamorphic rock to temperatures lower than those of their initial metamorphism

REVERSE FAULT A fault along which the hanging wall has been raised relative to the footwall

REVERSIBLE Capable of reestablishing the original condition after a change by the reverse of the change

REVERSIBLE PROCESS In thermodynamics, a process performed in such a way that, at its conclusion, both the system and the local surroundings may be restored

to their initial status without producing any change in the rest of the universe. The condition for such a process is that it can be performed quasistatically (a succession of equilibrium states) and that no dissipation effects occur. An example of a reversible cycle is the Carnot cycle and, as a consequence of the second law of thermodynamics, no heat engine can have a greater efficiency than the Carnot engine.

RHYOLITE The extrusive equivalent of granite

RIFT ZONE A system of crustal fractures and faults

SALINITY 1: A measure of the quantity of total dissolved salts in water 2: A measure of the total concentration of dissolved salts in saline water

SANDSTONE A cemented or otherwise compacted detrital sediment composed predominantly of quartz grains

SATURATED LIQUID On a PV diagram for a substance with liquid and vapor phases, as the vapor-liquid mixture is compressed along an isotherm - at that point where the vapor phase just disappears - the liquid is said to be saturated. The distinction between liquid and vapor phases disappears at pressures higher than the critical pressure and at temperatures higher than the critical temperature. On a T versus P plot, this is called the critical point. For water, the critical point is 218 atm and 375°C.

SATURATED VAPOR A vapor that is in equilibrium with its liquid at a given temperature and pressure

SCHIST Any of a class of crystalline rocks whose constituent minerals have a more-or-less parallel or foliated arrangement due mostly to metamorphic action

SCHLUMBERGER SOUNDING A technique used for detailed determination of layering in terms of electrical resistivity of earth strata to a great depth

SECOND LAW OF THERMODYNAMICS In the Kelvin-Planck statement, no process is possible whose sole result is the abstraction of heat from a single reservoir and the performance of an equivalent amount of work. From this law it follows that every actual process in an isolated system is accompanied by an increase in entropy. The important practical consequence in the second law is that no heat engine operating in cycles between two reservoirs at given temperatures can have as great efficiency as a reversible (Carnot) engine operating between the same two reservoirs.

SEDIMENTARY Descriptive term for rock formed of sediment, especially: (a) clastic rocks such as conglomerate, sandstone, and shales formed of fragments of other rock transported from their sources and deposited in water; (b) rocks formed by precipitation from solution, such as rock salt and gypsum, or from secretions of organisms, such as most limestone.

SEDIMENTARY BASIN A geologically depressed area with thick sediments in the interior and thinner sediments at the edges

SEISMIC Pertaining to an earthquake or earth vibration, including those that are artifically induced

SEISMIC ATTENUATION That portion of the decrease in seismic signal strength with distance not dependent on geometrical spreading. The decrease depends on the physical characteristics of the transmitting media, involving reflection, scattering, and absorption.

SEISMIC DISCONTINUITY Physical discontinuity within the earth separating materials in which seismic waves travel at significantly different velocities

SELF-POTENTIAL METHOD An electrical exploration method in which one determines the spontaneous electrical potentials (spontaneous polarization) that are caused by electrochemical reactions associated with metallic mineral deposits.

SERIES A time-stratigraphic unit that is ranked just below a system; a term loosely used in petrology for related igneous rocks

SERPENTINE A mineral group with the general formula $(Mg,Fe)_3\ Si_2O_5(OH)_4$, characterized by long fibrous crystals. Metaphoric rock consisting of these minerals are called serpentinite.

SHALE A laminated sediment in which the constituent particles are predominantly of the clay grade; shale includes indurated, laminated, or fissile claystones and silt-stones.

SIAL A layer of rocks underlying all continents that range from granitic at the top to gabbroic at the base. The thickness is variously placed at 30 to 35 km. Specific gravity is considered to be about 2.7. The name derives from the principal ingredients, silica and alumina.

SILIC CRUST The part of the earth's crust that is high in silica content

SILICEOUS Of or pertaining to silica, containing silica, or partaking of its nature; containing abundant quartz

SILICEOUS SINTER Siliceous sinter, geyserite, and fiorite are names given to the nearly white, often soft and friable, hydrated varieties formed on the evaporation of the siliceous waters of hot springs and geysers, or through the eliminating action of algous vegetation.

SILURIAN The third of seven periods (before Devonian and after Ordovician) of the Paleozoic; also the system of rocks deposited during that period

SIMA The basic outer shell of the earth; under the continents it underlies the sial, but under the Pacific Ocean it directly underlies the oceanic water. Originally, the sima was considered basaltic in composition with a specific gravity of about 3.0. In recent years it has been suggested that the sima is ultramafic in composition with a specific gravity of about 3.3.

SLATE The metamorphic equivalent of shale; a hard, fine-grained rock with slaty cleavage that may be grey, red, green, or black

SONIC LOG An acoustic log used for recording continuously the travel time of sound from surface to an instrument lowered down the borehole

SPACE HEATING The process of supplying the required heat for the physical comfort of human beings in houses, offices, or enclosed industrial plants. The heat required for a typical domestic dwelling on an average winter day in the U.S. is about 27 000 Btu/h or 7.8 kW.

SPECIFIC HEAT The quantity of heat necessary to raise the temperature of 1 g of a given substance 1°C

STEAM The invisible vapor into which water is converted when heated to the boiling point; a vapor arising from a heated substance

STOCK A body of plutonic rock that covers less than 100 km^2, has steep contacts, and is generally discordant

STRATA 1: A section of a formation that consists throughout of approximately the same kind of rock material 2: A single sedimentary bed or layer, regardless of thickness

STRATIGRAPHIC SEQUENCE A succession of sedimentary beds of interregional extent, chronologically arranged with the older strata below and the younger above

STRATIGRAPHIC UNIT A unit that consists of stratified, mainly sedimentary rocks grouped for description, mapping, and correlation

STRATIGRAPHY A branch of geology that treats the formation, composition, sequence, and correlation of the stratified rocks as parts of the earth's crust

STRIKE The course or bearing of the outcrop of an inclined bed or structure on a level surface; the direction or bearing of a horizontal line in the plane of an inclined stratum, joint, fault, cleavage plane, or other structural plane

STRIKE-SLIP FAULT (TRANSCURRENT FAULT) A fault in which the movement is lateral

SUBDUCTION The descent of one tectonic unit under another. Most commonly used for descent of a slab of lithosphere, but appropriate at any scale; refers to the process, not the site

SUBDUCTION ZONE An elongated region along which a crustal block descends relative to another crustal block. Deep oceanic trenches occur along subduction zones.

SUBHEDRAL A descriptive term for those crystals with partially developed crystal faces

SUBLIMATION The transition of a substance directly from the solid state to the vapor state, or vice versa, without passing through the intermediate liquid stage

SUBSIDENCE 1: A sinking of a large part of the earth's crust 2: Movement in which there is no free side and surface material is displaced vertically downward with little or no horizontal component

SUPERCOOL To cool below the freezing point without solidification or crystallization

SUPERHEATED 1: A process of adding more heat than is necessary to complete a given phase change 2: In magmas, the accumulation of more heat than is necessary to cause essentially complete melting; in such cases the increase in temperature of the liquid above the liquidus temperature for any major mineral components is called the superheat.

SUPERSATURATED A solution that contains more of the solute than is normally present when equilibrium is established between the saturated solution and undissolved solute

S-WAVE That type of seismic bodywave that is propagated by a shearing motion of material, so that there is oscillation perpendicular to the direction of propagation. It does not travel through liquids or through the outer core of the earth.

SYLVITE A mineral (KCl); the principal ore of potassium

SYNCLINE A fold in rocks in which the strata dip inward from both sides toward the axis. In other words, a fold that is concave upward

SYNCLINORIUM A broad regional syncline on which are superimposed minor faults

TECTOGENESIS The process by which rocks are deformed; more specifically, the formation of folds, faults, joints, and cleavage

TECTONIC Of, pertaining to, or designating the rock structure and external forms resulting from the deformation of the earth's crust

TECTONIC FRAMEWORK The structural elements of a region including the rising, stable, and subsiding areas

TECTONIC MAP A map on which are shown areas or lines of major structural features produced by uplift, downwarp, or faulting, together with the major lineation within such features

TELESEISM An earthquake whose epicenter is over 1000 km away

TELESEISMIC P-DELAY The delay in the arrival of P(compression) waves from distant epicenters, usually over 1000 km away

TELLURIC Pertaining to the earth, particularly the depths of the earth

TEMPERATURE A manifestation of the average translational kinetic energy of the molecules of a substance caused by heat agitation

TERTIARY The older of the two geologic periods comprising the Cenozoic era; also the system of rocks deposited during that period

THERMAL CONDUCTIVITY A quantity for measuring or specifying the ability of a material to conduct heat. For an area A, length x, and conductivity λ, the rate of heat transfer is given by

$$\frac{dQ}{dt} = \lambda A \frac{dT}{dx}$$ or the dimensions of λ (in CGS)

units in cal/s·cm·°C.

THERMAL DIFFUSIVITY Coefficient of thermal diffusion. A thermal property of matter, with the dimensions of area per unit time

THERMAL EFFICIENCY The ratio of the energy (heat or work) achieved by a system or device to the heat input to the system or device. Efficiency so defined has a maximum value determined by the first and second laws of thermodynamics; it is defined for a given system or device. It is possible to define efficiency from the point of view of the task to be performed and the device which most efficiently performs it (see "Efficient Use of Energy," AIP Conference Proceeding No. 25, American Institute of Physics).

THERMAL GRADIENT Pertains to the rate of increase or decrease in temperature with distance in a specified direction

THERMAL LOOP In any system, the piping that carries the heat-transfer medium, to which heat may be added or from which it may be extracted

THERMAL WATERS Pertains to water heated by a natural or artificial agency

THERMISTOR A resistor (usually a composite semiconductor) with a large temperature coefficient of resistance that is useful for measuring temperature

THERMOCOUPLE An electrical circuit consisting of dissimilar metals joined or welded at two junctions. A potential difference is developed between the junctions if they are at different temperatures.

THOLEIITIC MAGMA A type of basaltic magma containing little or no olivine (magnesium-iron silicate) and normative quartz. Opposite to the olivine-basalt magma type

THRUST FAULT A reverse fault that is characterized by a low angle of inclination with reference to a horizontal plane

TILTMETER 1: A device for observing surface disturbances on a bowl of mercury, employed in an attempt to predict earthquakes 2: An instrument used to measure displacement of the ground surface from the horizontal

TRACHYTIC Rock characterized by small prisms of feldspar lying roughly parallel and arranged in lines presumed to have been parallel to the flow lines of the lava from which the rock was formed

TRANSFORM FAULT A fault in which the dominant movement is lateral, characteristic of mid-ocean ridges and along which the ridges are offset

TRAVERTINE Calcium carbonate ($CaCO_3$) of light color and usually concretionary and compact, deposited from solution in ground and surface waters. Extremely porous or cellular varieties are known as calcareous tufa, calcareous sinter, or spring deposit. Travertine forms the stalactites and stalagmites of limestone caves and the filling of some veins and hot spring conduits.

TRIASSIC The earliest of the three periods of the Mesozoic era; also the system of strata deposited during that time

TRIPLE POINT A point or small region where three plates meet; also the condition under which a substance can exist in equilibrium in its three phases, gas, liquid, and solid

TUFF A rock formed of compacted volcanic fragments, generally smaller than 4 mm in diameter

TURBIDITE A current flowing down a slope and spreading out on the ocean floor; a sedimentary deposit consisting of material that has moved down the steep slope at the end of a continental shelf

TURBIDITY CURRENT A current of small solid particles carried in a moving body of water

TWO-PHASE FLOW The flow of a substance (e.g., water) under conditions of temperature and pressure at which both the liquid and vapor phase are present

ULTRAMAFIC (ULTRABASIC) Some igneous rocks and most varieties of meteorites containing less than 45% silica; containing virtually no quartz or feldspar, and composed essentially of ferromagnesium silicates, metallic oxides, and sulfides and native metals or of all three

UNAVAILABLE ENERGY For a heat engine working into a cold reservoir at temperature T_o, for any irreversible process, the thermal energy that is unavailable for work is given by $T_o \Delta S$, where ΔS is the increase in entropy for the isolated system

UNCONFORMITY A surface of erosion that separates younger strata from older rocks

UNITARY FLOW VECTOR A vector describing the displacement of water in the ground, the flux of which across any surface is equal to the mass of water that crosses the surface per unit time

UNSATURATED VAPOR A vapor at a certain temperature that does not contain the maximum amount of the substance in the gaseous phase

VAPOR DOMINATED A geothermal system in which pressures are controlled by vapor rather than by liquid

VAPORIZATION The process by which a liquid is converted into vapor

VAPOR PRESSURE The pressure at which a liquid and its vapor are in equilibrium at a given temperature

VISCOSITY Internal friction caused by molecular cohesion in fluids; the internal properties of a fluid that offers resistance to flow

VOLCANIC Of, pertaining to, like, or characteristic of a volcano; characterized by or composed of volcanoes; produced, influenced, or changed by a volcano or by volcanic agencies; made of materials derived from volcanoes

VOLUMETRIC SPECIFIC HEAT The amount of heat required to raise the temperature of a unit volume (usually 1 cm^3) 1°C. For rocks, the mass specific heat usually varies inversely as the density and the volumetric specific heat is a reasonably good constant, equal to about 0.6 cal/cm^3 °C over the range of normal exterior earth temperatures.

WATER TABLE The surface between the "zone of saturation" and the "zone of aeration;" that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere

WORK The product of the force acting upon a body and the distance through which the point of application of force moves

XENOLITHS A fragment of other rock or of an earlier solidified portion of the same mass enclosed in an igneous rock; an inclusion; an enclave

2. DEFINITION OF GEOTHERMAL TEMPERATURE GRADIENT

The geothermal temperature gradient is defined as dT/dr, where T is the temperature and r is depth below the earth's surface, measured vertically. In the earth's crust, the thermal gradient is (in general) positive, and its average value is

$$\frac{dT}{dr} = 25°C/km = 2.5 \times 10^{-2} \ °C/m$$
$$= 1.37 \ °F/100 \ ft \ . \qquad (1)$$

Where conduction is the dominant method of heat flow from the hot interior of the earth, the thermal gradient, while positive, is not constant, but can be given at any point in the earth's crust by

$$\frac{dT}{dr} = q/K \ , \qquad (2)$$

where q is the heat flow and K the thermal conductivity. The global average of the heat flow, from the interior through the surface of the earth is

$$q = 1.5 \times 10^{-6} \ cal/cm^2 \ s = 1.5 \times 10^{-2} \ cal/m^2 \ s$$
$$= 1.5 \ \mu cal/cm^2 \ s = 1.5 \ HFU \qquad (3)$$

The conductivity of rock typically varies from 0.4 to 1.0 cal/ms °C. If q is kept fixed at 1.5×10^{-2} cal/m^2 s, then

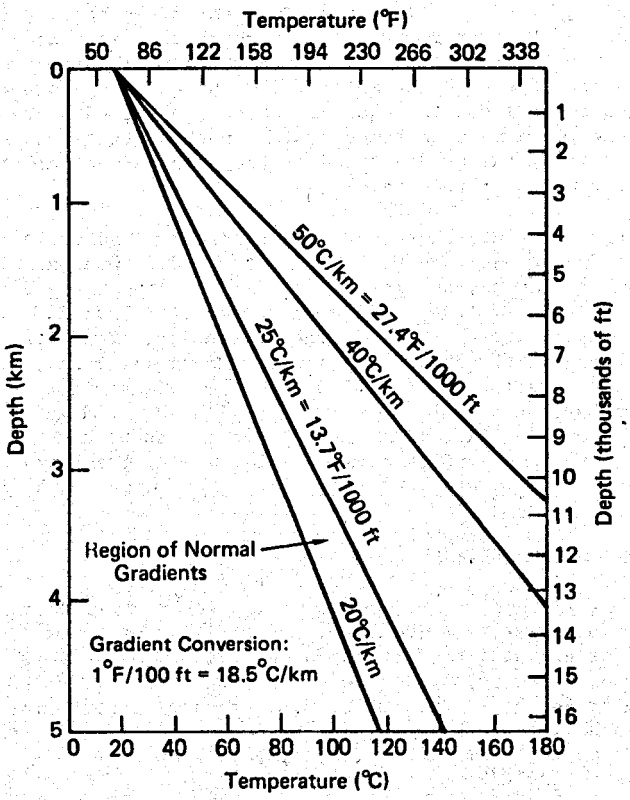
$$15°C/km \leq \frac{dT}{dr} \leq 37.5°C/km \ . \qquad (4)$$

Thus, for regions of near "normal" or average flow, deep holes in dry rock can show significant variations in thermal gradient from the difference in thermal conductivity alone.

In the presence of a fluid (water or steam), the convective flow of the fluid, not rock conductivity, will determine the local temperature. Thus if a water table exists, the thermal gradient can disappear or change sign as the aquifer containing the water flow is penetrated.

The regions that are presently of interest for applications of geothermal energy are those where the geothermal gradient is in excess of normal. In regions devoid of water, such a region can exist if there is an abnormally high heat flow caused by an intrusion of hot magma near the surface, a source of radiogenic heat capped by a layer of rock of low thermal conductivity, or any favorable combination of high heat flow and low thermal conductivity.

Until the present time, practical applications of geothermal energy have been limited to those cases where hot water or steam is available at depths accessible by conventional drilling methods. Such thermal reservoirs may be characterized by a high thermal gradient in the rock above the aquifer containing the hot fluid. But once the hot fluid region has been penetrated, the concept of the thermal gradient is not particularly useful and is difficult to measure in a meaningful way.



Temperature versus Depth for Various Gradients, Ground Temperature Assumed to be 17°C

3. EXAMPLES OF MEASUREMENTS OF GEOTHERMAL TEMPERATURE GRADIENT

HEAT CONDUCTION CONTROLLED SYSTEMS

Measuring the temperature of drill holes is usually a difficult task, and the literature does not often specify the conditions under which measurements were made. Since deep wells penetrate the aquifer of the local water table, temperature measurements are often made in water-filled holes unless precautions were taken to seal out the aquifer. Such measurements are accurate if they were made in holes small enough so that convection does not destroy the gradient and if they are made after thermal equilibrium has been reached.

For example, the temperature gradient measured in the Clubhouse Crossroads Core Hole No. 1 of the U.S. Geological Survey (near Charleston, SC) is 28°C/km, averaged over the depth of 752 m. The deepest hole drilled in the eastern United States, at Mingo County, WV, showed a temperature gradient of 25°C/km, which is very close to the normal gradient. The gradient is essentially constant to a depth of 6.6 km (20 000 ft). Higher than normal gradients have been measured near Maryville, MT, and in the Imperial Valley of California, where gradients as high as 75°C/km were measured (three times normal). In Europe, gradients of from 40 to 75°C/km have been measured in the Hungarian basin.

FLUID CONVECTION SYSTEMS

The geothermal gradient over hot water or steam regions is often much greater than normal at drilling depths of less than 100 m. For example, at Klamath Falls, OR, which overlays a region of hot water, typical gradients measured in dry holes are 400°C/km at depths of 200 to 300 m. Much deeper hot-water reservoirs, such as those near the Salton Sea, in California, show temperatures of 360°C at 2000 m depths, and cause thermal gradients in excess of 300°C/km near the surface.

Vapor-dominated geothermal systems, such as the geysers in California and the Larderello fields in Italy, have initial steam temperatures of about 240°C at well depths of 300 m. These dry-steam systems are characterized by prominent vent areas, heated ground waters of well-defined chemistry, and high rates of heat flow at the surface. Geothermal fields of this type are rare. The heat flow at the surface of the fields is believed to be a more significant observable parameter than is the thermal gradient.

4. CLASSIFICATION OF ROCKS

Rocks, which form essentially all of the earth's crust, may be classified according to their origin, mineral composition, and geologic age.

ORIGIN

Rocks are divided into the three major groups on the basis of origin: igneous, sedimentary, and metamorphic. They are further subdivided within each group according to mineral composition and texture, which provide data that allow us to interpret details of their origin.

Igneous Rocks. These are rocks that have solidified from a molten state. The solidification may occur beneath the surface of the earth from magma (intrusive) or at the surface from lava (extrusive or volcanic). Intrusives are coarse-grained (phaneritic); extrusives are fine-grained (aphanitic).

Sedimentary Rocks. Sedimentary rocks are composed in the location of formation by the depositions of debris from the chemical and physical weathering of the parent rock material. The formation of sedimentary rocks occurs at normal temperatures and pressures. Sedimentary rocks are further divided into those that consist of rock fragments or of organic structures that have been moved individually from their places of origin (clastics), and those that are deposited from aqueous solutions as a result of extensive or total evaporation of the solvent (evaporites).

Metamorphic Rocks. These rocks result from the transformation of igneous (metaigneous or metavolcanic) or sedimentary rocks (metasedimentary) under conditions of high temperature and pressure, and usually from the chemical actions of fluids and gases (metasomatism).

MINERAL COMPOSITION

The crust of the earth contains only eight elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium) with concentrations greater than 1% by weight. Minerals are compounds of these elements, each mineral having a specified crystalline structure. The most abundant minerals represent only five types of chemical compounds: silicates, carbonates, sulfates, halides, and oxides. Of these minerals, the silicates are more abundant than all the rest combined, comprising 95% of the

accessible crust of the earth. Some 2000 minerals have been identified in the earth's crust. They are variations of some 50 distinct types of chemical compounds. Rocks generally (80%) consist of three or fewer silicates.

GEOLOGICAL AGE

All known rocks are the result of a historical petrogenic cycle, the beginning of which is not revealed in the geologic record. The date of the beginning and duration of each period of the geological timetable is identical with the time of formation of the rock structure of the same name. Geological maps classify (usually by different colors) the geological period during which the subsurface or surface rocks formed. The period so indicated is the one during which the rock structure of the same system was formed (e.g., by sedimentation). However, it is possible that severe deformations have occurred since the formation of the stratification because of orogenic or other tectonic activity. Because certain geological periods were favorable for the formation of minerals of economic interest (ores and fossile fuels), the classification of surface strata by age and the knowledge of what underlies them has become a highly developed field of geology.

5. IGNEOUS ROCKS

One major systematic grouping of igneous rocks is made on the basis of combined chemical and mineralogical classification, the chemistry of the rocks being revealed largely by their dominant minerals and serving as a clue to the composition of the magmas from which they solidified. The names formerly used come from one of the first criteria applied when the igneous rocks were first being studied in the last century; that is, the amount of silica, SiO_2, in the chemical analysis. During that premodern period of chemistry, silica was thought to be derived from silicic acid, so the more silica in the rock the more "acidic" the magma. Granite, rich in silica, is the most abundant "acidic" rock. The rocks low in silica were called "basic." Gabbro, or its volcanic equivalent basalt, poor in silica, is the basic counterpart of granite. Though we now know that silica content is not a measure of acidity as the word is now used in chemistry, the terms persist even though what we mean is "more or less silicic." The amount of silica is not necessarily related to the amount of quartz, for much of the silica may be combined in other silicate minerals. In the classification by silica content, the coarse-grained igneous rocks range in sequence from granite on the more silicic side, through grandoiorite and diorite to gabbro on the less silicic side.

Chemis ry and mineralogical composition form the basis of the modern system of classifying the major groups, which turns out to be much the same as the classification by silica content. The two terms most commonly used come from a broad division into light and dark minerals, called, respectively, "felsic" and "mafic." These terms were used because the dominant minerals of the light group are quartz and feldspars, both rich in silica, and those of the dark group are pyroxenes, amphiboles, and olivines, all of which are rich in magnesium and iron. The varieties of feldspar are most important in the classification of igneous rocks, both because they are abundant and because the proportions of different kinds of feldspar vary systematically from felsic to mafic rocks. Granite is rich in potassium feldspar, whereas the more mafic rocks are dominated by sodium and calcium feldspars, the plagioclases. The dark rocks are dominated by biotite mica and amphibole at the felsic end and pyroxene and olivine at the mafic end. Pyroxene and olivine are the major minerals of the ultramafic rocks, which are even lower in silica than the basalts and gabbros; periodotite is dominated by olivine and pyroxene and dunite by olivine.

The other major basis for classification of the igneous rocks is a textural one, whereby we differentiate between the coarse-grained phanerites, and the fine-grained aphanites. The

texture and the size and arrangements of individual crystals depends upon the rate at which the magma cools. Extrusive (volcanic) igneous rock has a finer grain size than does the slower cooling intrusive (plutonic) rock. The slowest-cooling magmas congeal in the last stages of intrusion, when magmas become less viscous and contain more volatiles. These give rise to pegmatites, very coarse-grained rocks that may include huge crystals several meters across.

Many igneous rocks are made up of a mixture of both large and small crystals. If crystals are distinctively larger than the surrounding mass, or matrix, they are called phenocrysts. A rock with many phenocrysts is called a porphyry.

As is true of most classifications, the rocks do not all fall neatly into pigeonholes, for composition and texture vary continuously, and we draw arbitrary dividing lines between them to preserve as nearly as possible the traditional meanings of names that have accumulated over two centuries of geologic usage.

6. SEDIMENTARY ROCKS

Sedimentary rocks may be subdivided according to their mineralogy and texture. These two criteria are used in combination to set apart two main groups: the detrital and the chemical. The detrital sediments are those that have been mechanically transported and deposited as the debris of erosion by currents. The minerals are fragments of rocks or minerals broken and eroded from pre-existing rocks, and so are called clastic. The rocks of ancient mountains worn down by erosion can be reconstructed from the minerals of detrital rocks. Quartz, feldspar, and the clay minerals make up the bulk of that conbribution. The fragments tend to wear and abrade during transport and become rounded. During sedimentation, currents sort the minerals by size and weight with variable efficiency. Size and sorting of clastic sedimentary particles are characteristic of the nature of the currents that carried them. They also form the basis for subdividing the detrital sediments into (a) coarse-grained — the gravels and their lithified equivalents, the conglomerates; (b) medium-grained — the sands and sandstones; and (c) fine-grained — clays and muds and their lithified equivalents, the shales. Coarse sedimentary rocks that are composed of sharp, angular pieces of rocks and minerals are called "breccias," which contrast with the rounded pebbles and cobbles of conglomerates.

The chemical sediments are precipitated from solution, mostly in the ocean, so their minerals reflect the composition of the parent solution. The most abundant chemical rocks are limestone and dolomite, made up largely of calcium and magnesium carbonates. Limestones may be made up largely of calcareous fossils — shells formed by biochemical precipitation of calcium carbonate that organisms extract from seawater. The evaporites are composed largely of gypsum and halite, some including a complex group of other salts crystallized from evaporated sea water. The chemical rocks show a texture of crystal intergrowths resembling that of intrusive rocks.

Mineralogy is an important criterion for distinguishing varieties of detrital rocks, particularly the sandstones. Quartzose sandstones of quartz arenites are mainly composed of quartz grains. This composition results from the erosional disappearance of feldspars and mafic minerals, leaving quartz, which is the most stable and resistant, as the sole residual mineral. Arkose is a sandstone that contains much feldspar in addition to quartz. Graywackes are poorly sorted dark sandstones that contain much feldspar and sand-sized rock fragments of metamorphic or volcanic rocks.

Shale, sandstone, and limestone, the three most abundant sedimentary rock types, account for more than 95% of the total sedimentary part of the crust: shale accounts for more than 65%, sandstone for about 20%, and limestone about 10%.

The classification of sediments is based on mineralogy, texture, and chemical composition. The main criterion for the subdivision of detrital rocks is grain size. The detritals are further grouped by their mineral content, mainly the relative amounts of quartz, feldspar, micas, and clay minerals. The chemical sediments are grouped by chemical composition into the carbonates, limestone and dolomite; evaporites, including chlorides (halite) and sulfates (gypsum); cherts, or siliceous rocks, containing much silica either as quartz or other varieties of SiO_2; organics, the organic carbon sediments including coal, gas, and oil; and phosphates, rocks containing phosphate, for example, the mineral apatite.

7. METAMORPHIC ROCKS

Just as igneous rocks are divided into intrusive and extrusive, and sediments into detrital and chemical, so are the metamorphic rocks divided into two broad genetic classes. They result either from regional or contact metamorphism. Regional metamorphic rocks are produced by heat and pressure that transform deeply buried rocks of all kinds — igneous, sedimentary, and metamorphic. Contact metamorphics are made by the alteration of rocks near an igneous intrusion, largely from heat. The characteristic textures produced are the clues to the two modes of origin. Most regional metamorphics show foliation — a platey, wavy, or leafy structure imparted to the rock by parallel alignment of minerals, particularly the sheety ones like mica. Some contact metamorphics are also foliated, but most tend to be granular, such as hornfelses, which are very fine-grained silicate rocks of varied composition.

Foliation type and grain size are used, in combination, as the basis for subdividing the metamorphics into schist, slate, gneiss, and granulite. The schists are characterized by partings along well-defined planes of medium-grained, platey, micaceous minerals. The slates have more perfect planar partings and are finer grained, so that individual minerals cannot be easily seen. The gneisses are coarse grained and show much broader and less distinct foliation, and they do not split or cleave in the way schists and slates do. Granulites are like their textural equivalents the granular igneous rocks, in having a mosaic of interlocking, more-or-less equidimensional crystals.

Within these textural groups, mineral assemblages form the basis for further dividing the rocks into smaller groups, or facies. The metamorphic facies have a genetic basis, for the minerals are determined by the temperatures and pressures required to form them. For example, albite-epidote-amphibole schists are the product of moderate temperature and pressure in regional metamorphism, whereas pyroxene hornfels rock is the result of high temperature and moderate pressure in contact metamorphism. In normal field usage, metamorphic rocks are prefixed by the name of an abundant or prominent mineral constituent. Others are named for a mineral constituent that is greatly predominant, such as amphibolite. Marbles and metamorphosed limestones are largely made of calcite. Quartzites, which are metamorphosed quartz arenites, are mainly quartz.

Some metamorphic rocks have characteristic textures produced by the crushing and mechanical deformation as the rocks are folded and faulted. The broken, pulverized grain texture is called "cataclastic," and fine-grained rocks produced by this kind of friction action are called "mylonites."

8. GEOLOGIC TIME AND THE GEOLOGIC TIME SCALE

Geologic time may be thought of in two ways: relative and absolute. Relative time, that is, whether one event in earth history came before or after another event, disregards years. Relative time has been determined largely by the relative position of sedimentary rocks to each other. The basic principle used to determine whether one sedimentary rock is older than another is very simple and is known as the law of superposition. The law states that if a series of sedimentary rocks has not been overturned, the topmost layer is always the youngest and the lowermost is always the oldest. However, the difficulty lies in the fact that unknown hundreds of thousands of feet of sedimentary rock have been deposited during geologic time, and there is no one cliff where all these rocks are exposed. Consequently, rocks from different localities must be correlated to piece together the entire sequence. Correlation may be done in a number of ways, such as by physical features and by index fossils. Whether a geologic event took place a few thousand years ago or a billion years ago is reported in absolute time. Absolute time is expressed in terms of years and is determined by measuring the rate of decay of radioactive elements.

Using the law of superposition and the concept that fossils are an index to time, geologists have made chronological arrangements of sedimentary rocks from all over the world. The chronological sequence is called the geologic column, and rock formations are divided into groups, systems, and series. Similarly the geologic timetable is divided into the time terms "era," "period," and "epoch." Two sets of terms are used for each geological division because, for clarity, it is necessary to discriminate between the strata themselves and the time intervals they represent. Thus an era is the duration of a group; a period the duration of a system, and so on.

GEOLOGIC TIME SCALE

ERA	PERIOD OR SYSTEM		EPOCH OR SERIES	IMPORTANT PHYSICAL EVENTS AND FAUNA	MILLION YEARS AGO
CENOZOIC	QUATERNARY	NEOGENE	RECENT	Glaciers melted; milder climates. Many mammals disappeared.	
			PLEISTOCENE	Glaciation; fluctuating cold to mild climates. Most invertebrates living species. Dominance of large mammals. Man.	1
	TERTIARY		PLIOCENE	Continued uplift and mountain building. Climate cooler. Mammals reach peak in size and abundance.	10
			MIOCENE	Uplift of Sierras and Rockies. Moderate climates. Rise of grazing mammals.	25
		PALAEOGENE	OLIGOCENE	Lands generally low. Rise of Alps and Himalayas begun. Volcanoes in Rockies area. First sabre-tooth cats.	40
			EOCENE	Mountains eroded, many lakes in western North America. Climates mild to very tropical. All modern mammals present (first horses).	60
			PALAEOCENE	Mountains high, climates mild to cool. Primitive mammals, modern birds and new invertebrates.	70
MESOZOIC	CRETACEOUS			Lands low and extensive, mild climates. Last widespread oceans. Flowering plants expand rapidly. Giant reptiles become extinct; modern insects. Ammonites die out. Foraminifera. Period closed with Laramide Revolution (Sierra uplifted).	
	JURASSIC			Continents low; large areas of Europe covered by seas. Climates mild. Mountains from Alaska to Mexico rise; eruptions and intrusions in the north-west. Dinosaurs, marine reptiles, ammonites and belemnites abundant. Ginkgos, conifers and cycads.	135
	TRIASSIC			Continents mountainous, large areas arid. Eruptions in eastern North America and New Zealand. First dinosaurs and marine reptiles. First hemicorals, last ammonoids.	180
PALAEOZOIC	PERMIAN			First mammal-like reptiles, other reptiles diversified. Many marine invertebrates became extinct, last trilobites and hemicorals. Period ended with Appalachian Revolution.	220
	CARBONIFEROUS	PENNSYLVANIAN		Lands low, covered by shallow seas or extensive coal swamps, climates warm. Amphibians and reptiles reach large size; large insects, scorpions, cockroaches. Fusuline foraminifers abundant.	270
		MISSISSIPPIAN		Widespread seas recreated to result of mountain building in eastern United States, Texas, Colorado. Climates warm. Crinoids dominate; amphibians, sharks and bony fishes spread. Insects developed wings.	
	DEVONIAN			North America low and flat, but mountains and volcanoes present in eastern United States and Canada. Europe mountainous with arid basins. Fishes dominant, first amphibians, many brachiopods, corals, bryozoans and blastoids. First ammonites.	350
	SILURIAN			Continents relatively flat, mountain building in Europe; climates mild. Much salt deposited. Eurypterids and corals abundant. First air breathers; lycopod plants.	400
	ORDOVICIAN			Continents low with shallow seas, mountains rose at close in Europe and North America. Abundant graptolites, trilobites, nautiloids, cystoids; first ostracods and conodonts, seaweeds and algae. Climates uniformly mild.	440
	CAMBRIAN			Extensive seas in major synclines on all continents. Climates mild. Marine invertebrates and algae abundant. Trilobites dominant. All animal phyla probably existed.	500
PRE-CAMBRIAN	PROTEROZOIC (ALGONKIAN)			Shallow seas in geosynclines. Climates warm and moist to dry and cold. Glaciation in eastern Canada. Bacteria, marine algae, worm burrows sponge spicules. Probably most phyla lived but left no record. Few fossils. Iron ores of Lake Superior formed.	600
	ARCHAEOZOIC (PRIMITIVE LIFE)			Extensive mountain building with intrusions and eruptions. Iron deposits formed. Earliest known life, blue-green algae, fungi. Graphite and carbonaceous shales in Australia and Canada. Carbon in Rhodesian rock.	1000 2000 2600
	AZOIC (WITHOUT LIFE)			Formation of the Earth's crust. No rocks have been found, therefore cannot be dated by any known method.	3000 3500 4000 4500 5000 6000

The series of the systems in the Mesozoic and Palaeozoic are usually designated Lower, Middle, and Upper, but are given provincial names in many areas; thus the Chester series (Upper Mississippian) of the Mississippi Valley is the equivalent of the Visean (Lower Carboniferous) of Europe. The corresponding time terms that are applicable are *Early, Middle,* and *Late.*

The accuracy of dating decreases from the younger to the older periods, especially in the Pre-Cambrian. Beyond the age of the oldest known fossil (about 2,600 million years) life had its origin. The dates preceding this event can only be conjectural. Time estimates after Holmes, Arthur, 1960, a revised geological time scale: *Edinburgh Geol. Soc. Trans.*, v. 17, pt. 3, pp. 183–216.

9. TABLES OF CONVERSION FACTORS AND ENERGY EQUIVALENTS

The following tables of conversion factors and energy equivalents are chosen for their applicability to the utilization of geothermal energy. Since geothermal energy involves a combination of many disciplines, a number of unit systems are used, and an attempt is made here to include all of those commonly encountered and to relate them to other units commonly used in the field of energy utilization.

There is no method of writing conversion tables that meets universal acceptance or that avoids some degree of confusion. In what follows, an array system is used where possible and the equality sign is understood to exist when any line of the array is read horizontally. For units expressed in the English system, the symbol "lbm" is used for the pound as a unit of mass and "lbf" for the pound as a unit of force. In much of the literature, the sense of the term "pound" must be gotten from the context. The use of the "poundal" and the "slug" is now so rare that no purpose is served by introducing them here.

Table 1

Basic Units and Symbols

Quantity	mks or SI		cgs		English	
Length	meter,	m	centimeter,	cm	foot,	ft
Mass	kilogram,	kg	gram,	g	pound,	lb
Time	second,	s	second,	s	second,	s
Temperature	degrees kelvin,	°K	degrees kelvin,	°K	degrees Rankin,	°R

Table 2

Dimensionality of Force, Energy, and Power

	Force	Energy (work)	Power
mks or SI	kgm/s^2	$kg\ m^2/s^2$	$kg\ m^2/s^3$
Name	newton	joule	watt
Symbol	N	J	W
cgs	gcm/s^2	gcm^2/s^2	gcm^2/s^3
Name	dyne	erg	erg/second
Symbol	dyne	erg	erg/s
English	$lbm\ ft/s^2$	$lbm\ ft^2/s^2$	$lbm\ ft^2/s^3$
Name	pound	foot pound	foot pound/second
Symbol	lbf	ft lbf	ft lbf/s

Table 3

Conversion Factors, Force

	N	dyne	lbf	kgf
newton	1	10^5	0.2248	0.1020
dyne	10^{-5}	1	2.248×10^{-6}	1.020×10^{-6}
pound	4.448	4.448×10^5	1	0.4536
kilogram force	9.806	9.806×10^5	2.205	1

Table 4

Conversion Factors, Length

	m	cm	ft	in.	mi
meter	1	10^2	3.281	39.37	6.215×10^{-4}
centimeter	10^{-2}	1	3.281×10^{-2}	0.3937	6.215×10^{-6}
foot	0.3048	30.48	1	12	1.894×10^{-4}
inch	0.0254	2.540	0.08333	1	1.578×10^{-5}
mile (statute)	1609	1.609×10^5	5280	6.336×10^4	1

Table 5

Conversion Factors, Mass

	kg	g	lbm	mt	ton (Es)	ton (El)
kilogram	1	10^{3}	2.205	10^{-3}	1.102×10^{-3}	9.842×10^{-4}
gram	10^{-3}	1	2.205×10^{-3}	10^{-6}	1.102×10^{-6}	9.842×10^{-7}
pound	0.4536	453.6	1	4.536×10^{-4}	5×10^{-4}	4.46×10^{-4}
ton (metric)	10^{3}	10^{6}	2204.6	1	1.102	0.9842
ton English short	907.2	9.072×10^{5}	2000	0.9072	1	0.8928
ton English long	1016	1.016×10^{6}	2240	1.0161	1.1200	1

Table 6

Conversion Table, Temperature

	°K	°C	°R	°F
degrees Kelvin	1	°C+273.2	5/9 °R	5/9 °F+255.4
degrees Celsius	°K-273.2	1	5/9 °R-273.2	5/9 °F-17.78
degrees Rankine	9/5 °K	9/5 °C+491.7	1	°F+459.7
degrees Fahrenheit	9/5 °K-459.7	9/5 °C+32	°R-459.7	1

Table 7

Conversion Factors, Area

	cm^2	m^2	ft^2	mi^2	acre	hectare
cm^2	1	10^{-4}	1.076×10^{-3}	3.86×10^{-11}	2.47×10^{-8}	10^{-8}
$meters^2$	10^4	1	10.76	3.86×10^{-7}	2.47×10^{-4}	10^{-4}
$feet^2$	929	0.0929	1	3.58×10^{-8}	2.29×10^{-5}	9.29×10^{-6}
$miles^2$	2.58×10^{10}	2.58×10^{6}	2.79×10^{7}	1	640	259
acre	4.045×10^{7}	4.045×10^{3}	43 560	1.56×10^{-3}	1	0.4047
hectare	10^8	10^4	1.076×10^{5}	3.86×10^{-3}	2.471	1

Table 8

Conversion Factors, Volume

	m^3	cm^3	ft^3	in^3	liter	gal	bbl	acre ft
$meter^3$	1	10^6	35.32	6.10×10^4	1000	264	6.29	8.12×10^{-4}
$centimeter^3$	10^{-6}	1	3.53×10^{-5}	6.10×10^{-2}	10^{-3}	2.64×10^{-4}	6.29×10^{-6}	8.12×10^{-10}
$feet^3$	2.83×10^{-2}	2.83×10^4	1	1728	28.31	7.48	0.178	2.29×10^{-5}
$inch^3$	1.64×10^{-5}	16.4	5.79×10^{-4}	1	1.64×10^{-2}	4.33×10^{-3}	1.03×10^{-4}	8.13×10^{-10}
liter	10^{-3}	1000	3.53×10^{-2}	61.02	1	0.2642	6.29×10^{-3}	8.11×10^{-7}
gallon	3.78×10^{-3}	3.79×10^3	0.134	231	3.785	1	2.38×10^{-2}	3.07×10^{-6}
oil barrel	0.159	1.59×10^5	5.61	$9.70\ 10^3$	159	42.0	1	1.29×10^{-4}
acre foot	1.23×10^3	1.23×10^9	4.36×10^4	7.53×10^7	1.23×10^6	3.26×10^5	7.75×10^3	1

Table 9

Conversion Factors, Energy

	J	erg	ft lbf	cal	Btu	hp·h	kWh
joule	1	10^{7}	0.7376	0.2390	$9.485_{\times 10^{-4}}$	$3.725_{\times 10^{-7}}$	$2.778_{\times 10^{-7}}$
erg	10^{-7}	1	7.376	$2.390_{\times 10^{-8}}$	$9.845_{\times 10^{-11}}$	$3.725_{\times 10^{-14}}$	$2.778_{\times 10^{-14}}$
foot pound	1.356	$1.356_{\times 10^{7}}$	1	0.3240	$1.286_{\times 10^{-3}}$	$5.051_{\times 10^{-7}}$	$3.766_{\times 10^{-7}}$
calorie	4.185	$4.184_{\times 10^{7}}$	3.086	1	$3.968_{\times 10^{-3}}$	$1.559_{\times 10^{-6}}$	$1.163_{\times 10^{-6}}$
Btu	$1.054_{\times 10^{3}}$	$1.054_{\times 10^{10}}$	777.6	252.0	1	$3.929_{\times 10^{-4}}$	$2.930_{\times 10^{-4}}$
horsepower hour	$2.685_{\times 10^{6}}$	$2.685_{\times 10^{13}}$	$1.980_{\times 10^{6}}$	$6.414_{\times 10^{5}}$	2545	1	0.7457
kilowatt hour	$3.600_{\times 10^{6}}$	$3.600_{\times 10^{13}}$	$2.655_{\times 10^{6}}$	$8.601_{\times 10^{5}}$	3413	1.341	1

Other energy units in current usage are:

1 kg calorie = 1 food calorie = 1000 cal = 4184 J

1 eV = $1.602\ 10^{-19}$ J

1 therm = 10^{5} Btu = $1.054\ 10^{8}$ J

1 quad = 10^{15} Btu = $1.054\ 10^{18}$ J

1 ton of refrigeration (U.S. Standard) = 288 000 Btu = $3.035\ 10^{8}$ J, defined as the heat of fusion of 1 ton (more precisely 2009.1 lb) of water

Table 10

Conversion Factors, Power

	W	cal/s	hp	Btu/h	ft lbf/s	Tons of Refrigeration
watt	1	0.2389	1.341×10^{-3}	3.413	0.7376	2.441×10^{-5}
calorie/second	4.186	1	5.613×10^{-3}	14.29	3.087	5.881×10^{-6}
horsepower	745.7	178.2	1	2545	550	0.2120
Btu/hour	0.2930	7.000×10^{-2}	3.929×10^{-4}	1	0.2161	8.333×10^{-5}
foot-pounds/second	1.356	0.3239	1.818×10^{-3}	4.628	1	1.801×10^{-5}
tons of refrigeration (commercial)*	4.096×10^{4}	1.715×10^{5}	4.716	12 000	5.554×10^{4}	1

*As a unit of energy, the ton of refrigeration is the energy required to melt 1 ton of ice; as a unit of power (commercial), it is the power required to melt 1 ton of ice in a 24-h day.

Table 11

Conversion Factors, Pressure

	N/m^2	$dynes/cm^2$	lbf/in^2	atm	mmHg	in H_2O	bar	kg/cm^2	100 ft H_2O
$newton/m^2$ (pascal)	1	10	1.45×10^{-4}	9.87×10^{-6}	7.50×10^{-3}	4.01×10^{-3}	10^{-5}	1.02×10^{-5}	3.34×10^{-6}
$dyne/cm^2$	0.1	1	1.45×10^{-5}	9.87×10^{-7}	7.50×10^{-4}	4.01×10^{-4}	10^{-6}	1.02×10^{-6}	3.34×10^{-7}
$pound/in^2$	6.89×10^{3}	6.89×10^{4}	1	6.80×10^{-2}	51.7	27.6	6.89×10^{-2}	7.03×10^{-2}	2.31×10^{-2}
atmospheres	1.01×10^{5}	1.01×10^{6}	14.69	1	760	405	1.013	1.033	0.339
mmHg (Torr)	133.3	1.333×10^{3}	1.93×10^{-2}	1.316×10^{-3}	1	0.533	1.333×10^{-3}	1.358×10^{-3}	4.464×10^{-4}
inch water	249.8	2.498×10^{3}	3.62×10^{-2}	2.466×10^{-3}	1.874	1	2.502×10^{-3}	2.540×10^{-3}	8.33×10^{-4}
bar	10^{5}	10^{6}	14.5	0.9869	750.0	399.7	1	1.020	0.335
$kilogram/cm^2$	9.81×10^{4}	9.81×10^{5}	14.22	0.968	736	393.7	0.981	1	0.328
100 feet water	2.99×10^{5}	2.99×10^{6}	43.3	2.949	2.24×10^{3}	1200	2.987	3.05	1

Table 12

Energy Equivalents of Common Fuels

Fuel	Btu/lb	kcal/kg	Btu/industrial units
Hydrogen	51 570	28 650	275 Btu/ft^3
Methane	21 500	11 940	911 Btu/ft^3
Propane	19 930	11 070	2320 Btu/ft^3
Pipeline gas	23 500	13 050	1035 Btu/ft^3
Octane	19 260	10 700	
Gasoline	19 500	10 800	124 000 Btu/gal
Kerosene	18 500	10 300	127 000 Btu/gal
Fuel oil	18 200	10 100	136 000 Btu/gal
Crude oil	18 000	10 000	5.75×10^6 Btu/bbl
Carbon	14 540	8 078	
Coal (bituminous)	13 000	7 200	26×10^6 Btu/ton
Fission U^{235}	3.53×10^{10}	1.96×10^{10}	(8.21×10^{13} J/kg)

Table 13

Conversion Table, Energy Equivalents of Common Fuels

	Btu	kWh	oil (bbl)	gas/ft^3	coal (ton)
Btu	1	2.93×10^{-4}	1.74×10^{-7}	9.66×10^{-4}	3.85×10^{-8}
kWh	3.41×10^3	1	5.94×10^{-4}	3.30	1.31×10^{-4}
oil (bbl)	5.75×10^6	1.68×10^3	1	5.56×10^3	0.221
gas/ft^3	1.03×10^3	0.303	1.80×10^{-4}	1	3.98×10^{-5}
coal (ton)	2.6×10^7	7.62×10^3	4.52	2.51×10^4	1
U^{235} (kg)	7.79×10^{10}	2.28×10^7	1.35×10^4	7.53×10^7	3.0×10^3

Table 14

Properties of Solid and Liquid Fuels

Fuel	Approximate Energy Content/Unit Mass		Approximate Specific Gravity
	Btu/lb	kcal/kg	
Oak	7.9×10^3	4.4×10^3	0.83
Pine	8.7×10^3	4.8×10^3	0.48
Bituminous Coal	7.9 to 14.8×10^3	4.4 to 8.2×10^3	1.27 to 1.45
Anthracite Coal	9.0 to 14.1×10^3	5.0 to 7.8×10^3	1.4 to 1.7
Petroleum	18.8 to 19.5×10^3	10.1 to 10.8×10^3	0.81 to 0.98
Fuel Oil	18.0 to 19.4×10^3	10.0 to 10.8×10^3	0.94
Gasoline	20.0 to 21.0×10^3	11.1 to 11.7×10^3	0.72 to 0.74
Ethyl Alcohol	12.8 to 13.2×10^3	7.1 to 7.3×10^3	0.79

Density of water = 1 g/cm^3 or 62.4 lb/ft^3

Table 15

Properties of Gaseous Fuels

	Approximate Energy Content at STP		Gaseous Specific Gravity Air = 1	Liquid Specific Gravity Water = 1
	Btu/lb	kcal/kg		
Methane (CH_4)	23.7×10^3	13.2×10^3	0.55	0.466
Propane (C_3H_3)	21.7×10^3	12.1×10^3	1.55	0.501
n Butane (C_4H_{10})	21.3×10^3	11.8×10^3	2.08	0.579
Hydrogen	52 $\times10^3$	29 $\times10^3$	0.07	0.07

STP (Standard Pressure and Temperature) p = 1 atm, T = 0°C

Density of air = 1.29 kg/m^3 = 8.0×10^{-2} lb/ft^3

Density of water = 1 g/cm^3 = 62.4 lbm/ft^3

Table 16

Power Budget of the Earth

Power Received	Terawatts	Fraction
Solar radiation	174 000	0.9998
Geothermal heat	32	1.8×10^{-4}
Tides	3	1.7×10^{-5}
Total	174 035	1.000
Power Expended		
Direct reflection	52 000	0.30
Direct conversion to heat (ocean, air, earth)	82 000	0.47
Hydrological cycle	40 000	0.23
Ocean and air circulation	370	0.0021
Photosynthesis	40	2.3×10^{-4}
Human activity	6.5	3.7×10^{-5}
Human food	0.3	1.7×10^{-6}

Table 17

Properties of Water

Density = 1 g/cm^3 = 1 kg/liter = 1000 kg/m^3
= 62.43 lb/ft^3 = 8.345 lb/gal

Melting temperature at 1 atm = 0°C = 273.2°K
= 32°F = 491.67°R

Boiling temperature at 1 atm = 100°C = 373.2°K
= 212°F = 671.67°R

Specific heat = 1 cal/g°C = 1 kcal/kg°K
= 1 Btu/lb°F = 4184 J/kg°K

Molar specific heat = 18 cal/g-mole°C = 47.4 J/g-mole°K
= 18 Btu/lb-mole°F

Heat of fusion = 79.4 cal/g = 79.4 kcal/kg
= 143.5 Btu/lb = 3.336×10^5 J/kg

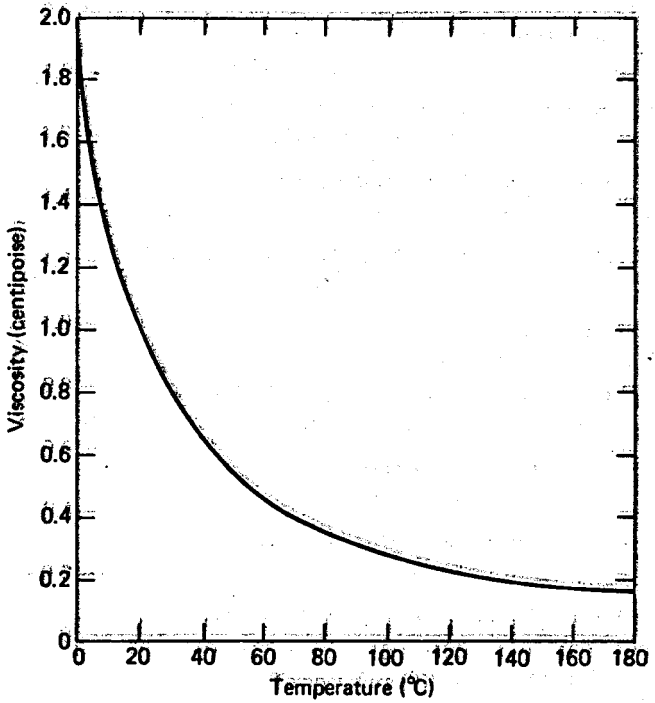
Molar heat of fusion = 1436 cal/g-mole = 6010 J/g-mole
= 2585 Btu/lb-mole = 0.0623 eV/molecule

Heat of vaporization = 539.4 cal/g = 439.4 kcal/kg
= 971 Btu/lb = 2.257×10^6 J/kg

Molar heat of vaporization = 9717 cal/g-mole = 40 660 J/g-mole
= 17 490 Btu/lb-mole = 0.421 eV/molecule

Viscosity = 1.789 centipoise = 4.33 lb/ft h at 0°C
= 0.6820 centipoise = 1.65 lb/ft h at 38°C
= 0.3059 centipoise = 0.74 lb/ft h at 93°C
= 0.186 centipoise = 0.45 lb/ft h at 149°C

Thermal conductivity = 1.350×10^{-3} cal/s cm°C = 0.327 Btu/h ft°F at 0°C
1.503×10^{-3} cal/s cm°C = 0.364 Btu/h ft°F at 38°C
1.619×10^{-3} cal/s cm°C = 0.392 Btu/h ft°F at 93°C
1.631×10^{-3} cal/s cm°C = 0.395 Btu/h ft°F at 149°C



Viscosity of Water Measured at Atmospheric Pressure below 100°C; at Saturation Pressure above 100°C

Table 18

Properties of Water and Saturated Steam

Temperature (°F)	Specific Volume (ft^3/lbm)			Enthalpy (Btu/lbm)		
	Pressure (lbf/in^2)	Saturated Liquid	Saturated Vapor	Saturated Liquid	Phase Change	Saturated Steam
32	0.088	0.0160	3306.	0.0000	1075.8	1075.8
80	0.507	0.01610	633.1	48.02	1048.6	1096.6
100	0.949	0.01613	350.4	67.97	1037.2	1105.2
140	2.88	0.01629	122.9	107.89	1014.1	1122.0
180	7.50	0.01651	50.23	147.92	990.2	1138.1
200	11.52	0.01663	33.64	167.9	977.9	1145.9
212	14.69	0.01672	26.80	180.07	970.3	1150.4
250	29.82	0.0170	13.82	218.48	945.5	1164.0
300	67.01	0.0174	6.466	269.59	910.1	1179.7
350	134.6	0.0179	3.342	321.63	870.7	1192.3
400	247.3	0.01864	1.863	374.9	826.0	1201.0
500	680.8	0.0204	0.6749	487.8	713.9	1201.7
600	1542.	0.0236	0.2668	617.0	548.5	1165.5
700	3093.	0.0369	0.0761	823.3	172.1	995.4
705.4	3206.	0.0503	0.0503	902.7	0	902.7

For specific volume in cm^3/g, multiply ft^3/lb^3 by 62.34

For specific enthalpy in cal/g, multiply Btu/lb by 0.5559

Table 19

Average Properties of Sea Water

Salinity = 35 g/kg of sea water
= 35 000 ppm

Principal salts in 1 kg of sea water

NaCl	= 28.01 g
$MgCl_2$	= 3.812 g
$MgSO_4$	= 1.752 g
$CaSO_4$	= 1.283 g
KSO_4	= 0.816 g

*Density = 1.0248 g/cm^3 at 20°C and atmospheric pressures

Freezing point	= -1.85°C
Specific heat	= 3.993 J/g = 0.9558 cal/g at 20°C
Conductivity	= 4.8×10^{-2} Ω^{-1} cm^{-1} at 20°C
Viscosity	= 0.01075 poise at 20°C
Velocity of sound	= 1518.5 m/s at 20°C

*Density of pure water at 20°C is 0.9982 g/cm^3

Table 20

Conversion Table, Concentration of Solute

	g/l	kg/m^3	ppm	grain/gal
grams/liter	1	1	1000	58.02
$kilograms/meter^3$	1	1	1000	58.02
parts/million	1.00×10^{-3}	1.00×10^{-3}	1	5.844×10^{-2}
grains/gallon	1.722×10^{-2}	1.722×10^{-2}	17.11	1

Table 21

Conversion Factors, Viscosity

	$\frac{g}{cm\text{-}s}$	$\frac{g}{hcm\text{-}s}$	$\frac{kg}{m\text{-}s}$	$\frac{lbm}{ft\ s}$	$\frac{lbf\ s}{in^2}$
poise $\left(\frac{gram}{centimeter\text{-}second}\right)$	1	10^2	10^{-1}	6.72×10^{-2}	1.45×10^{-5}
centipoise	10^{-2}	1	10^{-3}	6.72×10^{-4}	1.45×10^{-7}
$\frac{kilogram}{meter\text{-}seconds}$	10	10^3	1	6.72×10^{-1}	1.45×10^{-4}
$\frac{pounds\ mass}{foot\ seconds}$	1.49×10^{1}	1.49×10^{3}	1.49	1	2.16×10^{-4}
Reyn $\left(\frac{lbf\ s}{in^2}\right)$	6.89×10^{4}	6.89×10^{6}	6.89×10^{3}	4.63×10^{3}	1

Note: the dimensions of viscosity are force × time/$area^2$ = $\frac{mass}{length\text{-}time}$

Table 22

Conversion Table for Flow-Rates

	gal/s	gal/min	gal/h	ft^3/s	m^3/s	Water at 4°C lb/h	l/s	Water at 80°C kg/s
gallons/second	1	60	3.60×10^{3}	0.1337	3.785×10^{-3}	3.004×10^{4}	3.785	3.678
gallons/minute	1.667×10^{-2}	1	60	2.228×10^{-3}	6.308×10^{-5}	5.007×10^{2}	6.308×10^{-2}	6.130×10^{-2}
gallons/hour	2.778×10^{-4}	1.667×10^{-2}	1	3.71×10^{-5}	1.051×10^{-6}	8.346	1.051×10^{-3}	1.021×10^{-3}
$feet^3$/second	7.480	4.488×10^{2}	2.693×10^{4}	1	2.831×10^{-2}	2.247×10^{5}	28.31	27.51
$meter^3$/second	2.643×10^{2}	1.586×10^{4}	9.515×10^{5}	35.32	1	2.205×10^{3}	10^{3}	0.9718×10^{3}
pounds/hour (water at 4°C)	3.329×10^{-5}	1.997×10^{-3}	0.1198	4.449×10^{-6}	4.535×10^{-4}	1	1.259×10^{-4}	1.259×10^{-4}
liters/second	0.2642	15.85	9.515×10^{2}	3.532×10^{-2}	10^{-3}	7.938×10^{3}	1	0.9718
kilograms/second (water at 80°C)	0.2718	16.31	9.711×10^{2}	3.634×10^{-2}	1.029×10^{3}	7.938×10^{3}	1.029	1

At 4°C, the flow rate for water, in units of kg/s, is identical with that given for liters/s. For higher temperatures, the flow rate in mass units must be corrected for the decrease in density, as illustrated in the lower row and last column.

Table 23

The Ideal Gas Constant

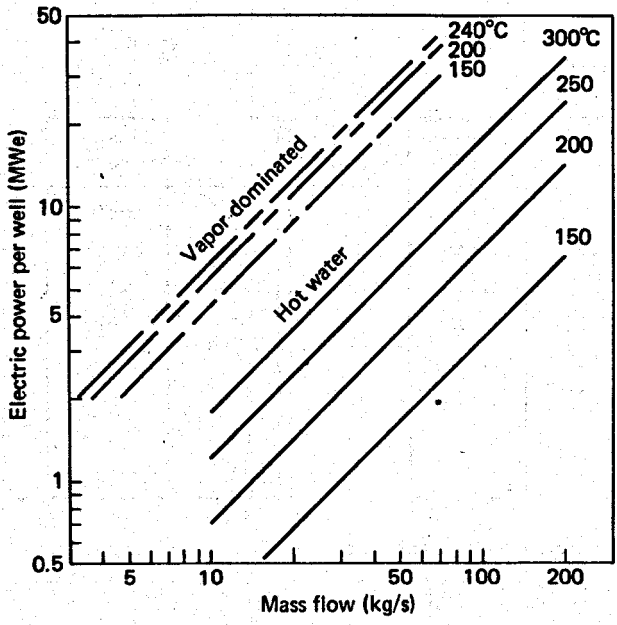
For the ideal gas written as:

$pV = nRT$ where n is the number of moles of gas or

$pv = RT$ where v is the molar specific volume $v = V/n$,

The universal gas constant R is given as below:

Unit of Pressure	Unit of Volume	Unit of Temperature	R
newton/m^2	m^3	Kelvin	8.314 10^3 J/kg-mole°K
atmosphere	liter	°K	8.206 10^{-2} liter atm/g mole°K
dynes/cm^2	cm^3	°K	8.314 10^7 erg/g-mole°K
dynes/cm^3	cm^3	°K	1.987 cal/g-mole°K
atmosphere	cm^3	°K	82.06 cm^3 atm/g-mole°K
atmosphere	ft^3	Rankin	0.7301 ft^3 atm/lbm-mole°R
lbf/in^2	ft^3	°R	10.73 ft^3 psi/lbm-mole°R
lbf/ft^2	ft^3	°R	1545 ft lbf/lbm-mole°R
lbf/ft^2	ft^3	°R	1.987 Btu/lbm-mole°R



Electric Power Per Well as a Function of Mass Flow, Various Temperatures of Hot Water and Vapor-Dominated Systems (from U.S. Geological Survey Circular 726)

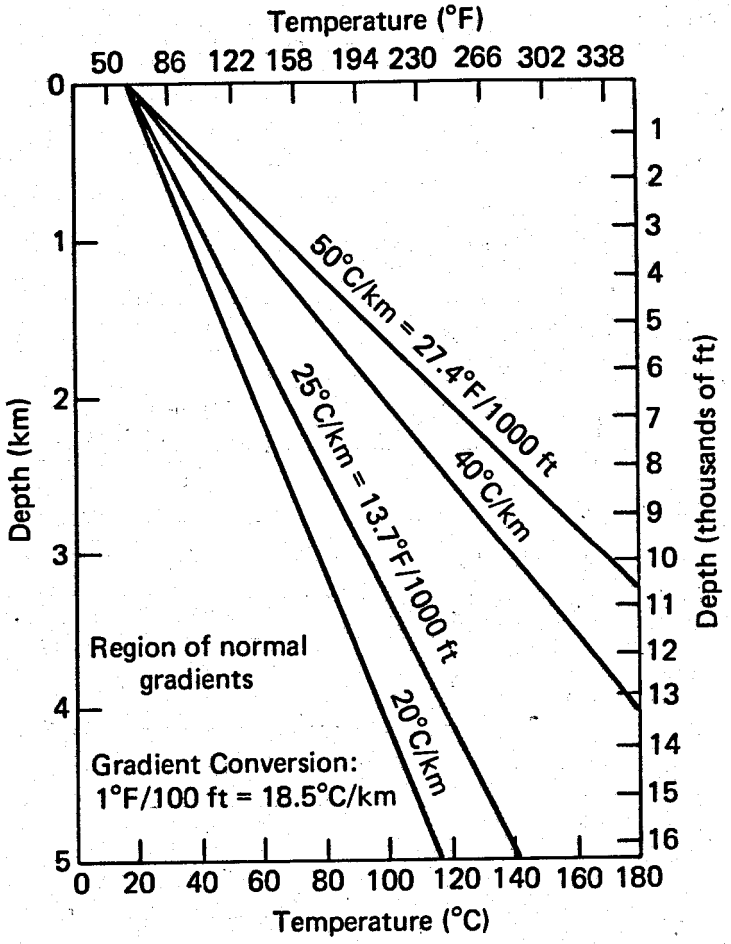
Table 24

Prefixes and Symbols

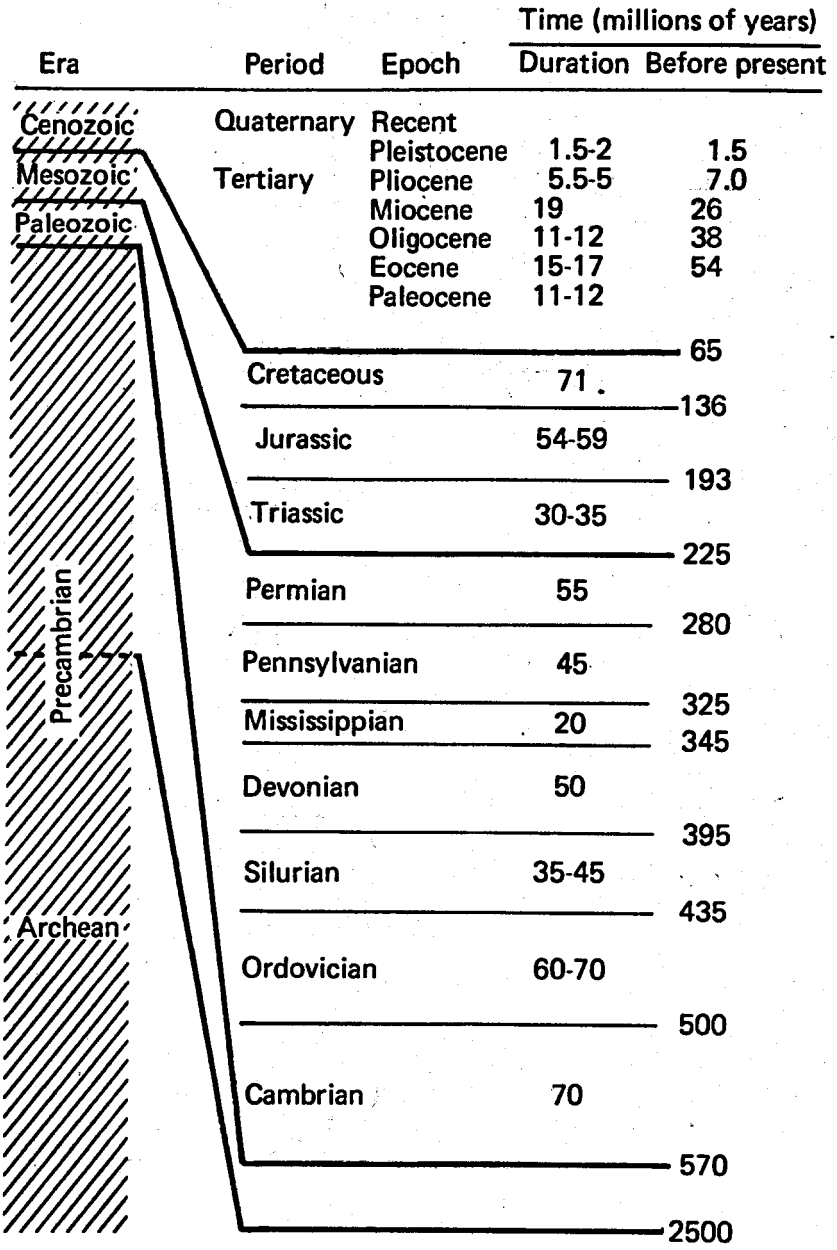
(SI units)*

Factor	Name of Prefix	Symbol	Factor	Name of Prefix	Symbol
10	deka	da	10^{-1}	deci	d
10^{2}	hecto	h	10^{-2}	centi	c
10^{3}	kilo	k	10^{-3}	milli	m
10^{6}	mega	M	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
			10^{-15}	femto	f
			10^{-18}	atto	a

*Also used by the National Bureau of Standards



Temperature versus Depth for Various Gradients, Ground Temperature Assumed to be 17°C


Time (millions of years)
Era
Period
Epoch
Duration
Before present
Cenozoic
Mesozoic
Paleozoic
Precambrian
Archean
Quaternary
Recent
Pleistocene
1.5-2
1.5
Tertiary
Pliocene
5.5-5
7.0
Miocene
19
26
Oligocene
11-12
38
Eocene
15-17
54
Paleocene
11-12
65
Cretaceous
71
136
Jurassic
54-59
193
Triassic
30-35
225
Permian
55
280
Pennsylvanian
45
325
Mississippian
20
345
Devonian
50
395
Silurian
35-45
435
Ordovician
60-70
500
Cambrian
70
570
2500