A THEORY OF MOUNTAIN-BUILDING.
DAVID GRIGGS.

The fact that a natural phenomenon admits of one mechanical explanation is proof that there is an infinity of such explanations.
(Paraphrase from Poincaré.)

Table of Contents.

Introduction.
Fundamental Orogenic Phenomena.
The Diastrophic Cycle.
The Crustal Downfold, or Tectogene.
Forces Available for Mountain Building.
Primary and Secondary Diastrophic Forces.
The Tidal Force.
The Polflucht Force.
The Coriolis Force.
Compression due to Thermal Contraction of the Earth.
The Force due to Viscous Drag of Subcrustal Convection Currents.
Depth of the Conveciting Shell.
The Convection-Current Cycle.
Solid Flow of Rocks.
Causes of Cyclic Convection.
Phases of the Cycle.
A Dynamic Model of the Earth’s Outer Shells.
Dimensional Analysis of Kuenen’s Model.
The Dynamic Convection Model.
Correlation of the Convection and Orogenic Cycles.
Application of the Cyclic Convection Theory to Earth Structures.
Alternative Interpretations of Major Structures.

Conclusion.
Acknowledgments.

ABSTRACT. A theory of mountain-building by cyclic convection, thermal and not chemical in origin, is synthesized from: (1) the suggestions of Holmes, (2) the mathematical analyses of Pekeris, Vening Meinesz, and Hales, (3) the writer’s experiments on solid flow of rocks, (4) thermal experiments and calculations, and (5) a dynamically similar model to demonstrate the action of cyclic convection currents. The way in which this theory predicts the intermittence of mountain-building is discussed, and its ability to explain the diastrophic cycle.

Previous theories of orogenesis are briefly reviewed and some of their points of inadequacy are discussed.

AM. JOUR. SC.—VOL. 237, NO. 9, SEPTEMBER, 1939.
41
Introduction.

In the following, some arguments are presented which tend to make more plausible the suggestion that convection currents may have operated in the earth's substratum to cause the development of our mountain systems. It is clearly recognized that any such attempt must be highly speculative because of the enormous and indeterminate complexities of the situation. The reasoning is based on a few credible assumptions as to the composition and behavior of the earth's shells. The validity of the argument, therefore, depends entirely on geological and geophysical verification of these assumptions.

Any adequate hypothesis of mountain-building must satisfy the three following conditions:

1. It must provide a tangential component of force sufficiently great to fold and thicken the continental crust.
2. It must provide locally sufficient contraction to account for the shortening of the crust in the regions of mountain-building inferred from geological evidence.
3. It must explain the intermittent nature of orogenic processes and the succession of three phases in the mountain-building cycle:
   a. Geosynclinal subsidence and sedimentation.
   b. Compression of the crust and folding of the geosynclinal filling.
   c. Later elevation of the compressed and folded mass.

The literature of geology contains abundant criticisms of all the prevalent theories of orogenesis, based mainly on their inability to satisfy one or more of these conditions. It is not the purpose of this paper to evaluate critically the theories or the objections to them, but to suggest a mechanism which seems physically competent to meet these three conditions.

The basic physical principle on which the present hypothesis depends is not new to geology. Thermal convection currents in the earth's substratum were suggested a century ago by Hopkins (1839).* Since that time, several types of convection have been invoked to explain various features of the earth's history. The theory that our mountain systems are the result of convection currents has been the subject of much discussion by European geologists, but has received relatively little attention in this country.

* Names followed by dates in parentheses refer to references listed at end of this paper.
Holmes (1932) has been led by his study of the thermal history of the earth to conclude that cooling of the earth has been inadequate to produce the contraction necessary for orogenesis. He further concludes that thermal convection is to be expected in the earth's substratum, and that the convection currents may be adequate to cause mountain-building. Vening Meinesz (1934) suggests that subcrustal convection currents compress and fold the crust, developing the "Tectogenes" which are thought to underlie the negative-anomaly bands observed in the East and West Indies. He develops simplified equations of convection and calculates the potential stress which they may exert on the crust. Pekeris (1936) develops more rigorously the convection equations, and shows that on the most probable assumptions of temperature, viscosity, and strength of the substratum, convection is to be expected if, in addition, the substratum is homogeneous enough to permit convection. He also calculates the tangential stress developed by such currents, using an entirely different method from Vening Meinesz's. Hales (1936) develops still another mathematical analysis of convection, which indicates the temperature gradient necessary for the maintenance of the currents. This analysis shows that the temperature gradient most commonly assumed by seismologists to explain the observed increase in seismic velocities will lead to the development of convection currents in a homogeneous substratum. Bull (1929) performed an interesting experiment which suggests that the action of convection currents is one of the few mechanisms which will produce nappe structure.

Many other papers have been published by European geologists dealing with various aspects of the convection-current theory of mountain-building, but the papers above referred to are among the most complete, and afford a representative discussion of the hypotheses of the convection mechanism. Most of the discussion of convection has involved the tacit assumption that a molten condition is necessary for convection. The mathematical analyses have been based on the assumption that steady-state convection has been established. The present paper presents some new ideas concerning the way in which subcrustal convection may cause orogenesis, and in particular, suggests the existence of a convection-current cycle, correlated with the mountain-building cycle.
THE DIASTROPHIC CYCLE.

It has long been recognized that in spite of the numerous irregularities of the earth movements culminating in the formation of mountain chains, this activity follows a cycle which has been intermittently repeated during the history of the earth. Bucher (1933) expresses this as Law 20 in his study of the "Deformation of the Earth's Crust": "The typical orogenic cycle begins with a geosynclinal depression and ends with a major uplift. The interval between these limiting events comprises two phases. The first phase is one essentially of quiet sinking, only occasionally interrupted by uplifts; the second phase consists of crustal foldings separated by diminishing epochs of renewed geosynclinal sinking."

For the purposes of the present discussion, it is convenient to divide this generalized cycle of diastrophism into three phases:

1. The geosynclinal phase, in which a strip of the earth's crust is gradually depressed, receiving sediments from the adjacent, slightly elevated land masses, on one or both sides of the trough.

2. The period of crustal folding, in which the contents of the geosyncline are compressed and folded, without major elevation of the area above sealevel. The forces during this period of folding act mainly in the horizontal direction, but with a sufficiently great downward component to prevent the thickened mass from attaining isostatic equilibrium.

3. The elevation of this folded and thickened mass until it reaches isostatic adjustment. The forces acting during this period are dominantly upward; compressive folding is secondary.

There are minor deviations from the average trend in all of these phases in the mountain ranges of the world, but it seems to be the consensus of geological opinion that the history of all the major mountain systems has followed this broad outline of events.

THE CRUSTAL DOWNFOLD, OR TECTOGENE.

One of the greatest contributions to the understanding of tectonics during the twentieth century has been Vening Meinesz'
Fig. 1. Series of Measurements of Gravity Anomalies Across the Pacific Ocean after Isostatic Reduction. Figure reproduced through the kindness of R. A. Daly.

Fig. 2. Gravity Anomalies in the East Indies, Showing Belt of Gravity Deficiency Peripheral to the East Indian Archipelago, Flanked by Bands of Positive Anomalies.
discovery of the great bands of gravity deficiency in the East and West Indies. His careful and painstaking measurements of gravity over the broad expanse of the Pacific Ocean basin disclosed no deviation from normal gravity of more than 50 milligals, as shown in Fig. 1. Peripheral to the East Indian archipelago, however, a persistent gravity deficiency of much greater magnitude was discovered.

Fig. 2 shows the distribution of the gravity anomalies observed by Vening Meinesz (1934) from the Malay Peninsula around the north coast of Australia to the Philippines. Fig. 3 shows the results of a similar set of measurements made in the West Indies by the cooperative enterprise of Vening Meinesz, Hess, Brown, Ewing, and Hoskinson. In each of these island arcs, there is a narrow strip of strong negative anomalies just outside the island festoon. Also in each case, this strip is flanked by irregular patches of less strong positive anomalies. Fig. 4 shows a profile across latitude 15° N. in the West Indies, which illustrates strikingly the intensity of the gravity deficiency and its relation to the topography of the ocean floor.

These negative anomaly bands can be explained only on the assumption of a mass deficiency in the earth's crust at this point. Further, the narrowness of the bands makes it imperative to assume that this mass deficiency is located in the outer 100 km. of the earth's crust. The only explanation that seems geologically possible is that the lighter crust of the earth has been downfolded into the heavier substratum. Fig. 5 (prepared by Hess) shows diagrammatically the way in which such a downfold may account for the observed gravity deficiency.

Both in the West and the East Indies, the distribution of these negative-anomaly strips coincides with the distribution of the most intense late Tertiary folding and thrusting (Vening Meinesz, 1934; Hess, 1938). Each island arc is a branch of the great Tertiary mountain system. It seems fair to conclude that the observations indicate crustal downfolds which were formed as a terminal event of the Laramide-Alpine revolution. It would appear that these regions have just passed through the second phase of the mountain-building cycle. On this assumption it is to be expected that they will, in the geologically near future, be uplifted to form minor mountain masses.

It is suggested that the crustal downfold postulated in these two areas is a universal development of the second phase of the diastrophic cycle. Kuenen (1936) has termed the downfold a
"Tectogene." If conditions during the first phase of the orogenic cycle are such that geosynclinal sedimentation takes place, then this sedimentary mass will be carried on the back

Fig. 3. Gravity Anomalies in the West Indies, Showing Similarity to the East Indies.

Fig. 4. Gravity and Topography Profiles Along Latitude 15° N, in the West Indies.

of the folding crust and will itself be much more intricately folded. Such a relation has been suggested as the primary movement of mountain-building, as illustrated in Fig. 6 from Hess). If this relationship be accepted, one must next search
for a force adequate to compress the crust and cause this great downfold and the concomitant folding of the sedimentary filling of the geosyncline.

*Forces Available for Mountain-Building.*

**Primary and Secondary Diastrophic Forces.**

The forces most easily observed or inferred from geological observations are the so-called secondary forces which tend toward the attainment of equilibrium. Thus, the forces of erosion would in a short time reduce the surface of the earth to a flat featureless plain, if there were not primary forces of earth deformation which continually distort the earth's face. Similarly, any deviation from isostatic adjustment develops forces which tend to restore equilibrium. All of these secondary forces depend on primary deformative forces for their existence, and hence cannot be considered the ultimate cause of mountains.

Five types of primary forces have been suggested in the various theories of orogenesis:

1. The tidal force.
2. The Polfluchf force.
3. The Coriolis force.
4. Compression due to thermal contraction of the earth.
5. Viscous drag of convection currents in the substratum.

Before proceeding to a discussion of the magnitude of these forces, let us consider the probable strength of the earth's crust and estimate the size of the compressive stress which is necessary to fold it as a unit. The normal compressive strength of granitic rocks tested in the laboratory is 2,000 to 3,000 kg./cm.². It has been shown that high confining pressure such as exists in the earth's crust will greatly increase this strength, if all other conditions are held constant (Adams, 1917; Karman, 1911; Griggs, 1936). Other factors acting simultaneously—high temperature, solutions, and long periods of stress application—undoubtedly change the strength of rocks, but these effects have not been adequately investigated. It is yet too early to deduce from laboratory experiments the probable average strength of the earth's crust.

Studies of the local and regional departures from isostasy serve as the most reliable basis for estimating the strength of the continental crust and substratum. These observations
admit of various interpretations, but in general they seem to indicate that the continental crust has a strength somewhere between 100 and 2,000 kg./cm.\textsuperscript{2} For the purposes of the present discussion, it seems that the assumption of an average strength of the continental crust of 1,000 kg./cm.\textsuperscript{2} will not lead to serious error, and will probably be as accurate, relatively, as many of the other values of physical properties which will be used in calculations.

![Graph showing crustal structure](image)

Fig. 5. Crustal buckle, specific gravity distribution and resultant anomaly curve. From H. H. Hess.

In contrast to this strength of the crust, the observed flow of the substratum under the load of the glacial ice-cap indicates that it is either lacking in strength altogether, or possesses a strength of less than 10 kg./cm.\textsuperscript{2} (Daly, 1938, p. 408).

**The Tidal Force.**

Some of the advocates of continental drift hypotheses have invoked the westward tidal pull of the moon and sun on the earth’s surface to account for westward drift of the continents and consequent mountain formation (Wegener, Joly, etc.). The most telling criticism of this theory is a calculation of the force which can be developed in this manner. This calculation has been made by several people, notably Jeffreys (1929, p. 304), who states, “Tidal currents at their strongest give a bottom drag of the order of 40 dynes/cm.\textsuperscript{2} (4 \times 10^{-5} \text{ kg./cm.}^2); but this is abnormal, and is reversed in direction in every tide where it does occur. The mean secular tidal friction producing
the slowing down of the earth's rotation corresponds to a westward stress of the order of only \(10^{-4}\) dynes/cm.\(^2\) \((10^{-11}\) kg./cm.\(^2\)) over the earth's surface."

This westward stress acts tangentially over the whole bottom of the continental mass. Hence the compressive stress in the crust is greater than this: roughly in proportion to the ratio between the area of the continent and its cross-sectional area. This factor would be at a maximum of the order of 100:1, which would make the compressive stress in the continents \(10^{-9}\) kg./cm.\(^2\).

The fact that this stress of tidal drift is only one trillionth \(10^{-12}\) of the stress necessary to compress and fold the crust seems to preclude its serious consideration as a cause of mountain-building, or even as a modifying influence.

**THE POLUMFLUCHT FORCE.**

Staub (1928) has been the chief exponent of the hypothesis of mountain formation as a result of equatorward drift of the continents in response to the "Polumflucht" force. Because the continents are lighter than the substratum and float in it, they are acted on differentially by the centrifugal force of the earth's rotation. This centrifugal force has a component parallel to the earth's surface which tends to make the center of gravity of the continents move toward the equator. It is easy to calculate this component. Using Lambert's \(1921\) equations, we find for a continent 100 km. broad and 6 km. deep, a compressive stress of \(5 \times 10^{-4}\) kg./cm.\(^2\). For a continent 15 km. thick, Jeffreys (1929, p. 301) calculates the stress to be \(4 \times 10^{-3}\) kg./cm.\(^2\).

Thus we see that the maximum Polfluftch force is of the order of one ten-thousandth of that required for mountain-building. Hence it would seem that this force may also be excluded from serious consideration as a primary cause of mountain-building.

**THE CORIOLIS FORCE.**

Because the earth's axis of rotation is inclined to the line of gravitational attraction of the sun, it wobbles, like a gyroscopic top that gets a little out of the vertical. The forces that cause this wobbling, or precession, act differentially on parts of different density, and produce a component of force which tends to make the continents move. Jeffreys calculates this force and
concludes (1929, p. 304), "The stress in precession that makes
the whole of the earth precess at the same rate, instead of dif-
ferent shells precessing at different rates, is at most of order
60 dynes/cm.² (6 x 10⁵ kg./cm.²), and this must be mainly
alternating in direction." So we see that this Coriolis force is
of the same order of magnitude as the tidal force, and much too
small to cause mountain-building deformation of the earth's
crust.

COMPRESSION DUE TO THERMAL CONTRACTION OF THE EARTH.

Cooling of the earth will produce a compressive stress in the
crust limited only by the strength of the shell resisting the
shrinkage so developed. Although there is no question that a
force so derived might be sufficient to deform the crust, its
adequacy must be examined on other grounds. Two consider-
ations are of prime importance in a discussion of the theory that
our mountain systems originated by a wrinkling of the earth's
crust resulting from thermal contraction:

1. Is the earth cooling rapidly enough to produce the amount
   of contraction observed in the Tertiary mountain belt?

2. Can the compressive stress developed by uniform shrinking
   of the earth's interior be transmitted through the crust for
   thousands of miles to produce the localized deformation
   observed in the Tertiary mountain belt?

1. Our present knowledge of temperature gradients and the
distribution of radioactive, heat-producing materials renders
the answer to the first question indeterminate. Holmes (1932,
p. 171) has shown that, if the radioactive elements were dis-
tributed throughout the earth in the proportion in which they
occur in the average rocks of the crust, and if radioactivity
proceeded at all depths in the earth, this in itself would provide
a supply of heat fifty times as great as the heat lost from the
earth's surface by radiation. The discovery of the amount of
radioactivity in rocks makes it impossible to estimate how much
the earth is cooling at the present time, and even renders pos-
sible the conclusion that the earth may not be cooling at all,
but may have reached an equilibrium in which all the heat lost is
supplied by radioactivity.

It is of interest to calculate the amount of cooling necessary
to account for the observed contraction of the Tertiary moun-
tain belt, assuming that all the contraction of the earth is
taken up in the shortening observed in this belt. For this calculation, it is necessary to know the coefficient of thermal expansion for the materials of the earth under the pressures and temperatures which exist at depth. This we do not know, but if we assume that they have the same value as rocks at the surface, we find that an average cooling of the order of 1,500° for the whole earth is necessary. It seems probable that the pressure in the earth would greatly lower the coefficient of expansion, so that this figure would be too low. Such an amount of cooling seems excessive for the last three per cent of the earth's history.

Fig. 6. General section of the Alps superimposed on the tectogene. Both features drawn to the same scale with no vertical exaggeration. From Hess.

2. The thermal contraction theory necessitates that the compressive stress in the crust be transmitted over a large fraction of the earth's circumference to cause the folding localized in the Tertiary mountain belt. If the substratum be assumed to have low strength compared with the crust, it will tend to contract uniformly in a radial direction, and stress differences will be equalized by flow. There will be little tendency to develop tangential motion in the substratum. It follows that the localization of deformation in the crust involves a tangential movement of the crust over the substratum, varying from zero in the center of the shields to a maximum at the mountain abutments. This over-riding motion of the crust is hindered by the viscous drag of the substratum, and it would
seem that the condition for transmission of compressive stress through the crust is that this force of viscous drag be small in comparison with the compressive stress.

In order to calculate the viscous drag of the substratum, we must know the amount of crustal motion (shortening of the crust in the mountain regions), the time required for the movement, the viscosity of the substratum, and the distribution of the cooling which is responsible for the motion. The last of these depends on solution of the thermal conditions in the cooling earth, which we have seen is inadequately known. The other three variables are known to a first degree of approximation. From simplifying assumptions of all these conditions, the writer has made a rough calculation that the compressive stress in the crust developed by the viscous drag in the substratum would be of the order of 750 kg./cm.². In the light of our poor knowledge of the thermal conditions, however, this must be considered as at best an enlightened guess. If it be true, then it would seem that the drag of the substratum would provide sufficient resistance to the motion of the over-riding crust to prevent transmission of stress over large areas, and would cause more widespread distribution of deformation instead of localization into two mountain belts over the whole face of the earth.

A rough approximation to the conditions to be expected from thermal contraction can be attained in a dynamic model of the earth's outer shells. We shall see later, in the discussion of the dynamic model, that it provides some measure of confirmation of the conclusion reached above.

Many other criticisms of the contraction theory are to be found in the literature. In the opinion of the writer, none of the criticisms rests on sufficient evidence to disprove the hypothesis, but in toto they present significant difficulties which stand in the way of its acceptance.

THE FORCE DUE TO VISCOUS DRAG OF SUBCRUSTAL CONVECTION CURRENTS.

Convection currents are familiar to anyone who has watched a bowl of soup being heated, a pot of coffee, or a maple syrup condenser. When heat is applied to the bottom of any body of liquid in excess of a certain amount, the hotter lower part becomes less dense than the upper part and instability is set up.
Convection currents arise at the first disturbance of this equilibrium. In a broad expanse of liquid these currents have the tendency to form definite cells of more or less polygonal outline. Fig. 7 shows a vertical section through some experimental convection cells. The breadth of the cell tends to be about three times the depth, for plane surfaces of heating and cooling.

Any liquid heated from below has a tendency to lose heat both by conduction and by convective transfer of material. Conditions favoring convection are: (1) low viscosity, (2) low conductivity of the material (increase in size has the same effect as lowering the conductivity), and (3) a large temperature gradient. The effectiveness of convective transfer of material depends on the rate of flow. The high viscosity in the earth hinders rapid flow, but the great size favors it. The velocity of convective flow decreases inversely in proportion to

![Fig. 7. Section through Experimentally Developed Convection Cells. After H. Bénard.](image)

the viscosity of the medium, but increases in proportion to the square of the size of the convecting cell. Another factor favoring convection in the earth is the fact that the amount of heat transferred by conduction in unit time decreases in proportion to the square of the thickness of the mass through which it travels. A third factor may be of cardinal importance in promoting convection—the substratum may not behave as a viscous liquid, but as a "pseudoviscous" solid. This will be discussed in detail later.

Setting up the equations for convection of the earth's substratum as a viscous liquid, Pekeris (1936) has calculated the drag which the current may exert on the continental crust. His equations are simplified in that the term for adiabatic temperature change is not included, and the effect of variation of the earth's gravitational field with depth is neglected. The corrections due to these effects, however, would probably not change the order of magnitude of the result.
For convection cells of the approximate size of the continents and extending down to the 2,900 km. discontinuity at the earth's core, Pekeris has calculated the velocity of the currents and the tangential stress developed on the continents. Fig. 8 shows the stream lines and the velocities of flow in the case of hypothetical currents rising under polar continents and sinking under equatorial oceans. These velocities were calculated on the basis of Jeffreys' assumption that the viscosity of the substratum decreases from $10^{22}$ units at the surface to $10^9$ at the core. The calculation of stress is independent of the viscosity assumed. Pekeris finds tangential stress (drag) on the continents of the order of 50 kg./cm.$^2$. Because this acts on the whole area above the convection cell, and is concentrated into compression at the junction of the descending currents from two adjacent cells, the compressive stress is many times greater than this tangential stress. If the crust behaved as a perfectly

Fig. 8. Convection Current Streamlines and Velocities of Flow (Velocity proportional to the length of the arrows). Under a Crust made up of two Polar Continents and an Equatorial Ocean. After C. L. Pekeris.
David Griggs.

rigid shell, but were free to move away from the center of the cell, the ratio between the compressive and tangential stresses would be the same as the ratio between the surface area of the convection cell and the area of cross-section of the crust peripheral to the cell. For Pekeris' case (Fig. 8) this ratio would be 200:1, and the compressive stress 10,000 kg./cm.\(^2\). Because the crust is not perfectly rigid, and because some force must be expended in thinning it at the center of the cell, the actual force would be considerably less than this. It is estimated that the actual compressive stress would be of the order of 3,000 kg./cm.\(^2\).

Vening Meinesz (1934, pp. 54-63) used a different mathematical approach to the same problem in connection with the interpretation of the gravity anomalies in the East Indies. Assuming convection cells extending only down to 1,200 km., Vening Meinesz calculates an effective compressive stress in the crust of the order of 5,000 kg./cm.\(^2\).

Pekeris also calculates the lateral temperature perturbation necessary to initiate convection on the assumption that the substratum has a threshold strength below which flow does not occur. He concludes that a lateral temperature perturbation of a few tens of degrees will start convection even if the substratum has a threshold strength of as much as 50 kg./cm.\(^2\).

Hales (1936) calculates the amount of heat transfer necessary to maintain convection in the substratum, assuming it to have a viscosity of \(10^{22}\) and a coefficient of thermal expansion similar to that at the surface. It appears probable from his calculations that an initial temperature gradient only .1°/km. in excess of the adiabatic gradient will be sufficient to develop convection currents.

In discussing the source of heat for this convection, Hales mentions Holmes' suggestion of deep-seated radioactivity with the comment, "It seems doubtful whether the assumption of a deep-seated layer of radioactivity is necessary. If the conductivity in the core is greatly in excess of that in the shell, then even with the lower temperature gradient the heat brought to the lower surface of the shell by conduction would be more than could be carried away by conduction through the shell. This supply of heat would therefore maintain the convection currents in the shell. The conductivity of the core is probably sufficiently large for this."

Successive Stages in the Development of a Tectogene During one of Kuenen's Experiments.
Fig. 1. Small Dynamic Model to Simulate the Action of Subcrustal Convection Currents and the Response of the Plastic Crust. Photograph Shows Revolving Drums Simulating Convection Currents and the Consequent Development of a Crustal Downfold.

Fig. 2. Large Dynamic Model after Development of Crustal Downfold and Two Underthrusts in the Crust.
Depth of the Convection Shell.

Among the most fundamental problems of a convection current hypothesis of orogeny is that of the thickness of the convecting layer. Since the convection here in question is due only to the thermal differences in density, any great density discontinuity would act to prevent these density currents from crossing that boundary.

Seismology gives us our only clue as to discontinuities in the earth's shells. Only two discontinuities have stood the test of time in seismological research—the Mohorovičić discontinuity at the bottom of the continental crust, and the first-order discontinuity at the boundary of the central core of the earth (2,900 km. deep). (The discontinuities within the crust are not considered here because it is thought that they act only as secondary modifying influences on the reaction of the crust to the subcrustal convection. It is entirely possible that this is erroneous, and that the crustal discontinuities play a fundamental rôle.)

Various discontinuities have been suggested between the crust and the core: at 475, 1,000, 1,200, 1,700, 2,000 and 2,450 km. The most recent work favors the retention of only the 475 and 1,000 km., and it is interesting to see that one of the masters in this field, Macelwane (1936, p. 231), says, "No one would be more prepared than those who have done the respective pieces of research to admit the tentative and provisional character of the picture of the earth's interior which has been presented... Other interpretations may conceivably be developed which will satisfy equally well the data we now have; and tomorrow new facts may be discovered which will sweep away much of our present interpretation."

It must be pointed out that certain types of discontinuities may be no barrier to density currents. Thus, if a discontinuity is due to a change in compressibility with pressure, or to polymorphism, it may have little or no effect on a density current crossing it. In the case of polymorphic transitions, the temperature of the material crossing the boundary will be changed slightly by the energy of transition, but this will be the only effect on the current. Jeffreys (1937) suggests that the 475 km. discontinuity is due to a polymorphic transition. The 1,000 km. (Repetti) discontinuity is not a sharp change in
properties, but a gradual change in the rate of increase of velocity with depth, and thus might be connected with a change in the compressibility with depth.

The depth of the convecting shell is of primary importance in the distribution of the convection cells over the surface of the earth. Thus, if the cell extends to the core, it is reasonable to expect that the surface extent would be comparable in size to the whole Pacific basin, but if it extended only to the 475 km. discontinuity, the cells would be much smaller. The tangential stresses developed decrease rapidly with the size of the convection cell. Vening Meinesz and Pekeris, however, have calculated that convection in a 1,200 km. shell will be adequate to develop crustal folds. The discussion that follows is based on the arbitrary assumption that the whole substratum down to the core is subject to convection. Other depths of convection will change the magnitude of the calculated effects, but will probably not affect the principles deduced.

The Convection-Current Cycle.

Holmes (1932) suggested a hypothesis of thermal cycles in the earth's history based on a chemical fluxing action of the molten substratum. This hypothesis presents thermal difficulties because melting is involved, and necessitates additional hypotheses as to the composition of the rocks of the substratum. Because of the lack of data as to the composition of the substratum, it seems impossible to work out quantitatively any details of this suggested chemically-cyclic convection and so test the theory.

In contrast to this suggested periodicity, the mathematical treatments of Vening Meinesz, Pekeris, and Hales have all been based on the assumption that the equilibrium state of steady transfer of material is attained, as in ordinary laboratory experiments. The convection equations have involved the further assumption that the flow of the substratum follows the laws of viscous flow.

Consideration of the effects of size, the rate of heat conduction, and the nature of rock flow observed in the laboratory have led the writer to the conclusion that convection currents in the substratum will not attain a steady state, but will be periodic in nature. This hypothesis of cyclic convection, thermal in origin, involves no assumption of melting, and the composition of the convecting shell is assumed to be uniform.
SOLID FLOW OF ROCKS.

It is suggested that the substratum does not behave as a viscous liquid, but as a "pseudo-viscous" solid. In a recent paper the writer experimentally demonstrated pseudo-viscous flow in crystalline rocks subject to small stresses for long periods of time in the laboratory (Griggs, 1939). Two types of experiment have now been performed in which it is possible to measure the velocity of this pseudo-viscous flow as a function of shear stress. Figs. 9 and 10 show the results of these two measurements. Fig. 9 presents observations of the pseudo-viscous flow in Solenhofen limestone under a confining pressure of 10,000 atmospheres (equivalent to that at 22 miles deep in the earth's crust). The data are taken from the creep curves published in an earlier paper (Griggs, 1936, p. 562). The shear stresses in this experiment were high and the deformation rapid. Fig. 10 shows a different type of deformation—pseudo-viscous flow of alabaster under small stresses and in the presence of its own saturated solution.* It has been suggested that this flow is due to solution and recrystallization (Griggs, 1939, p. 249). Both of these widely different types of experi-

* The latter experiments were performed with the aid of a grant from the Pennrose Fund of the G.S.A.
Fig. 10. Velocity as a Function of Compressive Stress in Creep Tests on Alabaster under Conditions of Recrystallization.
A Theory of Mountain-building.

ment show that the velocity of pseudo-viscous flow ($v$) is related to the stress ($\sigma$) as follows:

$$\ln v = k'\sigma, \text{ or } v = e^{k'\sigma} \quad (1)$$

whereas in viscous flow, the velocity is directly proportional to the stress. True viscosity is invariant with stress, but pseudo-viscosity ($\eta$) varies with stress as follows:

$$\eta = \frac{k'\sigma}{v} = \frac{k'\sigma}{e^{k'\sigma}} \quad (2)$$

Present experiments indicate that there may be a threshold stress below which no continuing flow occurs. This would be the "fundamental strength" of the rock under the conditions of pressure, temperature, and solutions which obtained in the experiment (Griggs, 1936, p. 564).

The importance of this type of flow in the present discussion is that as the stress is increased, the velocity of flow increases exponentially. The way in which this affects convection will be suggested in the next section.

CAUSES OF CYCLIC CONVECTION.

The condition for the steady transfer of material by convection is that the temperature of the transferred mass be materially changed by conduction during the time involved in the transfer. This maintains a temperature gradient which serves as a continuous driving force for the convection currents. Steady convection currents are most commonly observed in the laboratory.

Two factors in the earth, however, tend to violate this condition and to make the currents flow periodically:

1. The great size of the cells which makes possible the development of large forces from small temperature gradients, and permits the transfer of material faster than it can change temperature by conduction.

2. Pseudo-viscous rather than viscous flow of the substratum. This involves an extremely high viscosity for low-stress differences, which makes it possible for a temperature gradient to be set up before convection begins. It further involves a low viscosity at high stress-differences which facilitates rapid transfer of the material.

The driving force for convection is gravitational, due to the difference in density between the rising and sinking columns of
a convection cell. It is at once obvious that if the flow of material proceeds more rapidly than cooling by conduction, the hot material of the rising column will be carried over into the sinking column before it has time to cool by conduction, and similarly the cool material of the sinking column will be carried under and into the rising column before it can be heated by conduction. This bodily transfer of hot and cold masses decreases the driving force of convection, and if the transfer is complete enough, it follows that the convection current must stop.

Fig. 11. Experimental Cell to Demonstrate Periodic Convection in a System Subject to Constant Heating and Cooling.

Physicists instinctively distrust the idea of developing a periodic convective overturn from a steady supply of heat. In order to demonstrate that it is possible to produce periodic flow from constant heating and cooling sources, the writer has set up an experimental convection cell, illustrated in Fig. 11, in which the conditions are favorable to the production of periodic convection.* In this cell the heat source at the bottom and the cooling source at the top are shown, but the boundary conditions are artificial in that the rising and sinking columns are localized in the two side tubes of the cell. The unique feature of this cell is the valve at A. When this valve is removed and a constant temperature-difference applied to the top and bottom

* This experiment was suggested by Professor L. J. Henderson.
of the cell, normal convection may be observed. When the currents first start they accelerate, as the hot material from the region of the heat source is transferred up into the rising column, and simultaneously the material from the region of cooling moves into the sinking column, thus increasing the difference in density between these two columns. As flow proceeds, however, it slows down, and with a few oscillations the velocity approaches a constant rate.

The valve at A—a light inverted cup floating on mercury—opens when the driving force of convection exceeds a certain amount, and closes when the driving force is less than this amount. The introduction of this valve into the system simulates the behavior of a material which has a threshold strength below which flow does not occur, and thus more nearly reproduces the conditions in the earth's crust than convection of a viscous fluid.

When constant temperature-difference of the right magnitude is applied to this new cell, flow does not begin until the left-hand column of the cell has been heated and the right-hand column cooled sufficiently to develop a driving force large enough to open the valve. The valve then opens suddenly; the flow throughout the cell accelerates rapidly for a short period, and then decelerates just as rapidly and stops as the valve closes. After this sudden transfer of material no flow occurs until the temperature difference of the columns is re-established. This period of quiescence is just ten times as long as the period of flow, in the experiment here described. The cycle is repeated continuously with a constant period.

This serves as experimental verification of the suggestion that when flow is rapid enough to transfer hot and cold masses so quickly that they cannot change temperature by conduction, the driving force of convection will vary periodically.

It is instructive to make some rough calculations for the purpose of comparing the rate of convective transfer of material in the substratum with the rate of temperature change in the moving mass by conduction. Both Pekeris and Vening Meinesz have calculated the velocity of convective flow, assuming steady state convection. Pekeris calculates a maximum velocity of the order of 5 cm./yr. for a convection cell 2,900 km. deep; Vening Meinesz calculates 1 cm./yr. for a cell 1,200 km. deep. Two things would make the peak velocity in convection more rapid than that of the steady-state convection assumed in mak-
ing these calculations: (1) the initial period of acceleration when convective overturn is begun—laboratory experiments develop a peak velocity three times the steady-state velocity; (2) pseudo-viscous flow, which would make the velocity under the maximum stress differences considerably greater than that calculated from the assumption of viscous flow. From these considerations, it would seem likely that the peak velocity would be of the order of 50 cm./yr., and the average velocity of the fastest moving mass during the convective overturn would be of the order of 10 cm./yr.

On the basis of this estimated velocity, the convective transfer of material from the earth's core to the surface would take 30 million years. For comparison with this velocity of transfer, let us calculate the probable percentage temperature change of the transferred mass during this time. Since only the outer shell of the convection cell is moved rapidly, it would seem that we might estimate the order of magnitude of the heat loss by assuming that a layer 200 km. thick were displaced from the bottom to the top instantaneously and held there for 30 million years. Lovering (1935) developed graphically the heat equations applying to the problem of an extensive dike of uniform thickness, which is essentially our problem. If we assume that this 200 km. shell corresponds to the injection of a dike at the base of the continents, then we can use his derivations to calculate the percentage temperature change of this mass. Assuming a diffusivity of .012, a 200 km. dike would retain 75% of its average excess temperature at the end of 40 million years.

If, during convective overturn, the transferred masses lose less than half of their temperature difference, then it follows that the temperature gradient is reversed and the convective driving force drops to zero. For example, if we assume a temperature difference (in excess of the adiabatic temperature gradient) of 500° C. between the core and the surface, and suppose convective transfer of the top and bottom layers within a period of 40 million years, then on the basis of the above rough calculation, the hot mass which rose to the top will still be 375° hotter than its surroundings and the cool mass which sank to the bottom will be 375° cooler than its surroundings. That is to say, the top mass will be 250° warmer than the bottom mass, and we may expect a static equilibrium to be attained and persist until the unstable temperature gradient (hotter at the bottom) is re-established by conduction.
In these calculations the effect of radioactive heating has been omitted. Holmes (1932) has shown that if radioactive elements were distributed throughout the earth in the proportions in which they exist in the crust, the heat so developed would be fifty times as great as that lost from the earth by radiation. Our assumption of convection in the substratum depends on a fairly uniform distribution of radioactivity in the substratum, and so we may conclude that a probable maximum of such activity would be one per cent of that in the rocks of the crust. Taking Holmes’ figures for the average of rocks, this gives an annual radioactive heat output of the order of $3 \times 10^{-8}$ cal./gm. Assuming a specific heat for the rocks of the substratum of .3, this means that in 100 million years the temperature rise due to radioactivity would be only $10^\circ$ C., which indicates that its omission in the above calculation involves no serious error.

We may now make a rough estimate of the time required to re-establish a temperature gradient which will permit convection to recur. Using the same thermal equations and assumptions as before, we find that the transferred masses will lose 70 per cent of their temperature difference by conduction in about 700 million years. Radioactivity during this period will increase the temperature of the bottom mass by about 70$^\circ$. From this it seems that an estimate of 500 million years for the period of static equilibrium would be of the right order of magnitude.

These calculations and experiments lead the writer to believe that convection in the substratum must be periodic. Hypothetical phases of the convection current cycle are illustrated in the next section.

**PHASES OF THE CYCLE.**

Fig. 12 represents successive stages in convection in one cell extending from the surface to the core of the earth. Before convection begins, heat loss from the core sets up a temperature gradient roughly as shown in Fig. 12-1. In a uniform shell this constitutes an unstable equilibrium in which the hot material tends to rise and the cool surface material to sink. When lateral temperature variations become great enough, currents will start. Pekeris has calculated the magnitude of such variations needed to initiate convection and concludes that even in the case of a substratum having a strength of 50 kg./cm.², "a
temperature contrast of a few tens of degrees is sufficient to overcome the above-mentioned strength of the asthenosphere and to start horizontal flow" (Pekeris, 1936, p. 348).

Once started, the temperature instability greatly accelerates the currents. As the hot material rises and the cold material sinks, the central column becomes progressively less dense and the outer column heavier, thus increasing the driving force of the currents (Fig. 12-2). Because of the nature of solid flow

as outlined above, this stress greatly accelerates the velocity of the flow, producing an increase in the tangential stress exerted on the crust by the current.

It will be seen that this increase in tangential stress is not proportional to the velocity of the currents, as would be the case in viscous flow, but is proportional to the increase in the driving force due to the greater density difference between the rising and sinking columns of material. Pekeris (1936, p. 357) shows that the tangential stresses are independent of the viscosity (or "equivalent viscosity" in this case—Griggs, 1939, p. 229).
As the hot material spreads over the surface, the cool material covers the bottom of the cell (Fig. 12-3). This decreases the density difference between the rising and sinking columns and slows down the currents. Finally, when the cool material rises in the central column, and the hot material begins to come down the sinking column, a stage is reached in which density equilibrium is again attained (Fig. 12-4). At this time the currents stop.

The temperature gradient is now the reverse of that before the convection began. No more convection will occur until the original unstable temperature gradient is re-established by conduction from the core and cooling from the surface. The time intervals of these four stages of the convection current cycle are estimated to be of the following order of magnitude:

First Phase—slowly accelerating currents—25 million years.
Second Phase—period of rapid currents—5 to 10 million years.
Third Phase—decelerating currents—25 million years.
Fourth Phase—quiescence—500 million years.

It would seem probable that during the period of quiescence when the substratum is regaining its unstable gradient, new currents would originate in some other cell in the substratum. For this reason, it seems impossible to set a definite period of time for recurrence of convection in some other cell.

A Dynamic Model of the Earth’s Outer Shells.

In order to study the effect of sub-crustal convection currents on the continental crust, a dynamically similar scale model of the earth’s outer shells was developed. By applying the laws of dimensional analysis and model theory (see Hubbert, 1937) it is possible to construct a model in which all the important properties of the earth’s shells are accurately scaled down, and in which convection currents may be simulated.

Geologic models have progressed through several stages of approximation in the past, and no one of the various attempts has been subjected to a thorough dimensional analysis. The experiments most closely approaching dimensional correctness are those of Kuenen (1936). His apparatus (Fig. 13), utilized for the first time a fluid substratum, so that the crust was free to deform downward as well as upward. His choice of materials for the crust included a mixture of paraffin, vaseline, and oil.
which had the strength appropriate to a crustal strength of 2,000 kg./cm.²

Kuenen developed a compressive stress in the crust by pushing on it with a movable plunger. It was usually necessary to localize deformation of the crust by artificially producing a slight depression. The result of compressing the crust under these conditions was to produce a downfold of the type shown in Plate I. If, during the initial stages of an experiment, the broad geosynclinal depression was filled with thin layers of material weaker than the crust itself, it was found that these were intricately folded and thrust in a manner resembling alpine deformations.

![Diagram](image)

Fig. 13. Schematic Diagram of Kuenen's Model for Developing a Tectogene by Compression of a Crust Floating on a Liquid Substratum.

In this experiment of Kuenen's the strengths of the crust and substratum were reproduced approximately to scale, and for the first time in experimental geology the geometrical conditions were favorable to the production of a Tectogene. One important factor was neglected, however—dynamical similarity. Kuenen used water for his substratum, which because of its extremely low viscosity did not provide sufficient viscous resistance to the over-riding crust to duplicate conditions in the earth. This viscous resistance of the substratum exerts an important drag on motion of the crust, as shown by the discussion on page 623 of this paper. It is instructive to make a dimensional analysis of Kuenen's model to investigate this point. The principles and symbols for this analysis are those of Hubbert (1937), with Bridgman's (1931) concept of the dimensionless product.
A Theory of Mountain-building.

Dimensional Analysis of Kuenen's Model.

a. In order to have the time factor at all manageable, inertial forces must be vanishingly small as in the earth, so that body accelerations may be neglected.

b. The simplest way to avoid complications due to acceleration analysis in this derivation is to use weight (W) instead of mass as one of the fundamental units. The others are time (T) and length (L).

c. Dimensions of the important variables:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>L</td>
</tr>
<tr>
<td>Time</td>
<td>T</td>
</tr>
<tr>
<td>Density</td>
<td>D = WL⁻³</td>
</tr>
<tr>
<td>Viscosity</td>
<td>DLT = WL⁻²T</td>
</tr>
</tbody>
</table>

d. Model Ratios (Ratio of the magnitude of the property in the model to the magnitude in the earth):

<table>
<thead>
<tr>
<th>Dimensional Ratio</th>
<th>Value from Kuenen's model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of length</td>
<td>λ</td>
</tr>
<tr>
<td>Ratio of density</td>
<td>δ</td>
</tr>
<tr>
<td>Ratio of viscosity</td>
<td>ψ</td>
</tr>
<tr>
<td>Ratio of time</td>
<td>τ</td>
</tr>
</tbody>
</table>

e. From these four ratios it is possible to choose a combination which will be dimensionless. The value of this "Dimensionless Constant" will then be the same in the model as in the earth, and will permit calculation of the unknown ratio.

Dimensionless Product = 1 = \( \frac{\delta \lambda \tau}{\psi} = \frac{wL^{-3}t}{wL^{-2}t} \) ...............(2)

\[ \text{or, } \tau = \frac{\psi}{\delta \lambda} = \frac{1 \times 10^{-24}}{7 \times 10^{-7}} = 1.4 \times 10^{-17} \]

This means that a process requiring 10 million years in the earth must be reproduced in the model in 1/300 second for dynamical similarity. Such rapidity would violate the basic assumption of this analysis—negligible inertial forces—and so it is impossible for this model to be dynamically similar.

If we are to design a model of the same size and density of materials to be dynamically similar, then we have one variable property—the viscosity—whose value is at our disposal. This analysis shows us that by correctly choosing the value of the viscosity we may make a dynamically similar model to operate at any speed we desire, limited only by the viscosity of the
materials available. If, for example, we choose as convenient a model speed such that one minute in the model corresponds to a million years in the earth, we find:

\[ \tau = 1.9 \times 10^{-12} \]

Solving equation (3) for the viscosity ratio:

\[ \psi = \delta \tau = 1.9 \times 10^{-12} \times 1.9 \times 10^{-12} = 1.3 \times 10^{-19} \]

So that for the model, the substratum must have a viscosity of

\[ \eta = 1.3 \times 10^{-19} \times 10^{22} = 1,300 \text{ c.g.s. units} \]

In setting up a model to illustrate the action of convection currents, the writer used two sizes—a large model in which an earth process requiring a million years could be reproduced in one minute, and a smaller one in which the same process could be reproduced in two seconds. The properties of the larger one are summarized in the following table:

<table>
<thead>
<tr>
<th>Property</th>
<th>Model Ratio</th>
<th>Actual Value in Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1 x 10^-6</td>
<td>60 cm.</td>
</tr>
<tr>
<td>Density</td>
<td>.6</td>
<td>1.8 (substratum)</td>
</tr>
<tr>
<td>Viscosity</td>
<td>.8 x 10^{-16}</td>
<td>6300 c.g.s. units</td>
</tr>
<tr>
<td>Strength</td>
<td>.6 x 10^{-9}</td>
<td>.6 gm./cm.² (ca.)</td>
</tr>
<tr>
<td>Time</td>
<td>1.3 x 10^{-12}</td>
<td>1 min. = ca. 1 my.</td>
</tr>
</tbody>
</table>

It is interesting that when the viscosity of the substratum is chosen for dynamical similarity, the model does not behave in the same way as that of Kuenen. When the crust is compressed by a moving plunger in the same manner as in his experiments, it shows no tendency to develop a downfold, but instead the compression is taken up by thickening of the crust immediately in front of the advancing plunger. The viscous drag of the substratum seems sufficient to prevent the transmission of compressive stresses for long distances through the over-riding crust, and causes local thickening of the crust instead. This evidence from the behavior of a scale model provides some measure of confirmation of the conclusion reached on page 623 of this paper which would seem to be a substantial difficulty of the thermal-contraction theory of orogenesis.

The next problem is to produce the effects of subcrustal
convection currents in the model. Dimensional analysis shows that it is impossible to produce currents of sufficient velocity by thermal means. This would require a temperature difference between the bottom and top of the model of the same order of magnitude as that existing between the core and the crust of the earth—thousands of degrees. Since the effect on the crust is primarily that of a current passing under it and turning down at some point, however, this current can be simulated by the rotation of a paddle wheel strategically located in the substratum. In the actual model rotating drums were used, to avoid the irregularities of paddle motion. The friction at the surface of the drums sets up currents not greatly different from those observed in convection. This model corresponds to a vertical section across the boundaries of two adjacent cells. The third dimension is not reproduced.

THE DYNAMIC CONVECTION MODEL.

The principles of the dynamic model are best illustrated in Plate II, Fig. 1, which is a photograph of the small model. Here the small glass cell holds a clear liquid (glycerine) on which floats a black plastic crust (cylinder oil and fine sawdust). The drums are rotated by means of small pulleys belted to the larger pulleys which are turned by hand. When the rotation of the drums is slow, the plastic crust is thickened and pulled down into a slight trough (in this model the oil sticks to the glass walls so that it is impossible to see the surface configuration in the photograph). As the currents increase in velocity, the crust is thickened more and more until finally a narrow downfold is formed as shown in the photograph. At this time of rapid currents, the surface of the crust is irregularly folded, and its average level is just a little lower than before the currents began. If the currents are slowed down and stopped, the downward component of force disappears and the thickened mass rises to buoyant equilibrium, so that its surface is considerably above its original level. Thus the reaction of the crust to the three phases of the convection current cycle is demonstrated.

Because the inertial forces were not negligible in this small model, and because it was desired to study in more detail the structures produced, a larger model was built with the physical properties given in Table I. A photograph of this model in
operation is shown in Plate II, Fig. 1. Here the substratum was very viscous waterglass and the continental crust was a mixture of heavy oil and sand, which possessed a yield point that could be varied by changing the proportion of oil used, and so made to have the proper strength for the model scale. The rotating drums show in the foreground. At the time the photograph was taken, the drums were in motion, and had developed a downfold and the two thrust faults in the crust shown by the dark lines. The actual development of these structures cannot be satisfactorily depicted short of moving picture portrayal.

![Diagram](image)

**Fig. 14.** Stereogram of Large Model with Both Drums Rotating, Showing Tectogene and Surface Thrust Masses with Relations Similar to Kober's Orogen.

The writer has a series of movies of the apparatus and is endeavoring to make arrangements so that anyone interested can obtain them at a nominal cost.

The type of thrusts formed at the junction of two down-currents is shown in Fig. 14. This sketch illustrates the relations during the height of current velocity. The similarity in type of structure to that of Kober's Orogen is striking. An interesting feature of these thrusts is that they are formed by passive resistance of the overlying mass and active under-thrusting of the foundation.

When only one drum is rotated (corresponding to the development of a single convection cell), the effect on the crust is different—the crustal downfold formed is not so narrow, and is asymmetrical in that it is steeper on the side facing the cur-
rent. The structures are correspondingly asymmetrical. As the current velocity is increased, the crust is markedly thinned above it, and transported into the thickened part of the crust. Finally, the current sweeps all the crustal cover off and piles it up in a peripheral downfold. This stage in the development is illustrated in Fig. 15, drawn from the model.

This indication that a singly active cell may sweep off the superjacent continental crust opens wide avenues for speculation as to the formation of the circum-Pacific mountains and indeed as to the primary segregation of the continental masses themselves. Here is a possible deformative force which could effectively counteract the tendency of erosion to distribute the continental material uniformly over the surface of the globe.

**Correlation of the Convection and Orogenic Cycles.**

We began with a generalized review of the mountain-building cycle; progressed through the hypothesis of thermal convection-current cycles in the earth; saw from model experimentation how subcrustal currents may deform the continental crust; and now we proceed to a synthesis of the facts and inferences gleaned from these varying modes of approach.

Fig. 16 shows the suggested correlation between the convection-current cycle and the mountain-building cycle. During the first phase of the convection-current cycle, when the cur-

THE MOUNTAIN BUILDING CYCLE

1. First stage in convection cycle - Period of slowly accelerating currents.

2. Period of fastest currents - Folding of geosynclinal region and formation of the mountain root.


Fig. 16. Hypothetical Correlation between Phases of the Convection-Current Cycle and Phases of the Mountain-Building Cycle. Structural Relations Drawn from the Model.
rents are slowly accelerating, they will exert an ever-increasing tendency to compress the crust. The compressive force in the crust reaches a maximum where the convection current dives down at the boundary of a cell. At this point there is a vertical component of stress as well as the tangential drag, and the combination of maximum compressive stress and the vertical stress localizes the crustal deformation which in the first stage of the mountain-building cycle takes the form of a geosyncline (Fig. 16-1). If the currents were constant in velocity, the geosyncline would reach an equilibrium position in which no further sinking would occur. With the slowly accelerating currents, however, the compressive stress is constantly increasing and causes continued depression of the geosynclinal trough, in agreement with the geological evidence for continued subsidence of geosynclines. According to the estimate given above, this period of acceleration would be of the order of 25 million years.

When the currents attain high enough velocity, the compressive stress on the crust is sufficient to deform it violently. This increase in compressive stress is accompanied by an increase in the vertical component at the cell boundary, and between the two the crust is downfolded as shown in Fig. 16-2. The thrusts shown in the diagram were added from a study of the model.

In these diagrams and in the discussion of the model, no attempt has been made to reproduce the sedimentary filling of the geosynclinal trough. The thrusts shown in Fig. 16-2 are foundation thrusts, corresponding to similar features in the Alps described by Swiss geologists, and it is to be expected that, as in the Alps, each foundation thrust would be connected with a nappe or thrust in the sedimentary rocks above. The folding and faulting in the sedimentary filling, however, must necessarily be very much more complicated than in the relatively homogeneous and massive granitic crust. This increase in complexity can certainly be better demonstrated in the region of the "roots of the nappes" in the Alps than in any model.

During this period of orogenetic folding by the most rapid currents, which probably lasts from five to ten million years, the thickened mass of the crust is kept submerged by the downflow of the sinking current. The vertical component of stress developed by the current acts to prevent the swollen crust from rising to isostatic equilibrium. This persistent deviation from
isostatic adjustment which has been shown in the model is cor-
rborated by the common geological observation that mediter-
ranean sedimentation occurred simultaneously with the peak 
of diastrophism in the mountain systems of the world.

As the currents decelerate in the third phase of the convec-
tion cycle, the compressive force in the crust decreases, the 
downtown decreases, and the thickened mass rises buoyantly, 
gradually attaining isostatic equilibrium as the currents slow 
and stop (Fig. 16-3). This produces the elevation which char-
acterizes the third phase of the mountain-building cycle. 
Observation of the model shows that during this rise, the 
 thickened part of the crust expands laterally and exhibits a 
tendency to flow away from the center of the folded portion of 
the crust under the influence of gravity. The absence of com-
pression which characterizes this phase of the cycle, and the 
tendency toward lateral expansion are in agreement with geo-
logical observations that the period of elevation is not a period 
of dominant compression, but is one of dominant uplift and 
normal faulting. This change in character of deformation is 
difficult to explain by the hypothesis of thermal contraction, 
but can be readily demonstrated in the cyclic-convection theory.

The persistence of major isostatic disequilibria in the East 
Indies has puzzled Vening Meinesz, Umbgrove, and Kuenen 
(Kuenen, 1936, pp. 196-7). If the gravity deficiencies here 
observed are due to crustal downfolds, it is reasonable to sup-
pose that they were formed at the time of the greatest folding 
of the sediments on the adjacent islands. This conclusion seems 
unequivocally established by the exact parallelism of regions of 
most intense folding and the negative anomaly bands. The age 
of this folding is Miocene, so that one must explain the per-
sistence of the anomalies for something like 20 million years. 
This presents great difficulty to the thermal contraction theory 
of orogeny, but is to be expected from the cyclic-convection 
theory, since we have seen that the period of deceleration is 
estimated to last 25 million years.

Application of the Cyclic-Convection Theory to 
Earth Structures.

Alternative Interpretations of Major Structure.

The primary purpose of this paper is to suggest a possible 
mountain-building mechanism. The application of that mechan-
ism to details of earth structures is beyond the scope of this
discussion. It may be of interest, however, to suggest in the most speculative way how this cyclic convection might operate to produce the major trends of the mountain systems.

The most fundamental question in applying this hypothesis to orogeny is the depth of the convective cells. In the absence of conclusive seismological evidence of the existence of a sufficiently sharp density discontinuity in the earth to prevent convective overturn between the crust and the core, it may be assumed for purely speculative purposes that the convection extends throughout this 2,900 km. depth. This would predict a size of the convection cells of the order of 7,000 to 10,000 km. in diameter (at the surface).

Holmes (1932) and Pekeris (1936) have suggested that the blanketing effect of the continents with their high radioactive content will cause sufficiently excess temperature under the continents to initiate rising currents there. These currents would act to spread the continents and to form mountains peripheral to them. Holmes published maps showing the hypothetical effect of this action on continental structures.

It seems conceivable to the writer that the temperature differences within the substratum inherited from the preceding convection cycle may be of more importance in localizing the cells than the blanketing effect of the continents. This opens the attractive possibility of a convection cell covering the whole Pacific basin, comprising sinking peripheral currents localizing the circum-Pacific mountains and rising currents in the center. Such an interpretation would partially explain the sweeping of the Pacific basin clear of continental material, in the manner demonstrated by the model. A minor cell might be suggested with its center in the southwest Indian Ocean, accounting for the Himalayan-Alpine bifurcation.

If this be assumed, then one may carry the speculation further and suppose that the previous cycle occurred as far from this location as possible—namely, about the central Atlantic Ocean. This location is nearly central to the Appalachians, Hercynian mountains, and the Post-Carboniferous mountains of Brazil and Africa.

In favor of the first alternative of Holmes and Pekeris we have the advantage of the thermal explanation for the localization of convection currents. The predominant development of thrusts inclined toward the ocean basins also indicates, by analogy with the model structures, currents rising under the
continents. On the other hand, when slightly stronger crusts were used in the model, the direction of thrusting reversed. A tenuous argument in favor of oceanic rising currents is the distribution of deep-focus earthquakes. Visser, Leith and Sharpe, and Gutenberg and Richter all agree that foci of deep earthquakes in the circum-Pacific region seem to lie on planes inclined at about 45° toward the continents. It might be possible that these quakes were caused by slipping along the convection-current surfaces. These flow surfaces would be expected to dip toward the continents on the hypothesis of Pacific up-currents.

In contrast to the rest of the paper, this section is purely speculative.

Conclusion.

Of the five primary forces which have been invoked by various theorists to explain orogenic deformation of the earth's crust, three are totally inadequate in magnitude. In contrast, thermal contraction may produce abundant force, but is open to other objections as a mountain-building force. Chief among these are: (1) thermal contraction does not seem capable of providing sufficient shortening to produce the Tertiary mountain system; and (2) transmission of compressive stress through the earth's crust over long distances to provide the localized deformation of the mountain systems is greatly hindered by the viscous drag of the substratum on the overriding mass. Calculations indicate that this viscous drag would cause uniform thickening of the crust instead of localized downfolds. Kuenen produced localized downfolds in his model under conditions in which the crust transmitted the compressive stress as it would have to according to the theory of thermal contraction. Dimensional analysis of Kuenen's model shows that it is dynamically incorrect. A dynamically similar model was constructed and, under compression similar to Kuenen's, showed no formation of a downfold, but thickening of the crust at the point of stress application.

Pekeris', Vening Meinesz' and Hales' calculations show that convection currents can develop adequate compressive stress in the crust to cause orogenesis. A new mechanism of solid flow is suggested for the substratum, with experimental illustrations of this type of flow from two sets of creep tests. Consideration of what seem to be the first order factors leads to
the hypothesis of a convection-current cycle. Experimentation
with a dynamically similar model which simulates the action of
the convection-current cycle produces effects resembling dia-
strophism of the earth's crust. The structures developed by
the action of these currents in the model show striking resem-
bliance to the structures developed in the earth. The phases of
the convection-current cycle correlate with the phases of the
orogenic cycle.

The hypothesis of orogeny developed from these observations
is attractive because it seems to satisfy better than any other
the three fundamental conditions of a mountain-building
mechanism.

1. Provision of an adequate compressional force.
2. Local provision of sufficient contraction for orogenesis.
3. Explanation of the intermittent nature of orogenic processes
   and the threefold character of the mountain-building cycle.

Evidence sufficient to establish any theory of this kind can
hardly be found within a short time, and has never been put
forward in support of any previous theory. This difficulty
seems inherent in the very nature of the problem. Accordingly
the present theory, necessarily founded on insufficient evidence
is here presented because it can be effectively tested only by use
and the critical scrutiny of others.

Acknowledgments.

The writer wishes to express his deep appreciation to Mr.
A. Lawrence Lowell and the Lowell Institute for providing
incentive for the present work in the form of an invitation to
deliver a series of lectures at the Lowell Institute. The Lowell
Institute also financed the construction of the models. The
suggestions of Professors L. J. Henderson, P. W. Bridgman,
R. A. Daly, M. P. Billings, and Mr. R. W. Vose were most
helpful.

References.

Adams, F. D., and Bancroft, J. A.: "Internal Friction during Deformation
and the Relative Plasticity of Different Types of Rocks," Jour.
Press, 1933.


Society of Fellows,
Harvard University,
Cambridge, Mass.