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Heat Flow and Shallow Thermal Regime

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This subject is extremely broad and touches on many fields of geology and geophysics, some of which are covered in other sections of this report. Our focus is the measurement and interpretation of heat flow. However, information from other fields is noted where it appears to be of interest, but no attempt has been made to search these related areas. *Blackwell*'s [1971*a*] report for the previous quadrennium is our point of departure.

Major highlights and observations for this quadrennium include the following:

1. There is a growing awareness that water circulates deeply within the newly formed crust at ocean spreading centers and that hydrothermal processes may dominate the thermal regime there and to some distance to the sides. Such observations also suggest that the total heat flux (conductive and convective) at the spreading center is considerably higher than that previously supposed and that this may require a substantial upward revision of estimates of the total heat loss from the interior of the earth.
2. We have arrived at a better definition and understanding of continental heat flow provinces based on more heat flow determinations, as well as their better integration with other geological and geophysical observations.
3. Many areas of high heat flow have been discovered in the continents that indicate the existence of shallow magmatic heat sources, the convective transport of heat by groundwater, or both. The explosive interest in the exploration for and the development of such areas for geothermal power has promoted a wide range of geological and geophysical investigations which will give not only a better understanding of geothermal systems as such but a better understanding of a broad range of earth phenomena.
4. Many exciting ideas concerning convective motions in the asthenosphere and deeper mantle and their influences on the lithosphere have been presented. Hot spots, plumes, thermal runaways, and gravitational anchors have been advanced for the explanation of various phenomena. Right or wrong, these notions provide a stimulus for the design of more sophisticated experiments for examination of the mantle.
5. The first heat flow measurements on the moon have been made. As a part of the Apollo 15 and 17 missions, thermal probes were inserted 1–2 m into the lunar regolith, and temperature, thermal conductivity, and heat flow measurements were obtained.

MEASUREMENT OF TEMPERATURE

Few holes were drilled during this quadrennium primarily for the measurement of heat flow, even though information from such holes has provided the more important results to date. Most measurements have been made on an opportunistic basis in holes drilled for other purposes and suffer the uncertainties due to drilling disturbances and water flows along the holes. Such problems have been neatly overcome in the holes drilled for the Deep-Sea Drilling Project (DSDP). A self-contained device that inserts a probe ahead of the coring bit has successfully been utilized to obtain accurate temperatures [*Erickson,* 1973; *Erickson et al.*, 1974].

White et al. [1975] achieved satisfactory results in their drilling in the Yellowstone geothermal area by measuring bottom hole temperatures during interruptions in drilling.

The increased need to determine equilibrium temperatures in deep holes during or very shortly after drilling has led to renewed investigation of the thermal disturbance caused by circulation of drilling fluids and that caused by exchange of fluids with the rocks [*Oxburgh et al.*, 1972; *Keller et al.*, 1973; *Bodvarsson et al.*, 1974]. *Schneider* [1972] gives examples of distortion of the geothermal field in aquifers by pumping.

White [1969] and *White et al.* [1971] reported a novel way to map heat flow in areas of very high heat flow. They observed the retreat of the snow line sometime after snowfall and after suitable calibration obtained a measure of the heat fllux.

THERMAL CONDUCTIVITY

Samples suitable for measurement of conductivity by standard techiques are not available for many holes. This led *Sass et al.* [1971] to develop a technique for the measurement of the conductivity of rock fragments and *Beck et al.* [1971] to reexamine in situ techiques for the determination of thermal properties.

The compilation of thousands of conductivities, densities, and rock types contained in 'Basic Heat-Flow Data From The United States' [*Sass and Munroe,* 1974] is a useful guide to the range of conductivities that might be expected in various rock types and at many localities.

With regard to the conductivities of ocean sediments, *Kasameyer et al.* [1972] found high-conductivity quartz-sand layers in the northwest Atlantic and pointed out that the conductivities of such sediments cannot always be estimated accurately from the water content of sediments by using the empirical curve determined by *Ratcliffe* [1960], a fact earlier noted by *Lachenbruch and Marshall* [1966] in connection with carbonate-rich sediments of the Arctic Ocean. Measurements of the conductivity of cores retrieved from holes drilled hundreds of meters into ocean bottom sediments and basalts have been reported for many of the DSDP sites (see references in section on oceanic heat flow). These results show a range of conductivities that reflects variation in mineralogy and porosity; they also show that conductivities of a given type of sediment tend to increase significantly with depth below the bottom as a consequence of a reduction in porosity due to compaction.

Specialized studies included the conductivity of vesicular basalt [*Robertson and Peck,* 1974], the conductivity of unconsolidated oil sands [*Somerton et al.*, 1974], the conductivity-density relationship for the polymorphs of some silicates and germinates [*Soga et al.*, 1972], the effect of crack porosity on the thermal anisotropy of schists [*Chessman et al.*, 1974], the temperature coefficient of thermal conductivity of ocean sediments [*Macdonald and Simmons,* 1972], the theory of heat conduction in porous media [*Huang,* 1971], and lattice conductivity at high temperature and pressure [*Roufosse and Klemens*, 1974].

A knowledge of the radiative component of thermal conductivity of temperatures, pressures, and mineralogies prevailing in the mantle is important in determining the distribution of temperature in the mantle and for examining thermal instabilities that may exist there. Significant advances in this complex field continue to be reported [*Mao and Bell*, 1971, 1972; *Schatz and Simmons*, 1972; *Gaffney*, 1972, 1973; *Shankland et al.*, 1974].

RADIOACTIVE HEAT GENERATION

As a consequence of the discovery that heat flows measured in continental plutonic rocks (within a given heat flow province) are linearly related to the radioactive heat production of those rocks [*Birch et al.*, 1968; *Roy et al.*, 1968; *Lachenbruch*, 1968], the distribution of radioactive heat production in the crust continues to receive considerable attention [*Tilling et al.*, 1970; *Lachenbruch*, 1971; *Smithson and Heier*, 1971; *Lachenbruch and Bunker*, 1971; *Turcotte and Oxburgh*, 1972; *Smithson and Decker*, 1973]. Several localities have been the subject of special study: Idaho batholith [*Swanberg*, 1972; *Swanberg and Blackwell*, 1973], Sierra San Pedro Martir of Baja California [*Smith et al.*, 1971, 1974], Boulder batholith [*Tilling*, 1973, 1974], and Norway [*Swanberg et al.*, 1974].

OCEANIC HEAT FLOW

Groups of heat flow measurements have been reported, often along with other geophysical information, in many areas: the Reykjanes ridge [*Talwani et al.*, 1971], as well as other parts of the mid-Atlantic ridge [*Kasameyer et al.*, 1972*b*] and the Atlantic Ocean [*Sclater et al.*, 1971; *Von Herzen and Simmons*, 1972; *Schubert and Peter*, 1974]; the Cascadia basin off the Oregon coast [*Korgen et al.*, 1971]; the southwestern Pacific [*Sclater*, 1972*b*; *Sclater et al.*, 1972]; the western equatorial Pacific [*Halunen and Von Herzen*, 1973]; Melanesia [*Macdonald et al.*, 1973]; the Galapagos spreading center [*Sclater and Klitgord*, 1973; *Detrick et al.*, 1974; *Williams et al.*, 1974; *Sclater et al.*, 1974]; the eastern equatorial Pacific [*Von Herzen and Anderson*, 1972]; and the Gulf of California [*Lawver et al.*, 1973].

The holes drilled several hundred meters into the ocean bottom by the R/V *Glomar Challenger* as part of the DSDP provided opportunity for heat flow measurements at depths much greater than those sampled by the oceanic probe technique (typically <5 m). Many successful measurements have been made [*Burns*, 1970; *Von Herzen et al.*, 1971; *Erickson*, 1973; *Von Herzen*, 1973; *Sclater and Erickson*, 1974; *Girdler et al.*, 1974; *Marshall and Erickson*, 1974; *Hyndman et al.*, 1974]. These measurements generally agree with those obtained by the short-probe technique. Moreover, they do not show any consistent variation of heat flow with depth such as might be caused by long-term variation of bottom water temperature or upward migration of interstitial fluids [*Erickson et al.*, 1974].

For convenience of discussion the ocean basins might be divided into four heat flow provinces: spreading centers, subduction zones including the high heat flows over the deeper part of the subducted slab, the regions between the aforementioned, and the intraplate island chains and aseismic ridges.

A growing body of evidence suggests that oceanic water circulates deeply within the freshly formed lithosphere at and near the spreading centers [*Talwani et al.*, 1971; *Lister*, 1972, 1974; *Bodvarsson and Lowell*, 1972; *Williams et al.*, 1974; *Williams and Von Herzen*, 1974]. The evidence is of two kinds: (1) Although many high conductive heat flows are observed near the ridges, their averages are far too low to account for the amount of heat that must be released there according to any reasonable model for the generation of new lithosphere (see reference for earlier work in the article by *Blackwell* [1971*a*] and those references cited above and below as well as *Hanks* [1971], *Heirtzler* [1972], and *Parker and Oldenburg* [1973]). In addition, the pattern of heat flow variations and its relation to topography near the spreading center appears to require hydrothermal circulation in the crustal rocks [*Williams et al.*, 1974]. (2) The rocks exhibit hydrothermal alteration [*Miyashiro et al.*, 1971; *Corliss*, 1971; *Anderson*, 1972; *Christensen and Salisbury*, 1972; *Dymond et al.*, 1973; *Piper*, 1973; *Salisbury and Christensen*, 1973; *Nishimori and Anderson*, 1974; *Scott et al.*, 1974]. Moreover, it has been shown that the heats of hydration, dehydration, and oxidation reactions caused by circulating water are not trivial with respect to radioactive heat production [*Anderson*, 1972; *Fyfe*, 1974] and could significantly affect heat flow.

Consideration of the total heat flux (both conductive and convective) near the spreading centers leads to a significant increase in estimates of the total heat flow from the earth (see *Sclater and Francheteau* [1970] for earlier references; also see *Williams and Von Herzen* [1974] and *Williams et al.* [1974]).

The thermal regime of subducted lithospheric plates [*McKenzie*, 1969; *Minear and Toksöz*, 1970] continued to receive much attention, and considerable additional effort has been made to characterize the thermal aspects of subduction [*Hanks and Whitcomb*, 1971; *McKenzie*, 1971; *Minear and Toksöz*, 1971; *Toksöz et al.*, 1971; *Griggs*, 1972; *Turcotte and Schubert*, 1973]. Partial melting and penetrative convection of melts above the subducted layer have recently been considered by *Oxburgh and Turcotte* [1971] and *Wyllie* [1971*a*, *b*].

As the lithosphere moves away from the spreading centers, it cools primarily by conduction and becomes denser and thicker. As a consequence, heat flow and bottom elevation systematically decrease with the age of lithosphere (see for an example *Sclater* [1972*b*] and many of the references above for the history of the evolution of these ideas). Furthermore, seismic velocities increase with age in the lithosphere [*Hart and Press*, 1973; *Kausel et al.*, 1974], and the lithosphere thickens with age [*Leeds et al.*, 1974].

Heat flow and elevation of the ocean floor decrease with distance from the spreading centers, and for most regions the decreases are similar functions of age of the lithosphere. However, some regions may be anomalous; *Langseth and Zielinski* [1975] note that Iceland is at the midpoint of a vast region of high heat flow which correlates with shallow depths and positive free-air gravity anomalies. Here, heat flow is anomalously high with respect to the age of lithosphere. They suggest that the spreading plates may not be moving apart fast enough to dissipate the heat flow from the mantle and that the anomalous conditions including the Icelandic 'hot spot' may result from some constraints on plate motion.

MANTLE HOT SPOTS, PLUMES, AND CONVECTION

Wilson [1963] first advanced the idea that chains of volcanic islands and seismic ridges formed as the lithosphere moved over fixed hot spots in the mantle. *Morgan* [1971, 1972*a*, *b*] further developed and quantified this hypothesis and suggested that the hot spots were the surface expressions of narrow plumes some 150 km across, rising at a rate of about 2 m/yr from the deepest part of the mantle. Other causal mechanisms for the hot spots (or melting anomalies, as *Shaw and Jackson* [1973] would prefer to call them) have been advanced: propagating fractures [*Jackson and Wright*, 1970; *McDougall*, 1971], rheological intrusion [*Green*, 1971], shear melting [*Shaw*, 1973], bumps on the asthenosphere [*Menard*, 1973], and thermal runaways [*Anderson and Perkins*, 1974]. It is not clear which mechanisms are dominant or whether various types of hot spots may result from different mechanisms. Insofar as the island chains are concerned, additional radiometric ages, paleomagnetic evidence, and petrologic investigations may resolve some of the uncertainties [*Jackson et al.*, 1972; *Dalrymple et al.*, 1973].

Other aspects of mantle convection have been considered by *Elsasser* [1971*a*, *b*], *Hughes* [1971], *Ichiye* [1971], *Rice* [1971], *Torrance and Turcotte* [1971], *Turcotte and Oxburgh* [1972], *Shubert and Turcotte* [1972], and *Nitsan* [1973]. *Turcotte* [1975] considers many of the problems in more detail.

CONTINENTAL HEAT FLOW

The most recent syntheses of heat flow data were made by *Blackwell* [1971*b*], *Sass et al.* [1971], *Diment et al.* [1972], and *Roy et al.* [1972]. Thermal models for the continental crust and for upper mantle have also been given by *Herrin* [1972] and *Smithson and Decker* [1974]. *Slack* [1974] examined the variance in heat flow between the North American craton and the Canadian shield. The basic heat flow data (temperature, conductivity, heat production, rock type, and terrain) for many of the measurements are given in a compilation by *Sass and Munroe* [1974], which contains chapters authored by those cited in the references.

Substantial recent additions have been made in conterminous United States by *Blackwell* [1974*b*], *Bowen* [1973], *Blackwell and Robertson* [1973], *Combs and Simmons* [1973], *Costain and Wright* [1973], *Decker* [1972], *Decker and Smithson* [1973], *Hartman and Reiter* [1972], *King and Simmons* [1972], *Reiter and Costain* [1973], *Scattolini and Howell* [1974], and *Smithson and Decker* [1972]. Other studies have been made in Greenland [*Sass et al.*, 1972], Panama and Columbia [*Sass et al.*, 1974], Canada [*Sass et al.*, 1971], Antarctica [*Decker*, 1974; *Pruss et al.*, 1974], Norway [*Swanberg et al.*, 1974], east African lakes [*Von Herzen*, 1972], Swiss lakes [*Von Herzen et al.*, 1973], and Africa [*Chapman and Pollack*, 1972, 1974*a*, *b*].

In the petroleum-producing areas of North America, subsurface temperatures are now much better known. Many individuals, acting under the aegis of The American Association of Petroleum Geologists (AAPG), have compiled the bottom hole temperature records for more than 25,000 wells along with the appropriate mean annual surface temperatures. These data have been digitized and are available on tape, card, or printout from AAPG. Derived from these data are the following: (1) two maps covering North America on a scale of 1:5,000,000, the first being the Geothermal Gradient Map of North America [*AAPG-USGS*, 1975] and the second showing the depths to the 70°C, 100°C, and 150°C isotherms; (2) a series of computer-drawn gradient maps on a scale of 1:1,000,000, which are available from AAPG (reports of compilation procedures and interpretation are available now only in abstract form [*Gould*, 1974; *Kehle and Schoepel*, 1974; *Shelton et al.*, 1974]). Some temperature or temperature gradient maps have been produced for individual states or regions: Montana [*Balster*, 1974], the Illinois basin [*Cartwright*, 1970], Florida [*Reel and Griffin*, 1971], Arizona [*Scurlock and Conley*, 1972], and New Mexico [*Summers*, 1972].

A major objective of continental heat flow studies has been a better definition and understanding of the heat flow provinces and of the boundaries between them. In this regard, other geophysical techniques have yielded important results relevant to temperature distribution within the deep crust and uppermost mantle: electrical conductivity measurements by various deep sounding techniques [*Camfield et al.*, 1971; *Porath and Gough*, 1971; *Zohdy and Stanley*, 1972; *Keller*, 1974], seismic wave velocities and attenuation [*Solomon*, 1972; *Ryall*, 1974], seismicity and tectonics [*Scholtz et al.*, 1971; *Sbar et al.*, 1972; *Freidline et al.*, 1974; *Howell*, 1974; *Smith and Sbar*, 1974], and Currie temperature depth determination from aeromagnetic data [*Shuey et al.*, 1974].

CONTINENTAL ANOMALIES

The recently rifted areas of the United States such as the Salton trough [*Combs*, 1971, 1972; *Combs and Rex*, 1971; *Combs and Muffler*, 1973; *Elders et al.*, 1972], the Snake River plain [*Urban and Diment*, 1975], and the Rio Grande rift [*Hartman and Reiter*, 1972; *Reiter et al.*, 1975; *Smithson and Decker*, 1972] exhibit high and variable heat flow. At least some of the highest values are the result of hydrothermal convection at depth.

Exceptionally high values have been observed near Marysville, Montana [*Blackwell and Bagg*, 1973; *Blackwell*, 1974*b*], where there are no other proximal manifestations of recent geothermal activity. However, preliminary results from deep drilling (2050 m) indicate that the anomaly may be the result of circulation of hot water in fracture zones [*Blackwell*, 1974*c*].

The Long Valley caldera just east of the Sierra Nevada in central California exhibits recent igneous activity and abundant hot springs of high geochemical temperature and is regarded as a likely place for the production of geothermal power. The results of a wide range of geological and geophysical investigations are available in abstract form in *EOS* (volume 54, pp. 1211–1213) or as U.S. Geological Survey open file reports and will be published shortly [*Anderson and Johnson*, 1975; *Bailey et al.*, 1975; *Hill*, 1975; *Hoover et al.*, 1975; *Iyer and Hitchcock*, 1975; *Kane et al.*, 1975; *Lachenbruch and Sass*, 1975; *Lachenbruch et al.*, 1975; *Mariner and Willey*, 1975; *Sorey and Lewis*, 1975; *Stanley et al.*, 1975; *Steeples and Iyer*, 1975; *Steeples and Pitt*, 1975].

An equally broad and impressive array of investigations is underway at the hot spot in Yellowstone, Wyoming [*Armstrong*, 1974; *Christiansen*, 1974; *Eaton et al.*, 1974; *Iyer et al.*, 1974; *Leary and Phinney*, 1974; *Morgan et al.*, 1974; *Otis et al.*, 1974; *Pitt*, 1974; *Reynolds and Larson*, 1974; *Rinehart*, 1974; *Smith and Shuey*, 1974; *Smith et al.*, 1974; *Truesdell*, 1974; *White et al.*, 1971, 1975; *Wold et al.*, 1974].

Continued investigations of heat flow in the vicinity of the San Andreas fault system do not show high values associated with individual faults but rather a broad region of high heat flow. The measurements, as well as the constraints that they impose on the thermomechanical models of the fault system, are given by *Henyey and Wasserberg* [1971] and *Lachenbruch and Sass* [1973].

GEOTHERMAL ENERGY

Much of the impetus for recent heat flow studies stems from the importance of the earth as a source of heat for the generation of electrical power and for heating applications. Taken as a whole, the subject encompasses broad areas of both the geological and the engineering sciences, some aspects of which are covered in other sections of this report. We shall not delve into the technology of extraction, production of power, economics, or resources [see for an example *Grose*, 1971, 1972; *Grossling*, 1972; *Armstead*, 1973; *Kruger and Otte*, 1973; *Hubbert*, 1973; *Muffler*, 1973; *Koenig*, 1973; *Rex and Howell*, 1973]. Rather, we shall briefly note recent progress in understanding geothermal systems and techniques used in exploring for them.

Two basic types of natural hydrothermal systems have been identified: vapor-dominated ('dry steam') systems and hot water systems [*White et al.*, 1971; *White*, 1973]. Although the latter may evolve into the former, the vapor-dominated systems are rare. The best known are Larderello, Italy, and the Geysers, California [*White et al.*, 1971; *Garrison*, 1972; *Budd*, 1973; *Stanley and Jackson*, 1973; *Urban et al.*, 1975; *McLaughlin*, 1974].

The temperatures and pressures in the steam reservoir at both localities are near those for the maximum enthalpy of steam (~240°C and 33 bars). The fact that reservoir pressures are far below hydrostatic at production depths (up to ~3 km at the Geysers) requires an effective seal around the reservoir to prevent flooding by groundwater. Self-sealing mechanisms and rock alteration for both hot water and vapor-dominated systems have most recently been discussed by *White et al.* [1971], *Bargar et al.* [1973], and *White* [1973].

Hot water systems are much more numerous, and several subtypes have been recognized [*White*, 1973] on the basis of their chemistry, temperature, and geologic environment. Among other things, it is notable that many hot water systems exhibit a 'base temperature' [*Bodvarsson*, 1970] in their deeper parts that changes little with depth. This indicates transport of heat by convection. In some systems the base temperature is close to the boiling point curve for water, which may be considerably elevated by the presence of large amounts of dissolved solids [*Haas*, 1971]. Thus in the Cerro Prieto system of Baja California, temperatures as high as 388°C have been observed [*Mercado*, 1973; *White*, 1973].

Considerable attention has been given to the theoretical aspects of convection in porous media and to numerical modeling thereof [*Kassoy*, 1972; *Mercer and Pinder*, 1973; *Cheng and Lau*, 1974; *Sorey*, 1974].

Many regions of anomalously high near-surface temperatures do not possess sufficiently high fluid content or permeability to be exploited for geothermal power. Hydraulic fracturing of the rocks and forced circulation of fluid have been proposed as a means for extracting power [*Harlow and Pracht*, 1972; *Raleigh et al.*, 1974; *Smith et al.*, 1973, 1974]. Stimulation by explosions has also been suggested [*Austin and Leonard*, 1973; *Burnham and Stewart*, 1973; *Ramey et al.*, 1973].

Active volcanos would seem to be likely places to look for geothermal energy, but difficulties are formidable. Moreover, little is known of their hydrothermal regimes. The first deep drill hole (1262 m) at the summit of an active volcano was drilled at the Kilauea volcano, Hawaii, in 1973 [*Keller et al.*, 1974] at a site above a shallow (3–4 km) magma chamber inferred from ground deformation and microseismicity studies [*Kinoshita et al.*, 1975] and electrical resistivity surveys [*Jackson and Keller*, 1972]. Preliminary results from the geophysical logging [*Keller et al.*, 1974*b*; *Zablocki et al.*, 1974] indicate an isothermal zone from surface to water table (~500 m), a rather abrupt increase in temperature to 80°–90°C, a temperature reversal, and a steep gradient in the lower part of the hole (370°C/km) which suggest approach to hotter rock below.

Many types of information have been used in the search for geothermal resources: (1) the distribution and characteristics of hot springs [*Waring*, 1965; *Wright*, 1971; *Olmsted et al.*, 1973; *Tellier*, 1974; *Olmsted and Van Denburgh*, 1974]; (2) geochemical indicators of subsurface temperatures [*Barnes et al.*, 1973; *Barnes and Miller*, 1974; *Fournier*, 1973; *Fournier and Truesdell*, 1973, 1974*a*, *b*; *Fournier et al.*, 1974; *Mariner et al.*, 1974*a*, *b*; *White*, 1973; *White et al.*, 1973; *Rightmire and Truesdell*, 1974; *Wollenberg*, 1974; *Rowe et al.*, 1973]; (3) the distribution of post-Miocene silicic volcanic rocks [*Smith and Shaw*, 1973; *Bailey et al.*, 1975; *Walker*, 1974; *Walker et al.*, 1974]; and (4) various geophysical techniques (enumerated by *Combs and Muffler* [1973] and *Ward et al.* [1974]), including shallow temperature and heat flow measurements [*Olmsted et al.*, 1973; *Combs*, 1971; *Combs and Muffler*, 1973], microearthquake observations [*Ward and Bjornsson*, 1971; *Ward and Jacob*, 1971; *Ward*, 1972; *Hamilton and Muffler*, 1972], seismic noise measurements [*Douze and Sorrells*, 1972; *Goforth et al.*, 1972; *Iyer and Hitchcock*, 1974], seismic body wave studies based on teleseismic and local events [*Matumoto*, 1971; *Iyer*, 1974; *Iyer et al.*, 1974; *Pitt*, 1974], and various techniques for determining the subsurface distribution of electrical resistivity (see references cited in connection with specific areas and *Keller* [1970] and *Macdonald and Muffler* [1972]).

THE MOON

Details of the Apollo 15 lunar heat flow experiment and preliminary results of the experiment are given by *Langseth et al.* [1972*a*], who find that preliminary measurements from the two instrumented holes, which penetrate the lunar surface by about 1 m, indicate a considerable increase in thermal conductivity with depth [see also *Langseth et al.*, 1972*b*; *Keihm et al.*, 1973] and suggest a heat flow at this locality of about half that for the earth and therefore somewhat higher than would be expected from models based on the radioactive heat production of the classes of meteorites usually used to construct such models.

Heat flows obtained from the Apollo 17 site [*Langseth et al.*, 1973; *Langseth and Keihm*, 1974] from 2.3-m holes are somewhat lower (2.2×10^{-6} W/cm^2) but the same within experimental error as those obtained from the Apollo 15 site (3.1×10^{-6} W/cm^2).

Information relevant to the thermal properties of near-surface lunar materials has been given by *Cremers and Birkebak* [1971], *Pilbeam and Vaišnys* [1973], *Langseth et al.* [1974], and *Keihm and Langseth* [1975].

Many models for the temperature distribution within the moon and its thermal history have been advanced recently [*Duba et al.*, 1972; *McConnell and Gast*, 1972; *Toksöz et al.*, 1972; *Turcotte et al.*, 1972; *Anderson*, 1973; *Arkani-Hamed*, 1973; *Cassen and Reynolds*, 1973; *Murthy and Banerjee*, 1973; *Sonett and Runcorn*, 1973; *Toksöz and Solomon*, 1973].

OTHER TOPICS

As a consequence of petroleum exploration and pipeline construction in the Arctic, permafrost has received renewed attention. *Gold and Lachenbruch* [1973] presented an excellent review of thermal conditions in permafrost. *Lachenbruch* [1970] examined the thermal effects of a heated pipeline in permafrost.

Subsurface storage or disposal of radioactive wastes continues to receive attention. Some thermal aspects have been considered by *Mulfi* [1971, 1972] and *Sullivan and Greer* [1972].

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High-Temperature Flow of Rocks

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A lot of activity has taken place in this area of tectonophysics during the last quadrennium, all of which has led to a much more fundamental understanding of the mechanical behavior and deformational processes of rocks undergoing flow in the crust and upper mantle. The most important advancements have come in the following areas: (1) direct observations of dislocation configurations and substructure in several important rock-forming minerals deformed both experimentally and in natural environments, (2) determinations of preferred crystal orientations resulting from plastic deformation and from syntectonic and annealing recrystallization, (3) determinations of flow laws for several important types of aggregates undergoing steady state flow in laboratory experiments, and (4) detailed investigations of the internal structure of certain alpine-type peridotites and of textures and deformational processes in peridotite xenoliths from the upper mantle. This information has provided the basis for preliminary interpretations of the creep state of the upper mantle as well as a better understanding of the origin of certain crustal structures.

PLASTIC DEFORMATION AND RECOVERY

Perhaps the most significant advance in high-temperature rock deformation in recent years has been direct observations of dislocations in deformed rocks using transmission electron microscopy (TEM). This advance has been made possible by the development of ion-thinning sample preparation techniques in which the center of a disc of rock is reduced by argon ion bombardment until it is sufficiently thin for penetration of electrons [*Barber*, 1970; *Heuer et al.*, 1971; *Gillespie et al.*, 1971]. Most of the TEM investigations have confirmed major processes deduced from optical studies, which should still be the first step in analysis of microstructures and textures, but have provided important additional information on the nature of imperfections and on substructure not resolvable by optical microscopes.

Quartz. Most of the recent work on quartz has been conducted on experimentally deformed synthetic single crystals, although some work has been done on natural crystals and on naturally deformed aggregates. In these studies, attention has been focused mainly on substructures associated with deformation lamellae in attempts to determine the origin of those elusive but ubiquitous features that have intrigued sicentists for decades. *Ave'Lallemant and Carter* [1971] found a strong pressure dependence of lamellae orientations in experiments on quartzite, in accord with the earlier work of *Heard and Carter* [1968], who also found a strong temperature and strain rate dependence. *Tullis et al.* [1973] also observed the temperature and strain rate dependence and noted further that lamellae orientations are influenced by strain in specimens deformed at low temperatures and/or high strain rates. *Gay* [1974], in experiments on quartzite containing abundant lamellae, found that deformation bands formed at the expense of subbasal lamellae and zones of undulatory extinction when the quartzite was deformed at conditions near the brittle-ductile transition.

McLaren et al. [1970], in TEM studies of lamellae in synthetic quartz, found narrow bands of tangled dislocations parallel to the lamellae and interpreted the bands as subgrain boundaries. They suggested that the basal lamellae produced earlier by *Christie et al.* [1964] were not due to elastic strains from dislocation arrays as proposed but were plane phase objects (artifacts resulting from objects smaller than the resolving power of optical microscopes and devoid of any information about the object). A similar interpretation was applied by *McLaren and Hobbs* [1972] to natural lamellae in three quartzites from Australia and by *White* [1973] to natural lamallae in a mylonite from the Outer Hebrides. *Green and Radcliffe* [1972*a*], who found arrays of dislocations parallel to deformation lamellae in experimentally deformed olivine, objected to the plane phase object interpretation by analogy and pointed out that *McLaren et al.* [1967] had earlier observed straight mixed dislocations parallel to basal lamellae in the specimens of *Christie et al.* [1964]. They also noted that the synthetic crystals deformed by *McLaren et al.* [1970] were deformed in the hydrolytically weakened regime [*Griggs and Blacic*, 1965; *Griggs*, 1967, 1974] and that the structures produced in synthetic quartz under such conditions are very different from those in naturally deformed quartz and in natural quartz deformed experimentally. *Twiss* [1974], in his TEM study of