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The Deep Structure of Continents

Heat-flow and gravity observations and satellite data shed light on the origin of continents and oceans.

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The structures of continents and ocean basins differ dramatically at and near the surface. Recent evidence indicates that large-scale differences are not restricted to the upper layers but extend to depths of several hundred kilometers. We cannot, of course, directly observe that continents extend to great depths; it is a conclusion demanded by the analysis of many heat-flow and gravity observations scattered over the surface of the globe, combined with new and important information secured from observations of artificial earth satellites. The recently discovered deep structure of continents throws new light on the classical problems of the origin of continents and ocean basins and of the stability of continents over geologic time.

The density of surface rocks in oceanic areas, on the average, exceeds that of continental rocks. Seismological research has established that the thickness of the low-density crustal material in continents exceeds that of oceanic areas by a factor of 5 to 8. This conclusion, when considered along with the known topography of continents and ocean basins, implies that a real difference in mean density must exist between a column under a continent and one under an ocean. The determination of gravity measures, in a reasonably precise way, the mass per unit area of the subjacent earth. Measurements on the surface and measurements obtained through satellite observation establish that, on the average, gravity over continents equals gravity over oceans, and consequently that the mass per unit area is the same beneath the water and beneath the land, despite great differences in surface density. Only differences in density of deeply buried material can compensate for the observed inequalities at the surface.

Simultaneous determinations of the temperature gradient and thermal conductivity in rocks accessible from the surface measure the rate at which heat escapes from the interior of the earth. On the average, the outward flow of heat in continental areas equals that through the ocean bottom. But the thick continental crust contains far more of the heat-producing radioactive elements than the thin basaltic oceanic crust does, so in order to account for the observed equality of heat flow at the surface, I assume that differences in radioactive composition of mantle material extend to depths on the order of hundreds of kilometers.

Clearly, then, both the gravity and the heat-flow observations imply differences at depth between continents and oceans. Seismology can provide some direct evidence of these dissimilarities. As yet, the evidence is meager but suggestive. Surface waves show continent-ocean changes in velocity down to a depth of 500 kilometers (*1*). Moreover, no earthquake foci have been found below 720 kilometers; thus, thermal stresses are of larger magnitude above this depth than below it. Indeed, Benioff argues that the striking localization of deep earthquakes at the continent-ocean boundary demonstrates that continents have deep structure (*2*).

Finally, the balance of mass and of heat-producing elements between continent and ocean basin tells us much about continent-forming processes. The equality of heat flux rules out the possibility that the continental crust formed as a surface scum swept into place by internal convection, a mechanism that sometimes has been proposed. On the contrary, the average equality of mass and heat flow argues for dominant vertical segregation of material in continent formation; large-scale horizontal convection transport has played only a minor role.

Let us now consider the bases for the foregoing assertions.

Flow of Heat from the Earth's Interior

Bullard found in the Atlantic, and Revelle and Maxwell in the Pacific, that the heat flow in the two oceans was of the same order as the flux in continental areas (*3*). Since then, over 1000 determinations of heat flow, scattered over the surface of the globe, have confirmed this finding. Lee and I (*4*) have analyzed over 900 measurements of surface heat flow. An orthogonal-function representation of 757 values yields a global mean of 63.9 $\pm$ 3.4 erg $cm^{-2} sec^{-1}$. The average over continents is 68.9 erg $cm^{-2} sec^{-1}$, while the average over oceans is 62.0 erg $cm^{-2} sec^{-1}$. The averages represent 92 continental measurements and 665 oceanic measurements. These averages suggest that

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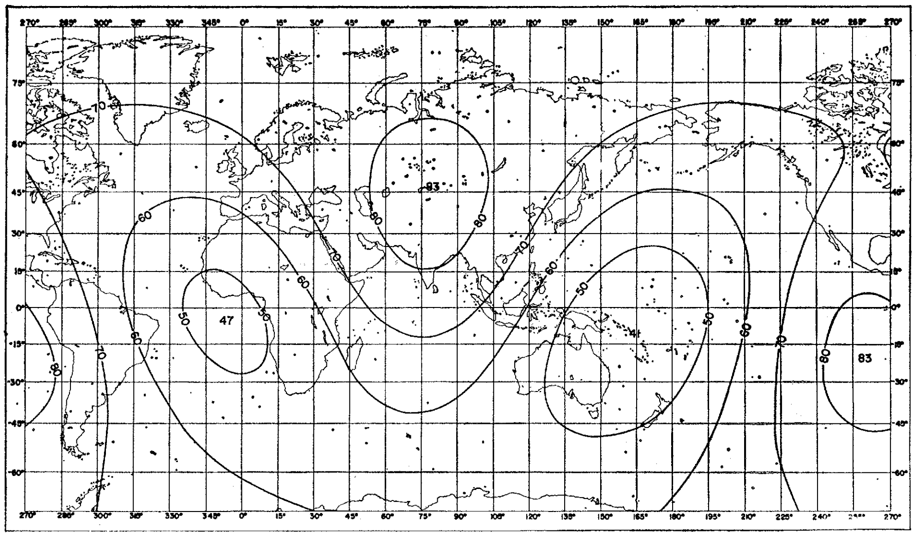


Fig. 1. Orthogonal-function representation of 757 heat-flow values (*4*). Contours are in ergs cm^{-2} sec^{-1}; 92 of the measurements are in continental areas, 665 are in oceanic regions.

the heat flow over continents exceeds that over oceans, but the difference is not significant at the 95-percent level of confidence. In assessing the measurements for continents and oceans, one should note that the measurements for the oceans represent samples that are largely uncorrelated with ocean-bottom conditions. In contrast, observers have avoided hot springs and other thermal regions in making continental observations.

While the principal result of the thermal investigations shows that heat flows through continents and oceans do not differ, on the average, a number of anomalous regions have been discovered. Figure 1 shows the large-scale regional variations in heat flow derived through harmonic analysis of the available data. This analysis averages out many of the fine variations that exist in the heat-flow field; nevertheless, on the average, the heat flow is high in the eastern Pacific and low in the western Pacific and in the Atlantic. The lack of adequate measurements makes the indicated high for central Asia most uncertain.

Since the heat flows through the continental surface and ocean bottoms are approximately equal, and since the heat productions of the surface rocks in the two regions are different, the consequent differences in the vertical distribution of radioactive material require quantitative examination. Let Q_0 represent the surface heat flow. The equilibrium heat flow at a depth z in a homogeneous material is then $Q(z) = Q_0 - Az$, where A is the heat production per unit volume. To evaluate A at the base of the crust, we need to know the near-surface structure and the heat production of common rock types. In Table 1 are listed typical continental structures. The content of radioactive elements in common rock types varies appreciably. In Table 2 are listed average values obtained by Tilton and Reed (*5*). In Table 2 the thorium-to-uranium ratio is taken to be 3.7.

Let us suppose that the values for "intermediate rock" of Table 2 represent the heat production in the continental crust. The range of heat productions given in Table 2 corresponds to a heat production of between 30 and 60 erg cm^{-2} sec^{-1}. Since the continental heat flow is 69 erg cm^{-2} sec^{-1}, the heat flowing from below at a depth of 30 to 40 kilometers is between 9 and 39 erg cm^{-2} sec^{-1}. The difficulties in correctly assessing the relative contributions of the various rock types contribute to the large uncertainty in the value for the heat flowing into the base of the continental crust. In the ocean, the material above 35 kilometers produces heat at a rate of 3.4 to 5.3 erg cm^{-2} sec^{-1}; if the volcanic material is basalt, the sediments have a radioactivity of intermediate rock and the subcrustal material is eclogite. A flux in oceanic regions of 62 erg cm^{-2} sec^{-1} implies that between 56 and 59 erg cm^{-2} sec^{-1} must be flowing from the interior into the region above 35 kilometers. The difference in flux between continents and oceans at a depth of 35 kilometers is, then, between 17 and 50 erg cm^{-2} sec^{-1}. Even when we take the extreme limits of error in the values of heat production and heat flow as a basis of calculation, we find a considerable difference in the amounts of heat flowing into the crust beneath land and beneath the sea. The difference in outward heat flow at a depth of 35 kilometers implies deep-

Table 1. Distribution of mass in crust. [Lines 1 to 5, after Worzel and Shurbet (*15*); lines 6 to 10, after Hess (*16*)]

Unit	Oceanic crust: Unit density ($g\ cm^{-3}$)	Thickness (km)	Surface density ($g\ cm^{-2}$)	Continental crust: Unit density ($g\ cm^{-2}$) Crust	Unit density Mantle	Thickness (km)	Surface density ($g\ cm^{-2}$)
Water	1.03	5	5.15×10^5	2.84		33	9.37×10^6
Sediment	2.30	1	2.30×10^5				
Volcanic rock	2.84	4.5	1.28×10^6				
Mantle	3.27	22.5	7.36×10^6				
Total		33	9.37×10^6			33	9.37×10^6
Water	1.03	5	5.15×10^5	2.85		34	9.69×10^6
Sediment	2.3	1.3	2.99×10^5		3.31	6	2.08×10^6
Serpentine	2.8	4.7	1.32×10^6				
Mantle	3.325	29	9.64×10^6				
Total		40	1.18×10^7			40	1.18×10^7

Table 2. Heat production in rocks and chondritic meteorites (*16*).

Rock	Average concentration (parts/10^6): Uranium	Potassium	K/U	Average total heat production ($erg\ g^{-1}\ yr^{-1}$)	Approximate range in heat production ($erg\ g^{-1}\ yr^{-1}$)
Granite	4.0	35,000	8.7×10^3	285	220–300
Intermediate	2.0	18,000	9.0×10^3	143	100–200
Basalt	0.8	7,500	9.4×10^3	58	50–80
Eclogite	.043	530	1.2×10^4	3.2	
Peridotite	.006	10	1×10^4	0.38	
Dunite	.001	10	1×10^4	.08	
Chondrite	.011	830	7.5×10^4	1.56	

seated differences in temperature under continents and under oceans: these, in turn, will produce inequalities in density if the materials underlying the continents and oceans are identical in composition and phase. Temperatures under the oceans should be higher, and if the subcontinental and oceanic mantles are identical in bulk composition and phase, then the oceanic areas should stand higher than the continental regions. I shall return to this paradox.

The Earth's Gravity Field

Studies of the earth's gravity field have long since shown that the amount of mass under continents very nearly equals that under oceans (*6*). Knowledge of the earth's gravity field has increased significantly in recent years, principally through observation of close satellite orbits. These studies establish regional variations in gravity, over large horizontal distances, which cannot be accounted for in terms of the near-surface crustal structure.

A representation of the external gravitational potential of the earth is

$$U = \frac{GM}{r}\left\{1 - \sum_{n=2}^{\infty}\left(\frac{R}{r}\right)^n \left[J_n P_n(\sin\theta) + \sum_{m=1}^{n} \times (J_n^m \cos m\lambda + K_n^m \sin m\lambda)\, P_n^m(\sin\theta)\right]\right\}$$

where R is the mean equatorial radius; P_n^m is the associated Legendre function; θ is the geocentric latitude; λ is the longitude; G is the gravitational constant; M is the mass of earth; and r is the geocentric distance. The coefficients J_n^m and K_n^m are dimensionless quantities weighting the contribution of each harmonic in the external gravitational potential. The coefficients can be obtained from data on the orbits of artificial earth satellites. The estimates of Kozai and of Kaula (*7*) are given in Table 3.

If the earth were a fluid devoid of strength, the odd-order zonal harmonics (n odd, $m = 0$) would vanish, and the earth's rotation and its internal distribution of density would determine the even-order harmonics. The difference between the observed values and the values appropriate for a fluid earth rotating at the same velocity and having the same density distribution as the real earth is shown in Table 3, column 3.

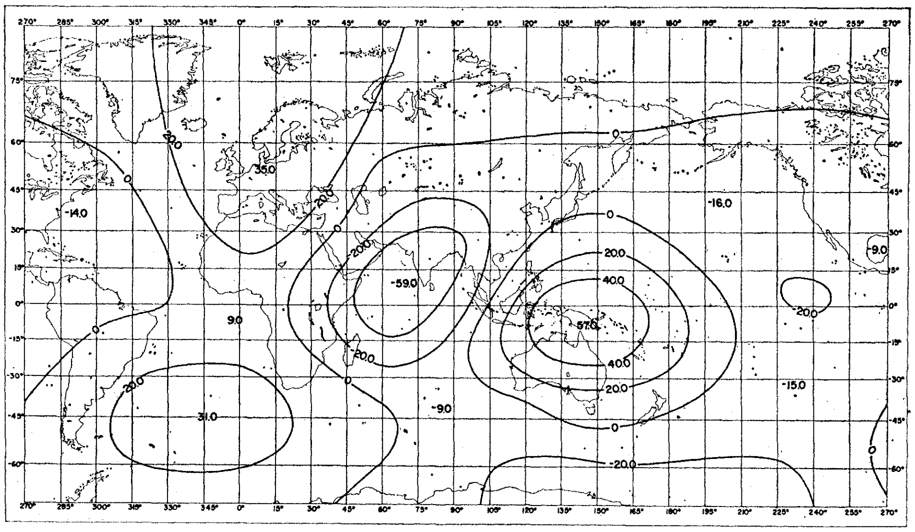


Fig. 2. Geoid heights (in meters) relative to an ellipsoid with a flattening of 1/298.3 (*7*).

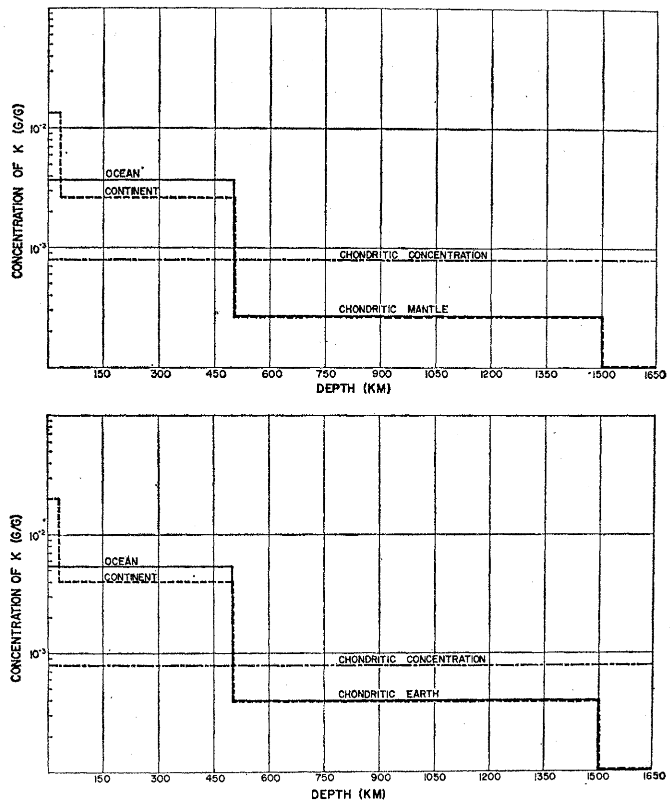
These discrepancies represent, in a sense, the strength of the earth, since they measure the deviation of the earth from hydrostatic equilibrium. The gravity anomalies corresponding to the nonhydrostatic components of the external potential are given in Table 3, column 4.

Part of the observed nonhydrostatic contribution to the external gravitational potential could arise from an isostatically compensated crust. We recall that free-air gravity can be interpreted in terms of the number of lines of gravitational force per unit area. An isostatically compensated mass will give rise to the second-order anomaly because of the geometric increase in area through which the lines of force pass. Table 3, column 5, lists the gravity anomaly expected from an isostatically compensated crust having the structure given in Table 1, rows 1–5. This anomaly is calculated on the assumption that the crust extends to the 1000-fathom line. For the low-order harmonics, the gravity anomaly expected from the crust is small as compared with the observed gravity anomaly and is of opposite sign. Thus, satellite observations establish discrepancies in the mass distribution that are correlated with the continent-ocean structure, but in the sense opposite to that expected from ordinary isostasy. The magnitude and sign of the nonhydrostatic anomalies demonstrate that a standard crust in isostatic balance cannot account for the observed gravity anomalies.

In the usual treatments of isostasy, mass is calculated above a certain level, usually about 30 to 40 kilometers; the columns under oceans and under continents are found to have approximately the same mass, provided reasonable values are assigned to the densities of the constituent materials (see Table 1). Implicit in such calculations is the assumption that the mantle below a given level is horizontally homogeneous. Unless all crustal material of the continents

Table 3. Comparison of observed gravity and gravity calculated for an isostatically compensated crust.

Harmonics	Observed (dimensionless, unit = 10^{-6})	Nonhydrostatic residual (dimensionless, unit = 10^{-6})	Gravity anomaly (mgal)	
			Observed (δg_n^m)	Expected from isostatic standard crust out to 1000 fathoms
J_2^0	1082.48	12.0	−11.8	0.27
J_2^2	−1.6	−1.6	1.6	−0.26
J_3^0	−2.56	−2.6	5.1	−0.25
J_3^1	−1.9	−1.9	3.7	−0.47
J_4^0	−1.84	0.5	−1.5	0.88
J_5^0	−0.064	−0.06	0.23	−2.1
J_6^0	0.39	0.39	−1.9	0.93
J_7^0	−0.47	−0.47	2.8	−2.3
J_8^0	−0.02	−0.02	0.18	−0.20
J_9^0	0.12	0.12	0.94	



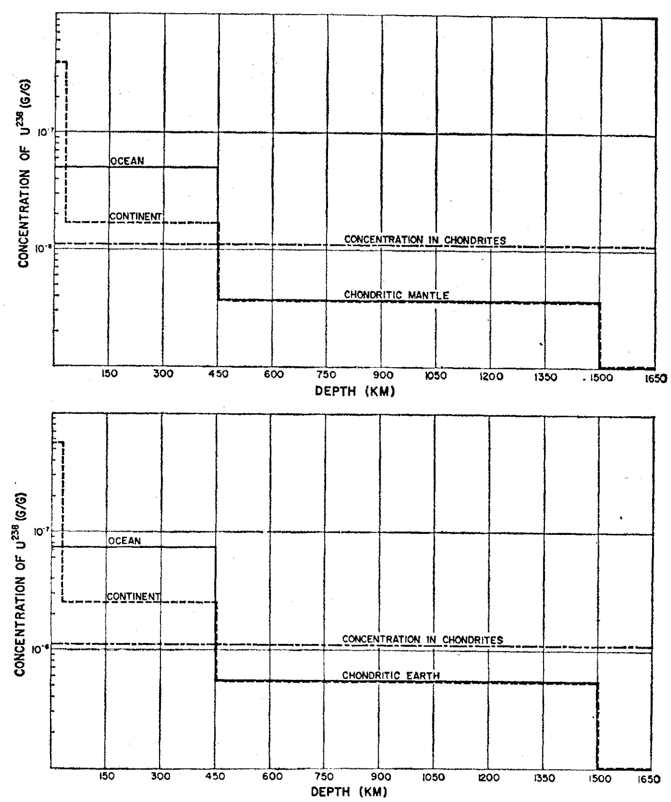
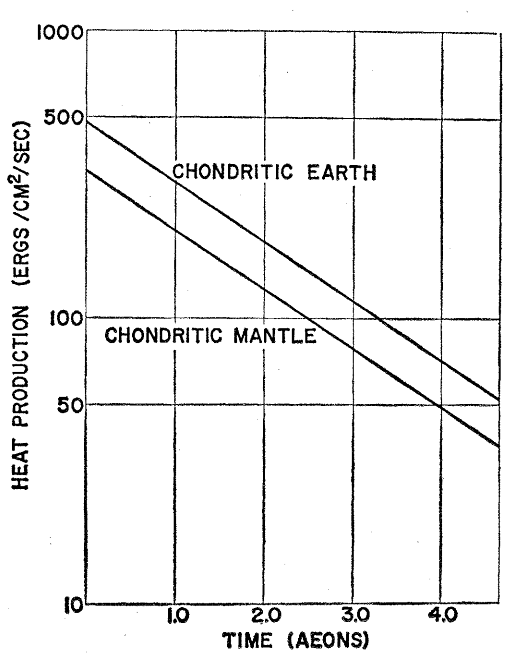


Fig. 3 (left). Concentration of potassium (in grams per gram) in the thermal models of continents. All radioactivity is concentrated above depths of 1500 kilometers. Fig. 4 (right). Vertical distribution of uranium (in grams per gram) for the thermal models of continent formation.

was extracted from a very thin layer of mantle, this assumption must be invalid. The difference in chemical composition of the continental and the oceanic crust requires a difference in chemical composition over some depth within the mantle. In addition, as we have seen, the distribution of radioactivity and the equality of the heat flow through continents and oceans implies a thermally induced difference in density which can be compensated for by a difference in chemical composition or phase. The equality of mass and heat flow at the surface shows that mass can be balanced only over a considerable depth, not over a shallow depth.

The implied difference in temperature between the continental and the oceanic crust is consistent with gravity observations, provided the elements concentrated in the continental crust form denser compounds at depth. Take a continental crust 35 kilometers thick with a mean density of 2.75. The same material with a 20-percent greater density of 3.33 would be 29.15 kilometers



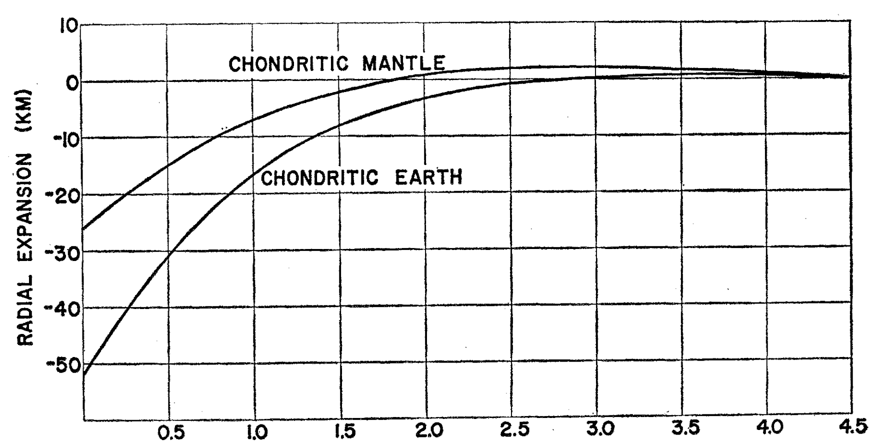


Fig. 5 (left). Heat production, as a function of time, for a column of unit surface cross section extending to a depth of 1500 kilometers for two concentrations of radioactivity assumed in the model calculations. Figure 6 (right). The calculated radial expansion for two earth models. The present radius is taken as the reference radius. For a chondritic model, the radial expansion is 52 kilometers over 4.5×10^9 years. This calculated value is based on a constant value of 1×10^{-12} g erg^{-1} for the ratio of thermal expansion to heat capacity.

thick; thus a continental crust of this material, of density 2.75, having the same mass as an oceanic crust of density 3.33, would stand 5.85 kiliometers above the ocean floor. The 20-percent difference corresponds approximately to the increase in density observed in a large number of phase transitions in silicates at pressures above 10 kilobars. Since the observed difference in height between continents and ocean floor is about 4.1 kilometers, a 1.7-kilometer discrepancy exists, attributable to temperature effects. Using laboratory values for the thermal expansion of silicates (that is, using a factor of about 1×10^{-5} per degree Celsius), we find that a difference in height of 1.7 kilometers would result from a difference in temperature, below continents and oceans, of 70° at depths between 35 and 450 kilometers; of 50° at depths between 450 and 1500 kilometers; and of 25° at depths between 1500 and 2000 kilometers.

The foregoing considerations imply that the elements forming low-density phases in the continental crust are found in higher-density form at depth. This requirement demands, not that the Mohorovičić discontinuity be a phase transition, but that within the upper mantle, alkalies, aluminum, and silicon occupy volumes about 20 percent less than the same elements occupy in the common crustal minerals.

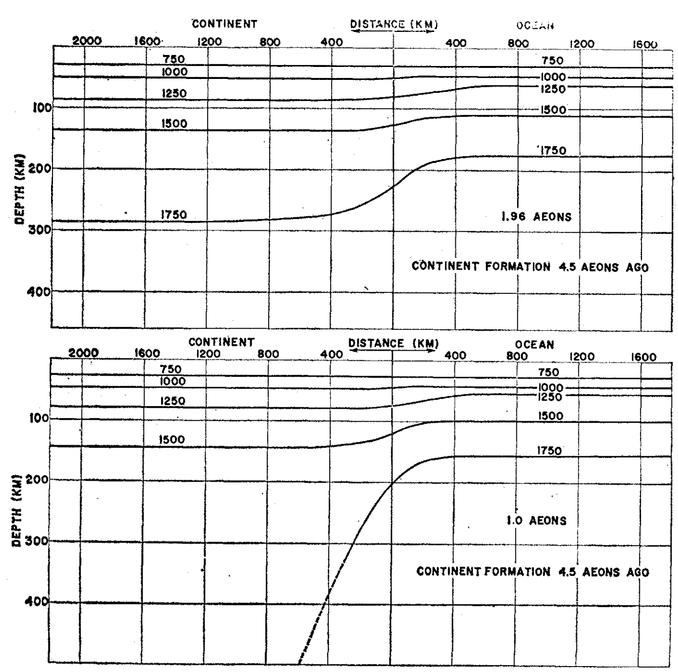
Comparison of Heat-Flow and Gravity Observations

Figure 2 shows a geoid, constructed solely from satellite observations, in which 35 spherical harmonic coefficients are used (*7*). The geoid heights, in meters, measure deviations from an ellipsoid with flattening 1/298.24. The geoid obtained from satellite observations agrees quite well with geoids constructed from surface measurements of gravity in the Eastern Hemisphere but differs somewhat from those constructed from measurements in the Western Hemisphere (*8*). Figure 2 illustrates the close mass balance between continents and oceans and indicates the anomalous regions.

Figures 1 and 2 show striking similarities, suggesting a relationship between gravity and thermal anomalies. The region of steepest horizontal gradients in heat flow runs through the East Indies. Similar high gradients in the geoid traverse this region. High gradients of the geoid are also found in Arabia and the eastern Mediterranean. Again, this is a region of high heat-flow gradients, though the lines of constant heat flow run at a high angle to the lines of constant elevation of the geoid in this region. The maxima and the minima for the heat flow appear to be correlated, respectively, with the minima and the maxima for the geoid. The high areas in the geoid correspond to excesses of mass. If thermal equilibrium is approximated, the highs in the heat flow correspond to regions of excess radioactive materials. There is, then, the apparent contradiction that where there is an excess of mass there is a deficiency in the radioactive elements.

A Primitive Model for Continent Formation

Observational data suggest that continents evolved in such a way that, on the average, matter making up the continental crust has never resided at depth under oceans. The process of continent formation must involve vertical segregation of the lighter elements in horizontally localized regions. Let us suppose that the earth accreted in such a way that the initial temperature was below the melting temperature of silicate material. The early history of the earth was profoundly influenced by the higher rate of heat production. The decay of the radioactive isotopes of uranium, thorium, and potassium all contribute heat, but potassium, with its half-life of about one-fourth the age of the earth, contributed heat in a proportionately much greater rate 4.5×10^9 years ago than it does at present. Indeed, if the concentration of radioac-



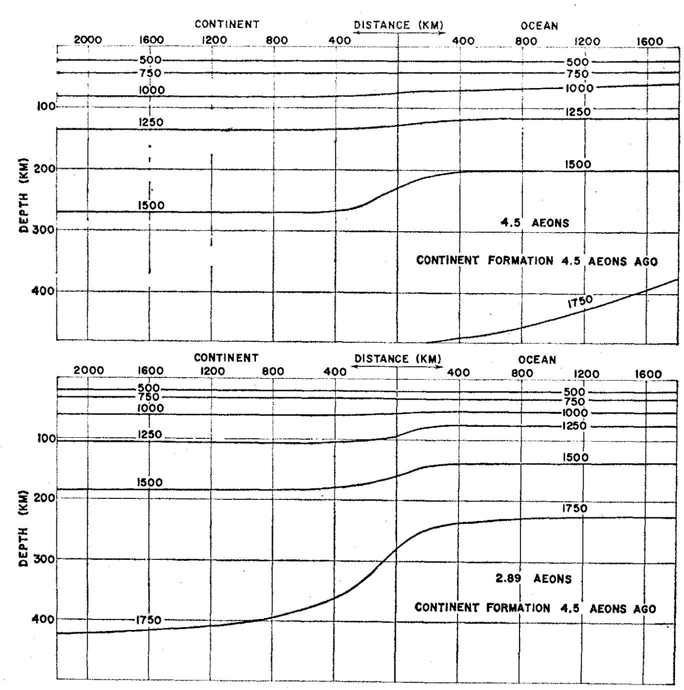
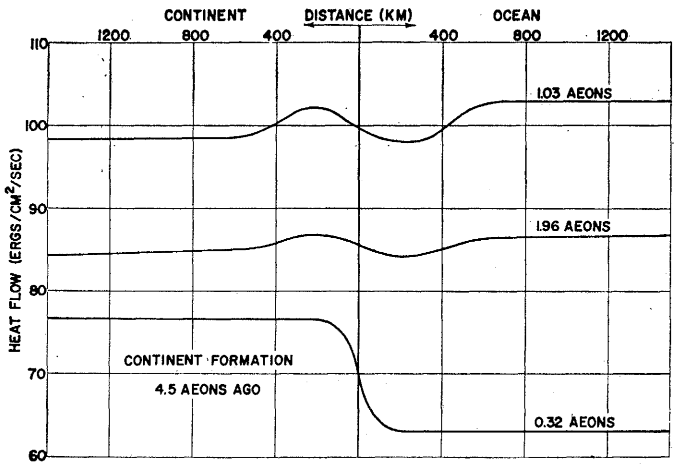
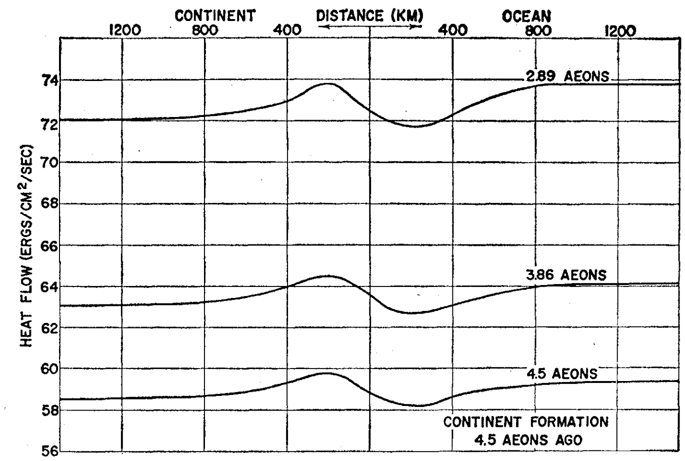


Fig. 7 (left). Vertical distribution of temperature over continents and oceans in an earth model. The total radioactivity is equivalent to that of a chondritic mantle, but the radioactivity is concentrated above a depth of 1500 kilometers, as in Figs. 3 and 4. The continent is supposed to have formed 4.5×10^9 years ago. Fig. 8 (right). Further development of the temperature field represented in Fig. 7.





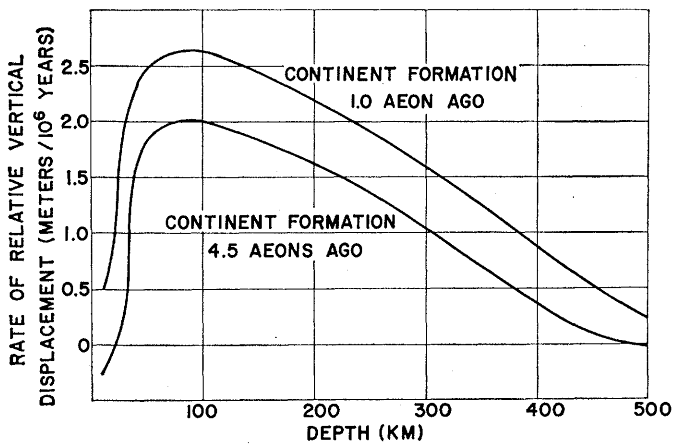


Fig. 9 (top left). Development of surface heat flow as a function of time for the model represented in Fig. 7 and 8.

Fig. 10 (top right). Further development of the surface heat flow for the model represented in Figs. 7, 8, and 9.

Fig. 11 (left). Relative vertical displacement of the continent-ocean boundaries.

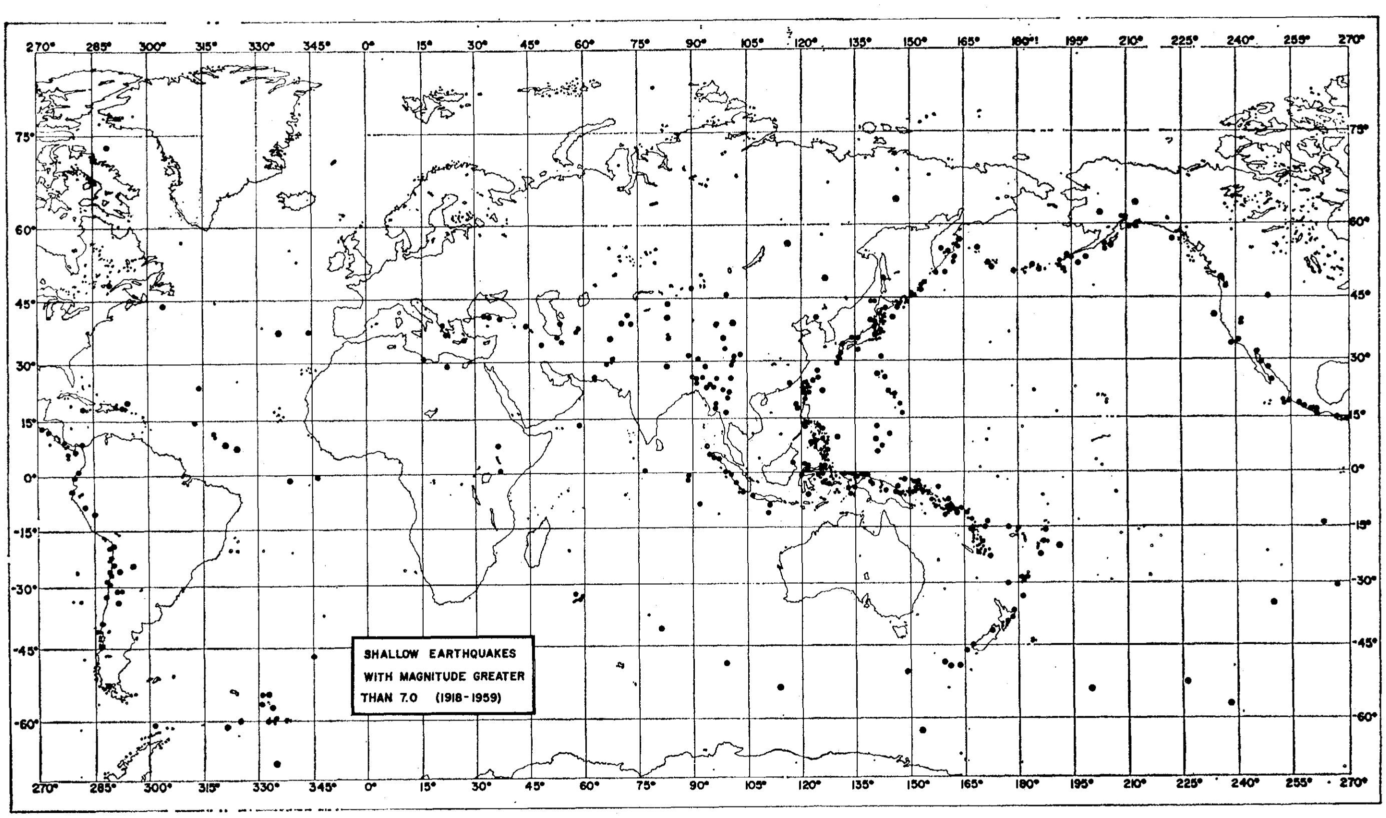


Fig. 12. Distribution of shallow earthquakes (focal depth, less than 60 km) of magnitude greater than 7.0.

tive elements within the earth equals that of chondritic meteorites, then radioactivity produced eight times as much heat at the beginning of the earth's history as it produces at present. The potassium content of the earth may be substantially less than the potassium content of an earth made up of chondritic meteorites would be, yet it is clear that the early rate of heat production exceeded the present rate by at least a factor of 3 (*9*). If the earth were so built that the internal temperature during the early phase was well below the melting temperature, the heat produced by the radioactivity would be trapped within the earth by the cold, insulating outer layers. Since the rate of heat production would exceed the rate at which heat was lost through the surface, the earth, after its formation, would expand. As I discuss later, the rate of radial expansion depends on the uncertain physical properties of the materials of the earth's interior and on the distribution of radioactivity. Proposed rates on the order of 50 to 100 kilometers per 10^9 years cannot be far wrong for the first 10^9 years of earth history.

The early high rate of heat production relative to heat loss resulted in a thermally expanding earth with major fractures and tension faults in the cold outer layers. The fracture zones, perhaps penetrating to a depth of several hundred kilometers, formed passageways for the upward movement of magma with a basaltic or andesitic composition. The mere creation of a fracture by expansion would not result in melting. The initial melting must have taken place in localized regions containing a great abundance of the initially statistically distributed radioactivity. In the early stage of intensive fracture, the entire surface was covered to form a primitive crust. Further restrictive fracture led to localization of the early protocontinents. From these elements the continents evolved through the accretion and secular differentiation of the subjacent mantle, in the manner outlined by Engle (*10*). Differentiation in the heat-producing elements extended to a depth of about 500 kilometers, but at greater depths the effects of continentality on chemical composition were minor.

Partial melting and upward movement of the melt left the subcontinental mantle depleted in radioactive elements. The resulting difference in the vertical distribution of radioactive heat sources below continents and oceans ensured that the boundaries between them became discontinuities in subsurface vertical motion. Faults and volcanic activity concentrated in the narrow boundary regions. Today, activity along these border faults is most pronounced at the limits of young continental regions. In the older regions, existing thermal stresses are lessened by a closer approach to horizontal thermal equilibrium. Thermal stresses result in predominantly vertical movement along the fault planes; nonthermal sources of strain energy, such as result from the secular change in the earth's rotation, may also lead to large horizontal displacements localized along the thermally stressed and weakened perimeters of the continents.

In summary, heat flow and gravity measurements imply that the structure of continents extends to great depths. The deep structure of continents requires that the material forming continents be withdrawn from the subjacent mantle, since large-scale horizontal motions would eliminate the evidence for the deep structure. On the average, material initially placed along the radial direction remains in the vicinity of that radius. Such a vertical segregation proceeds by the partial melting of the mantle material. In the early stages of the earth's history, extensive fracturing connected with the initial rapid expansion of the earth led to world-wide exudation of basaltic or andesitic magma, which formed the primitive globe-encircling crust. Further localization of fracturing led to the development of protocontinents. The concentration of thermal stresses at the borders of these early elements further concentrated growth on the perimeter. Continents grew by accretion and secular differentiation.

Thermal History of Continents

I have carried out a number of large-scale machine computations of the possible thermal development of continents, based on the model just outlined. Not all features of such models can be tested. However, it is possible to test whether or not a heat-source distribution differing under continents and oceans and extending to depths on the order of 500 kilometers can result in nearly equal heat flows over continents and oceans. In addition, the proposed rate of thermal expansion can be evaluated, as can be the relative rate of vertical motion at the boundaries of continents and oceans.

The local variation of temperature at a point within the earth depends on the balance between the rate of heat production within a small-volume element and the rate of heat flow in and out of the element. The rate of heat production is most uncertain, and, in the long run, it is the term which determines the distribution of temperature and surface heat flow. The total radioactivity and the relative proportions of the principal heat-producing elements are not well known, and neither are the vertical and horizontal variations in radioactivity. In the models studied I have assumed that the earth has radioactivity equivalent to that of chondritic meteorites, with uranium, thorium, and potassium as follows: U, 1.1×10^{-8} g g^{-1}; Th, 4.0×10^{-8} g g^{-1}; K, 8×10^{-4} g g^{-1}. Two total radioactivities have been explored —one with a model in which the whole earth is made up of chondritic meteorites and one with a model in which only the mantle has a chondritic composition. In both models all the radioactivity is concentrated at depths above 1500 kilometers.

Figures 3 and 4 illustrate the vertical distribution of radioactivity used in the model calculations. In the models for this distribution, an attempt was made to approximate the near-surface concentration of radioactivity in continental areas and the deeper distribution under oceans. Figures 3 and 4 show the potassium and uranium content, respectively. I assume that at depths greater than 1500 kilometers the concentration of the radioactive elements becomes zero. Small amounts of radioactivity at greater depths could be admitted without altering the near-surface conditions, because the earth has long thermal time constants.

Figure 5 shows the total heat production per unit column for the two models studied. If thermal equilibrium were maintained at all times, then the surface heat flow would equal the heat production, and for a chondritic earth the initial equilibrium heat flow would be 500 erg cm^{-2} sec^{-1}. Figure 5 clearly shows the high rate of heat production early in the earth's history; if the surface heat flow did not keep up with the heat production, the earth would heat up with a consequent thermal expansion.

Figure 6 shows the total radial expansion expected for two earth models.

For a total radioactivity equal to that of chondritic meteorites, the radius, 4.5×10^9 years ago, was 52 kilometers greater than the present radius, which is taken as the reference radius. An earth with a chondritic mantle would expand 27 kilometers in 4.5×10^9 years. In the calculations, the rate of expansion depends on the ratio of the thermal expansion to the heat capacity. In the laboratory, silicates at high temperatures show a more-or-less constant value for this ratio, and the calculations have been made on the basis of an assumed ratio of 1×10^{-12} sec^2 cm^{-2}.

In the calculations illustrated in Fig. 6, a value is assumed for the ratio of thermal expansion to heat capacity that is appropriate for silicates and oxides not undergoing phase transitions. A phase transition effectively increases the thermal expansion, since a change in temperature at a given pressure will bring about a large change in volume. Birch (*11*) has shown that it is very likely that, at depths between 200 and 100 kilometers, material undergoes phase transitions to denser forms. If the earth were initially cool, as I have assumed, then the heating by radioactivity would have moved the transition outward, and this would have led to an increased rate of expansion. Using data on analog systems and on the transition of SiO_2 to high-density phase (*12*), I have calculated that the effective value for the ratio of the thermal expansion to the heat capacity is increased by a factor of about 3. The total expansion during the first 10^9 years is then greater than 100 kilometers.

The calculations with respect to the phase change are very uncertain, since they are based on arbitrary, though reasonable, values for the constancy curve of the transition. However, it is clear that the occurrence of phase transitions amplifies the thermal effects, and that in the initial stages the earth expanded at a rate on the order of 50 to 100 kilometers per 10^9 years. Initial deep distribution of radioactivity favors high values for the rate of expansion, as does the occurrence of phase transitions. This result suggests that tension fractures formed during the early stages of the earth's history, and that these tension fracture zones provided conduits through which the constituents of the mantle that melt at lower temperatures could rise to the surface. The regions of fracturing and lava flow would be topographic highs, provided either that the material at depth was drawn from an area larger than the area covered by the fissures or that there was a change of phase associated with the mobile components. In the picture presented, the earth is at present contracting at a slow rate.

Figures 7 and 8 show the thermal development of a thermal model of the earth in which the total radioactivity equals that of a model with chondritic mantle. This calculation exhibits the principal features of a large number of calculations that I have carried out (*13*). On the average, the temperature under continents is 50° to 150°C lower than that under oceans. Figures 9 and 10 show the equality of the heat flow under continents and oceans. Even with a very large difference in vertical distribution of heat sources, the heat flow at present in continental areas equals the heat flow in oceanic areas. The continents show a higher heat flow in the early stages of the earth's history; as a result of this higher flow, the present temperature is lower under continents than under oceans.

Relative Motion of the Continent-Ocean Boundary

In the earth models the heat flow in oceans very nearly equals that in continental areas. As the rate of heat production in the unit column under oceans equals the rate under continents, there is little relative vertical motion at the surface, since continents and oceans are expanding or contracting at nearly equal rates. However, because of the difference in the vertical distribution of heat sources, there is relative motion at depth, and the resulting elastic stresses are concentrated near the continent-ocean boundary.

Figure 11 represents an estimate of the present rate of relative vertical displacement for a model earth. At a depth of 100 kilometers there is a relative vertical displacement on the order of 2 meters per 10^6 years for a continent formed 4.5×10^9 years ago; the rate of displacement for a continent formed 1.1×10^9 years ago is somewhat higher. The relative rate of vertical displacement drops off rapidly toward the surface and decreases more gently toward the interior.

The displacement rate on the order of meters per million years corresponds to an energy release on the order of 10^{23} ergs per year, provided the strength of the material is about 1000 bars (*13*). The amount of energy released by such stresses is small, but it is not insignificant when compared to the energy released in earthquakes (*14*).

Figure 12 shows the distribution of shallow earthquakes (focal depth, less than 60 km) with a magnitude greater than 7.0. The concentration of earthquakes near the continental borders is clearly exhibited. Intermediate and deep-focus earthquakes are also found on the continental borders. The fact that earthquakes having a focal depth greater than 300 kilometers are concentrated in this region establishes the pertinence of the difference in vertical distribution of heat sources to the problem of earthquake generation.

Summary and Conclusions

Observations of heat flow and gravity suggest that continental structure extends to depths on the order of 500 kilometers. The preliminary studies of surface waves tentatively confirm the assumed existence of regional differences between the continental and the oceanic mantle. The distribution of earthquake foci along continental borders and the concentration of deep-focus earthquakes at the borders similarly imply differences in thermal structures extending to depths on the order of a few hundred kilometers.

Calculations of the thermal history of the earth have been made on an electronic computer for a number of earth models. The calculations demonstrate that rather wide differences in the vertical distribution of heat sources lead to very nearly equal heat flows under continents and oceans. The temperature under oceans exceeds that under continents, on the average, by about 100°C over the uppermost 700 kilometers of the mantle. This temperature difference produces a density difference which must be compensated for. Phase changes in materials making up the continental crust are sufficient to provide the temperature-induced differences in density as well as the observed differences in height between continents and oceans.

The high rate of heat production in the earliest stage of the earth's history led to a rapid thermal expansion of the planet. The formation of the earliest continents is associated with this period of rapid expansion and extension of the crust. Further growth of the continents proceeded by accretion and secular differentiation of the subjacent mantle.

The deep structure of continents places heavy restrictions on any theory of continental drift. A relative motion of the continents must involve the mantle to depths of several hundred kilometers; it is no longer possible to imagine thin continental blocks sailing over a fluid mantle.

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Lactic Dehydrogenases: Functions of the Two Types

Rates of synthesis of the two major forms can be correlated with metabolic differentiation.

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The molecular heterogeneity of many proteins, particularly of individual enzymes, has recently come to be clearly recognized. The various forms of these proteins are usually separable by physical means, but the physiological significance of the separate molecular species has frequently been obscure. Regarding the enzyme lactic dehydrogenase (LDH), however, the different molecular forms appear to have different functions and it has become clear that they are associated with different modes of metabolism and are quite characteristic of specific tissues.

The molecular forms of LDH were first separated by electrophoresis; by this means up to five separate forms can be distinguished. Recent studies have demonstrated that in fact only two principal or parent forms of LDH exist. The present view, now supported by evidence from many sources, is that LDH is a tetrameric molecule made up of four subunits of the two parent molecules. We have termed the parent forms H (heart) and M (muscle), for the organs from which they are readily obtained; "pure" H type is thus composed of four H subunits (H_4), "pure" M type is composed of four M subunits (M_4), while the other three forms of LDH are molecular hybrids consisting of mixtures of subunits: M_3H, M_2H_2, and MH_3. The evidence that we and others have adduced in support of this concept has been presented elsewhere in detail (*1–4*). It rests on the orderly differences among these molecular hybrids in terms of their catalytic behavior, heat lability, and amino acid composition, and the ability of pure parent forms to yield the intermediate forms under certain in vitro conditions (*5*). A comparison of some of the physical, chemical, and catalytic properties of the H_4 and M_4 forms, as compared to the hybrid H_2M_2, are given in Table 1. The H and M types are also immunologically distinct. Antibodies prepared against the H type do not cross-react with the M form. The converse is also true: antibodies against the M LDH do not react with H protein. Hybrids of LDH will react with both types of antibody (*1*). The two types are synthesized within the same cell, as shown by tissue cultures of pure cell strains and by histochemical demonstrations (*6*).

We have previously proposed that the two types of LDH have significantly different functional roles (*1*). This concept is based on the demonstration that there is a marked difference in the degree to which the activity of the two types is inhibited by pyruvate. The LDH found in the heart (predominantly H_4 in most species) is maximally active at low concentrations of pyruvate and is strongly inhibited by excess pyruvate (approximately 10^{-2} *M* in vitro). The M form of LDH, on the other hand, maintains activity at relatively high pyruvate concentrations. These facts may be related to function in the following way. In the heart, a steady supply of energy is required, and this is maintained by the complete oxidation of pyruvate and lactate in mitochondria. The inhibition of heart LDH by pyruvate favors this oxidative pathway. In skeletal muscle there is a requirement for sporadic, sudden releases of energy in the relative absence of oxygen. This energy is supplied by glycolysis, which produces large amounts of pyruvate and requires its reduction to lactate. Muscle LDH allows this reaction to take place despite temporarily high levels of pyruvate. The lactate formed enters the blood stream and joins metabolic pathways elsewhere.

We have used the catalytic differences between muscle and heart enzymes to demonstrate the proportions of M and H subunits in tissue extracts. In this method we have measured the rates of reaction at high and low concentrations of pyruvate and have compared these rates with those for pure M_4 and H_4.

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