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TECHNICAL REPORT

THE DEEP STRUCTURE OF THE EARTH INFERRED FROM A SATELLITE'S ORBIT
PART I: THE DENSITY ANOMALY

by

Ernst W. Schwiderski
Computation and Analysis Laboratory

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U. S. NAVAL WEAPONS LABORATORY
DAHLGREN, VIRGINIA

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TABLE OF CONTENTS

APPENDICES:

ABSTRACT

A model of a fluid mantle is described which retains the significant features of the earth's interior and is adjustable to the outside gravity field. It is shown that the density anomaly is within the order of approximation governed by Laplace's equation regardless of a fluid or solid mantle hypothesis. The density anomaly is numerically evaluated on the basis of the most recently available satellite-sensed gravity data. While it is virtually impossible to interpret the computed world density maps in terms of tectonic features of the earth's crust on the grounds of a solid mantle assumption, the fluid mantle theory permits such an interpretation which is consistent up to many small details. Since every density anomaly computed seems to have played some role in the evolution of the crustal tectonics of today and, vice versa, because every major tectonic feature appears to be explainable by just the computed density anomalies, it is concluded that the gravity data used yielded a resolution of all essential density anomalies of the mantle. While it seems almost incredible that a satellite is sensitive enough to feel all those little density variations of the mantle, it must be hailed as a triumph of modern science and technology to read off such an enormous amount of information from the path of a satellite.

FOREWORD

Based on empirical evidence it is generally agreed by all geophysicists that the mechanical processes, which affected the earth's crust and produced the gigantic tectonic features of the world that captivate the sight-seer and the scientist of today, must be attributed to thermal activity in the mantle. It is the intention of the present report to demonstrate that studies of the following sort are potentially promising to substantiate this conjecture and, hence, open a way to a well-founded understanding of the earth's interior. Since the thermally produced density anomalies of the mantle manifest themselves through the gravity force in the path of an orbiting satellite, one recognizes a close link between the exploration of outer space and the exploration of inner space which can be of mutual benefit. Indeed, the subsequent use of the most recently available satellite-sensed gravity data proves the almost incredible fact that a satellite soars over the density highs and lows of the earth at an altitude of 200 km and more just as a creeper crawls over hill and dale. At this point it is the author's obligation to acknowledge the superior accuracy of the satellite gravity coefficients which were made available by the Astronautics Division of the U. S. Naval Weapons Laboratory headed by Mr. R. J. Anderle, and without which the following conclusions could not have been possible.

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/s/ BERNARD SMITH
Technical Director

SYNOPSIS OF GEOPHYSICAL RESULTS

It is one of the most fortunate coincidences in scientific research that the exploration of outer space provides the geophysicist with significant data for the exploration of inner space. This important link is established by the earth's irregular mass distribution which through the gravity force affects the path of an orbiting satellite and becomes, thus, visible to the observer on the earth. In the following study the essential density anomalies of the earth's mantle are inferred from a satellite-sensed outer gravity field by a one-to-one relationship based on the hypothesis of a fluid mantle. Since this theory associates the density anomalies in the mantle with thermally driven convection currents lasting over multimillions of years, it is possible to interpret every density low and high in the computed world density maps (Figs. 7 and 8) as a fluid source or sink, respectively. Hence, if one follows the mantle currents from the sources to the neighboring sinks and evaluates simultaneously the bending, compression, and tension forces, which these flows exert on the floating thin (5 km) ocean floors and on the thick (35 km) continental crusts, then one can envision in time-lapse motion how the earth's tectonic features might have evolved through the geological ages. In fact, it is a rather frightening disclosure to see the thermally activated mantle currents playing at ease with the covering crust which man has yet to penetrate.

Due to the strong grip, which the undercurrents hold on the thicker continental crust, one can visualize the long predicted drifts of the continents which inflicted under seismic and volcanic activity severe damages on the surrounding thin ocean floors. On the continents the diverging currents from the low-density sources can be considered as at least partly responsible for the construction of the vitally important drainage systems of the world. The same tension-effecting sources appear to have ripped off chunks of the continents such as Greenland and Madagascar which they are now thrusting toward the nearby sinks. Under Southeast Africa the torque-producing low-density source seems to be the cause of the earth's most awesome rift valleys which slice the entire continent from south to north. Perhaps the most spectacular effects of the mantle currents can be imagined over high-density sinks between opposing low-density sources. It is not difficult to conceive of swelling currents which have successively folded together the world's mighty mountain systems. On their peripheries one can see majestic mountain ranges or arcs winding between the sources while yielding gently to their strengths.

Along the ocean shores continental drifts and local undercurrents can be seen to have effected trenches and island arcs through overthrusting of the thin oceanic crust. The southward drift of Eurasia, which appears to produce a counterclockwise rotation of the Pacific floor, is opposed by the southwesterly drift of North America and by the northeastward thrust of Australia. This may well explain the mysteriously straight Northeast Pacific Fracture Zones as tension-effected brittle deformations and the more yielding West Pacific Fold Ridges as compression-effected plastic deformations of the oceanic crust. Since volcanic irregularities accumulate distinctly on or along fold ridges, fracture zones, and trenches, it is suggested that volcanic activity might be ignited by producing pressure lows between the mantle and the floating crust through one of the following three mechanisms: by folding and uplifting, by fracturing and faulting, or by fracturing and over-thrusting of the crust. In agreement with seismic observations and with heat flow measurements the Mid-Atlantic Mid-Indian Ocean, and South Pacific-Antarctic Ridges appear to have been folded up between opposing low-density sources. Only the East Pacific Rise is resolved as an up-thrusted ocean floor (see Fig. 3b).

With respect to the empirical gravity field used it can probably be said that the most recent satellite data yielded just the right resolution of all essential density anomalies of the mantle. They display a rather rapid decay with the mantle depth and an almost stationary behavior with time. In fact, crustal irregularities known since Paleozoic age seem to be explainable by the same mantle currents of today. The present positions of the subcurrents were even pointed out as favorable to verify the global continental drift from one ur-continent as it was ingeneously envisioned by Wegener so early in 1912.

1. Introduction

While the exploration of outer space is advancing at a spectacular pace, the equally fascinating science of inner space still remains in its initial stages. With the exception of some empirical facts, hypothetical theories and conclusions concerning the interior of the earth are controversial and changing. All that is conclusive is that the physics of the earth's interior is subject to Newton's classical laws of mechanics. However, as the principles of mechanics are grouped around the essentially different theories of solids and fluids, two rather opposed directions are being followed by geophysicists of the last half century.

Seismology (see Gutenberg [1], Heiskanen and Meinesz [2], Jeffreys [3], Scheidegger [4], and Bullen [5]) has established the fact that the earth's interior is divided by sharp discontinuity surfaces into the three major layers (Fig. 1): the crust, the mantle, and the core. The crust which averages a thickness of 5 km under oceans and 35 km under continents is considered solid. The outer surface of the crust displays the topography of the earth with its beautiful mountains and valleys over the continents and its monstrous ridges and deeps in the oceans. They have inspired artists as well as scientists who seek to explain their mysterious formation.

The core of the earth, which has a radius of about 3,500 km, appears to be divided by a transition layer of about 300 km thickness into an inner core and an outer core. The outer core, which is about 2,000 km thick is definitely a fluid of low viscosity as it represents a shadow zone for transverse waves. Since longitudinal waves which enter the core increase their speed in the inner portion, it is concluded that the inner core might be rigid.

The mantle between the crust and the core, which is roughly 2,900 km deep, transmits transverse waves as well as longitudinal waves. However, the transmission velocity appears to be somewhat higher in the lower portion of the mantle so that the mantle must be divided into an inner mantle of about 2,000 km thickness and into an outer mantle of 600 km depth with a transition layer that seems to be 300 km deep. From the fact that the mantle acts as a solid with respect to seismic waves, it is concluded that the mantle is either strictly a "solid" or a "fluid" with solid characteristics with respect to short term forces (such as seismic forces) and with liquid properties with respect to long term forces (such as thermal forces acting over multimillions of years). It is this important uncertainty which divides the geophysicist into two schools. One school under Jeffreys [3], MacDonald [6,7], and Munk [6] as principals promotes the theory of a solid mantle. The other school under Wegener, Meinesz [2], and Runcorn [8,9,10,11] as principals advances the theory of a fluid mantle.

Because of the highly liquid properties of the outer core, it is generally agreed by all geophysicists that the mechanical processes, which affected the crust and led to the fascinating topography of the earth, must have occurred in the mantle with pronounced concentration in the lighter outer layer. This hypothesis is supported by the observed shallowness of earthquakes the foci of which rarely exceed the

600 km depth of the outer mantle. It is also generally accepted by both schools that the mechanical processes are essentially due to heat differences in the mantle which are believed to originate from heat sources (radio active material) in the core and in the mantle.

Under the hypothesis of a solid mantle the heat differences are exclusively due to heat conduction from unevenly distributed heat sources which are assumed to exist especially in the earth's mantle. The highs and lows in the earth topography are attributed to regional expansions or contractions of the mantle under the crust which consists of lighter material. Extreme expansions or contractions of the mantle result in large stress differences which trigger fractures, faulting, and violent earthquakes.

The theory of a fluid mantle ascribes the heat differences to heat transfer which includes conduction and convection. This theory receives a major support from the physical fact that convection currents occur even in homogeneous fluid layers heated from below. If the buoyant forces of the heated lighter fluid under the heavier masses overcome the viscous forces in the fluid, a potentially unstable arrangement is reached which tends to stabilize itself through cellular convection flows. Such motions subject the crust to vertically down-bending or up-bending forces as well as to horizontal compressions or tensions.

Bending forces may be thought to be associated with moderately strong currents. A weak down-going flow will produce a down-bending of the thin crust under oceans as well as of the thicker crust under continents (Fig. 2a). On the other hand a weak up-coming flow must be expected to cause an up-bending of the crust regardless of its thickness (Fig. 2b). The horizontal compressions or tensions associated with such moderate motions may be considered as non-critical. However, as was pointed out by Meinesz, Runcorn, et alii, a locally strong convection flow may generate critical horizontal compressions or tensions which result in a violent uplifting or down-buckling of the crust. Under the thin crust of the oceans a descending flow will be connected with a down-buckling leaving behind a large ocean deep (Fig. 3a). A strong ascending flow will thrust up an ocean rise (Fig. 3b). Under the thick crust of the continents the opposite results must be anticipated. A severe compression over a down-going flow will fold up mountains (Fig. 4a). On the other hand, a critical tension over an up-coming flow will produce a rift valley.

Convection flows are also thought to have created the continents from one urcontinent through splitting the crust and drifting the pieces into the present position. Since a breaking of the urcontinent has been thought to require large convection cells which exceed the present depth of the mantle, Meinesz (see Heiskanen and Meinesz [2, p. 421]) postulated an earth with essentially no core at the time of the creation of the continents. However, it is also possible that the breaking of the urcontinent and the subsequent continental drift may be the result of the combined action of smaller convection cells on the crust.

In order to reach a conclusive decision between the solid mantle hypothesis and the fluid mantle assumption, it is important to determine the proper equations which govern the dominant mechanical phenomena in the solid or in the fluid. Moreover, these equations must be supplemented by appropriate boundary conditions. After establishing the corresponding solution it must be thoroughly scrutinized against the observed physical facts.

Up to now such a comprehensive test of either theory was virtually impossible. The equations which have been considered were highly simplified and the empirical data needed to set up proper boundary values were much too sporadic. Conclusions based on such models could be used for or against either one of the two theories. The fine structure of the earth's mantle requires a detailed theoretical and experimental investigation.

It is one of the most fortunate by-products of the exploration of outer space that it simultaneously provides the geophysicist with very significant data for the exploration of inner space. For the exploration of the mantle and crust this important link is established by the earth's gravity force which affects the path of a satellite orbiting the earth. Since the gravity field is uniquely determined by the mass distribution of the earth, a satellite senses the earth's surface gravity from which the mass and heat distributions can be computed on the basis of a proper solid or fluid mantle model. This access to the mass density inside the earth is a key to a study of the mechanical phenomena occurring in inner space.

The fundamental idea of exploring inner space through measuring the gravity field of the outer space is due to Meinesz (see Heiskanen and Meinesz [21]). His ingenious interpretations of his own extensive measurements of the surface gravity represent the framework of the convection theory of a fluid mantle. Following Meinesz's idea Runcorn [11] made the first attempt to establish a one-to-one mathematical relationship between the outside gravity field and the assumed convection currents in a postulated fluid mantle. Runcorn based his investigations on Chandrasekhar's [12,13] general works on cellular convection currents in spherical shells.

Adopting the ideas of Meinesz, Runcorn, and Chandrasekhar the following study derives a model of an assumed fluid mantle which is adjustable to a given outside gravity field and which is believed to retain the significant global features of the earth. Hence, provided the hypothesis of a fluid mantle is correct and assuming that the available gravity data are sufficiently accurate, the model should meet satisfactorily all expectations characterizing a proper description of the earth. The corresponding complete set of equations, which governs the convective motion in the mantle, is simplified without loss of essential generality. As a result of this procedure the potential equation is obtained for the density anomaly (= density deviation from the horizontal average) in the mantle which can be solved without the knowledge of the entire flow field.

While the solution of the flow equations is left to the forthcoming Part II of these investigations, the density anomaly is computed on the basis of the most recently obtained satellite gravity data (see Anderle [14]). The results are displayed in Figs. 7 and 8. Provided one accepts the theory of a fluid mantle with the interpretation of descending and ascending flows under oceans and continents given above, one recognizes an agreement between the computed density anomaly and the well-known tectonic features of the earth up to many small details.

2. The Model of a Fluid Mantle

In the following study the mantle of the earth is considered as a spherical shell of an almost incompressible Newtonian fluid of very high viscosity. Creeping thermal convection currents, which are due to the earth's gravitational force, are assumed to be governed by the Stokes and Boussinesq approximations of the Navier-Stokes equations of steady laminar motion (compare Runcorn [11] and Chandrasekhar [12,13])

$$\nu\nabla^2\vec{v} = \nabla p - \rho\vec{g}, \tag{1}$$

the continuity equation

$$\nabla \cdot \vec{v} = 0, \tag{2}$$

the gravity potential integral

$$U = \frac{GM_c}{r} + G\int_{SM} \frac{\rho(r_1,\theta_1,\varphi_1)}{|\vec{r} - \vec{r}_1|}\, dV_1\,, \tag{3}$$

the equation of gravity

$$\vec{g} = \nabla U, \tag{4}$$

the heat (energy) equation (for ε see Sec. 3)

$$\nabla^2 T + \varepsilon = 0, \tag{5}$$

and an equation of state (see Sec. 3)

$$\rho = \rho(p,T). \tag{6}$$

These equations must be supplemented by the following boundary conditions:

$$\rho_0 = \frac{3}{4\pi(a^3 - b^3)} \int_{SM} \rho(r_1, \theta_1, \varphi_1)\, dV_1 , \tag{7}$$

$$M = \frac{4\pi}{3}(a^3 - b^3)\rho_0 = M_E - M_C , \tag{8}$$

$$\rho(b, \theta, \varphi) = \rho_b , \tag{9}$$

$$U(a, \theta, \varphi) = \frac{GM_E}{a}\left[1 + \sum_{n=1}^{\infty} \sum_{m=0}^{n} P_n^m(\cos\theta)(C_{nm}\cos m\varphi + S_{nm}\sin m\varphi)\right], \tag{10}$$

$$\vec{v}(a, \theta, \varphi) = \vec{v}(b, \theta, \varphi) = 0. \tag{11}$$

The notations are:

(r, θ, φ)	polar coordinates.
$\vec{r}$	radius vector to any point in space.
$dV_1 = r_1^2 \sin\theta_1\, dr_1\, d\theta_1\, d\varphi_1$	volume element around the point $\vec{r}_1$.
$a, b \approx 0.55a$	outer and inner radii of the spherical mantle "SM".
∇	nabla differential operator.
$\vec{v} = (v_r, v_\theta, v_\varphi)$	velocity vector.
$\vec{g} = (g_r, g_\theta, g_\varphi)$	gravity vector.
G	gravity constant.
U	gravity potential.
(C_{nm}, S_{nm})	coefficients of gravity at the earth's surface (determined from satellite observations).
$(M, M_C, M_E = M + M_C)$	total masses of the mantle, core, and earth.
ρ	density of the mantle.
ρ_0	average density of the mantle.
ρ_b	constant density of the mantle at the inner surface $r = b$.
p	pressure in the mantle.

T temperature in the mantle.

ν' kinematic viscosity of the mantle.

ϵ heat source distribution in the mantle reduced by the thermometric conductivity.

A proper evaluation of the model specified above relies essentially on the intention of the study to either support or disprove the fluid mantle theory with its consequences upon the earth's tectonic features. Accordingly, the effects of the earth's rotation are ignored. The equations of motion (1) exclude the centrifugal and Coriolis forces. The mantle, which includes the mass of the thin crust, is assumed as a perfect spherical shell without the equatorial bulge. In order to be in agreement with these simplifications, the gravity coefficient C_{20}, which owes its large magnitude to the equatorial bulge, is neglected. Various estimates for anomalous C_{20}, which have been used in the numerical computations, showed no qualitative changes of the results.

The Stokes slow motion approximation, on the basis of which the inertial terms in Eq. (1) and the convection terms in Eq. (5) are neglected, is justified as they cannot affect the qualitative features of the anticipated creeping currents. In fact, it is possible to set up an iteration procedure for the solution of the complete equations of motion in which the integral of Eqs. (1) through (6) assumes the role of a first approximation. The neglect of the convection terms for the temperature is also desirable, because an analogous simplification of a solid mantle model would result in the same heat equation. In other words, the temperature distribution in the earth's mantle is at least qualitatively governed by Eq. (5) regardless of a fluid or solid mantle hypothesis. This important result appears to reflect the fact (see Sec. 1) that a fluid mantle enjoys also features of solids. However, while the fluid mantle theory can historically explain the present temperature arrangement by the natural phenomenon of thermal instability, the solid mantle theory must make a proper, a priori, assumption about the original heat source distribution (see MacDonald [7]). Nevertheless, the conclusive support of either one of the two theories must be left to the final interpretation of the explicit results in terms of the well-known tectonic features of the earth.

The slow convection currents are considered as steady because creeping motions of large spatial extent are known to have extremely small damping coefficients (see Lamb [15, p. 640], Lugt and Schwiderski [16], and, for another justification, Runcorn [11]). The heat equation (5) excludes dissipation as a second order effect. The reduced heat source distribution ε is assumed as constant or at least sufficiently independent of latitude θ and longitude φ.

The viscous fluid of the mantle is characterized by a constant Newtonian kinematic viscosity ν. Investigations of Non-Newtonian fluids (see, for instance, Lugt and Schwiderski [17]) revealed the same qualitative features as Newtonian liquids for sufficiently slow motions. Arguments against a uniform kinematic viscosity throughout the outer and inner mantle are debatable (see Heiskanen and Meinesz [2, p. 403]). The small density decrease in the upper mantle may simply be due to active convection currents which penetrate into the lower mantle of normally higher density (due to the increased pressure) only when they become sufficiently strong. In fact, the following numerical results yielded density anomalies which decrease very rapidly with depth (Fig. 6). For example, the density anomaly under the Himalayan Mountains (compare Figs. 7 and 8) vanishes before the lower mantle is reached. In any case, whatever other assumptions concerning the fluid constant ν one may prefer, because of the extremely slow motions in question, no drastic changes of the results in favor or against the fluid mantle theory can be expected.

As follows from Eqs. (9) and (10) the heat equation (5) is properly supplemented by boundary data at the inner and outer surface of the mantle. The Navier-Stokes equations (1) are directly supplemented by the boundary values (11). The constant temperature at the inner surface appears justified as the very fluid outer core (Sec. 1) can be assumed to heat the mantle in a uniform manner from below. This assumption tends also to prevent convection currents from entering the lower mantle, which explains the latter condition (11) and reflects the general opinion of geophysicists of today (see Heiskanen and Meinesz [2], Mac Donald [7], and McKenzie [18]). At the surface of the earth the temperature is adjusted to the gravity potential obtained from satellite observations. It is important to note that through those empirical boundary values possible effects of heat convection and of heterogeneous heat sources are correctly accounted for at least near the outer boundary of the mantle. The hypothesis of a solid crust of negligible thickness leads to the first of the two boundary values (11).

3. The Perturbation Equations

The integral of the equations of motion (1) - (6) may be sought as a perturbation of the following static solution which is denoted by the subscript s:

$$\vec{v}_s \equiv 0, \qquad \rho_s = \rho_s(r) = \rho(p_s, T_s), \tag{12}$$

$$\nabla p_s = \rho_s \vec{g}_s, \quad \nabla^2 T_s + \varepsilon = 0, \tag{13}$$

$$U_s = \frac{GM_C}{r} + G\int_{SM} \frac{\rho_s(r_1)}{|\vec{r} - \vec{r}_1|} dV_1, \quad \vec{g}_s = \nabla U_s . \tag{14}$$

These equations must be supplemented by the boundary conditions (see Eqs. (7), (8), and (9))

$$\rho_s(b) = \rho_b, \quad M = 4\pi \int_b^a \rho_s(r) r^2 dr . \tag{15}$$

It may be noted that Eq. (14) together with the latter condition of Eq. (15) results in (compare Eq. (10))

$$U_s(a, \theta, \varphi) = \frac{GM_E}{a} . \tag{16}$$

The explicit integration of this static problem, which depends only on r, requires the full specification of the equation of state $\rho(p,T)$ and the reduced heat source distribution ε. Fortunately, the subsequent perturbation equations contain only the static density distribution $\rho_s(r)$ which is more accessible through seismic measurements than $\rho(p,T)$ and ε.

With the substitution

$$\left.\begin{array}{lll} \vec{v} = \vec{v}', & \vec{g} = \vec{g}_s(r) + \vec{g}', & U = U_s(r) + U', \\ p = p_s(r) + p', & \rho = \rho_s(r) + \rho', & T = T_s(r) + T' \end{array}\right\} \tag{17}$$

one derives from Eqs. (1) - (6) after neglecting all second order terms in the perturbation variables $\vec{v}'$, $\vec{g}'$, U', p', ρ', and T' the linear perturbation equations:

$$\nu\nabla^2\vec{v} = \nabla p' - \rho_s(r)\vec{g}' - \rho'\vec{g}_s(r), \quad \nabla\vec{v} = 0, \tag{18}$$

$$U' = G\int_{SM} \frac{\rho'(r_1,\theta_1,\varphi_1)}{|\vec{r} - \vec{r}_1|}\, dV_1, \quad \vec{g}' = \nabla U', \tag{19}$$

$$\nabla^2 T' = 0, \qquad \rho' = -\alpha\rho_0 T'. \tag{20}$$

The latter Eq. (20), which correlates the density anomaly ρ' with the temperature anomaly T' by means of the constant thermal expansion coefficient α, is evidently a simple version of the equation of state (6). In contrast to the static values (ρ_s, p_s, T_s), which obey a more complicated law (Eq. (12)), it appears justified to assume the relationship between the small deviations (ρ', p', T') as essentially independent of the pressure anomaly p'. As was mentioned above because of the lack of a proper equation of state (12) and of an appropriate heat source distribution, the r-dependent static density $\rho_s(r)$ occurring in Eq. (18) may be taken from the seismic measurements published by Bullen [5].

A solution of the perturbation equations (18) through (20) is specified by the boundary values (see Eqs. (7) - (11), (15), and (16))

$$\vec{v}(a,\theta,\varphi) = \vec{v}(b,\theta,\varphi) = 0, \qquad \rho'(b,\theta,\varphi) = 0, \tag{21}$$

$$U'(a,\theta,\varphi) = \frac{GM_E}{a}\sum_{n=1}^{\infty}\sum_{m=0}^{n} P_n^m(\cos\theta)(C_{nm}\cos m\varphi + S_{nm}\sin m\varphi). \tag{22}$$

It may be noted that the boundary data (21) and (22) guarantee that the perturbation quantities $(\vec{v},\vec{g}',U',p',\rho',T')$, which integrate the differential equations (18) - (20), all average zero over any spherical surface of radius r ($b \leq r \leq a$), for instance,

$$\int_{\theta=0}^{\pi} \int_{\varphi=0}^{2\pi} \rho'(r,\theta,\varphi) r^2 d\theta d\varphi = 0. \tag{23}$$

This verifies the meaning of the perturbation variables as anomalies, i.e., as deviations from the corresponding horizontal averages which are identical with the static integral ($\vec{v}_s = 0, \vec{g}_s, U_s, p_s, \rho_s, T_s$).

The remaining boundary value problem (18) through (22) consists of two separated integration problems. The flow-independent density and temperature anomalies will be investigated in the following sections. The flow field, which depends on the density anomaly, will be studied together with its consequences regarding flow cell formations and shear stresses in the forthcoming Part II of these investigations (see [19]).

4. The Density Anomaly

The perturbation equations (20) lead to Laplace's potential equation which governs the density anomaly in the earth's mantle

$$\nabla^2 \rho' = 0. \tag{24}$$

Under the pertinent boundary conditions (21) and (22) its solution is easily established in terms of spherical harmonics:

$$\rho' = \frac{M_E}{4\pi a^3} \sum_{n=1}^{\infty} \sum_{m=0}^{n} \rho_n(r) P_n^m(\cos\theta)(C_{nm} \cos m\varphi + S_{nm} \sin m\varphi), \tag{25}$$

with

$$\rho_n(r) = \frac{(2n+1)(2n+3)}{1 - \left(n + \frac{3}{2}\right)\left(\frac{b}{a}\right)^{2n+1} + \left(n + \frac{1}{2}\right)\left(\frac{b}{a}\right)^{2n+3}} \left[\left(\frac{r}{a}\right)^n - \left(\frac{b}{a}\right)^n \left(\frac{b}{r}\right)^{n+1}\right]. \tag{26}$$

It is interesting to note that the density anomaly ρ', which within the order of approximation is valid for a fluid and solid mantle model, is independent of all fluid constants. The essential parameters are the total mass M_E of the earth, the outer and inner radii (a,b) of the mantle, and the coefficients (C_{nm}, S_{nm}) of the gravity potential at the earth's surface.

The numerical evaluation of the density anomaly of the mantle (Eq. (26)) was based on the most recent gravity coefficients available from satellite observations (see Anderle [14]). More specifically a closed field of coefficients up to n = 12 with several resonant harmonics up to n = 19 was used. As was mentioned in Sec. 2 the large coefficient C_{20} was forced to zero in agreement with the neglected equatorial bulge. Assumed anomalous values for $C_{20} \neq 0$ did not change the distribution of low and high densities which is of primary importance.

In order to test the sensitivity of the density anomaly with respect to the accuracy of the gravity coefficients, several computations were carried out with varied coefficients. The results remained qualitatively and quantitatively very stable. However, as was anticipated considerable differences were obtained when the field of coefficients was replaced by smaller sets which were earlier available from less accurate satellite observations. The resolution decreased with the extent of the field of coefficients. For example, the smaller set of coefficients which was published about two years ago by Anderle [20] resolves, e.g., the enormous masses of the Himalayan, Rocky, and Alpine Mountains only as saddle points between density highs and lows (compare Figs. 7 and 8). Of course, the deep-rooted features such as the highs under the Andes, Greenland, the Indonesian Archipelago and the lows under Canada, Siberia, and the northern Indian Ocean are correctly recognized. Computations based on the gravity coefficients obtained by Gaposchkin and Kozai [21] displayed only slight improvements over the older data by Anderle [20].

A comparison between the corresponding anomalies of density ρ' and gravity potential U' at the earth's surface (compare [21]) has also been made. Since the latter is obtained through integration of the density anomaly (Eq. (19)), the gravity potential is considerably smoother and reveals rather few tectonic features of the earth.

The density anomaly (Eq. (25)) has been evaluated at the spherical surfaces $r_j = a - (a - b)j/4$, $(j = 0,1,2,3)$. The results at the earth's surface ($r_0 = a$) and at one quarter of the mantle depth ($r_1 = a - (a-b)/4$) are qualitatively sketched as world density maps in Figs. 7 and 8. Both maps are rough copies of originals composed of several pieces each of which was pointwise plotted by an electronic and photographic process with some distortions. No effort was made to improve the quantitative contents of the maps as this study is only concerned with the phenomenological features of the earth's interior.

5. Density Anomaly and Earth's Tectonics

As can be seen at first sight the world density maps presented in Figs. 7 and 8 contain such an enormous amount of information that one is tempted to question their physical meaning. In fact, it seems incredible that an orbiting satellite is sensitive enough to really feel all those little density anomalies which deviate from the mean density at the outer surface of the mantle ($\rho_a \approx 3.3 g/cm^3$) by less than 0.16%. If the results are physically acceptable, then one concludes that a satellite soars over the density highs and lows of the earth at an altitude of 200 km and more just as a creeper crawls across country. Assuming again that this is true, then it must be hailed as a triumph of modern science and technology to read off all those little wiggles from the path of a satellite.

A second look at the density maps seems to deepen the credibility gap. It is immediately clear that there exists no identical correlation between the surface density anomaly and the well-known topography of the earth (compare the early statements of Munk and MacDonald in [22]). The line of zero density anomaly does not even fairly follow the coast line of the continents whether one includes the continental shelf or not. Nevertheless, the following physical interpretation of the density anomaly under the earth's crust will restore the needed confidence in the geophysical meaning of the density maps computed. Indeed, it will be demonstrated that the density variations match the known tectonic features of the earth even up to many small details.

A first point toward confidence can be gained from the fact that the small density deviations computed are correct in their order of magnitude. The relative density anomaly given above is of the same order as the relative topographic height (= topographic height divided by sea-level height). Furthermore, the differences between the density anomaly and the earth's topography must be expected on geophysical grounds. With the exception of small depressions and islands the topography is characterized by positive data over continents and by negative values over oceans. In contrast to this simple feature density highs and lows must be anticipated under continents as well as under oceans. For example, while the immense crustal masses of the Rocky Mountain system indicate an excess of density, the upbending of the Canadian Shield reveals a considerable deficiency of mass. Hence, a line of zero density anomaly, which has nothing in common with the continental coast line, must traverse the North American Continent.

Reading instructions for the world density maps, which translate the density anomaly into terms of tectonic features of the earth, must be derived either from the hypothesis of a fluid mantle or from the assumption of a solid mantle. As was pointed out in Sec. 2, the preference of either one of the two alternative theories belongs to that conception which permits a consistent correlation between the density and the earth's tectonics. Of course, such a decision between the two controversial hypotheses presupposes a sufficiently accurate determination of the gravity coefficients utilized in evaluating the density anomaly by Eq. (25). Though considerable perturbations (see Sec. 4) of the coefficients used did not change the qualitative contents of the maps, an improvement of their power of resolution can most probably be expected in the future. However, even if the sensitivity of a satellite permits a resolution of, say, Mount Everest and Mount Kanchenjunga, it might confuse more than contribute to the final solution of the controversy, as they are evidently the result of a joint mechanical event. The world density maps, presented here are intended to demonstrate that studies of this sort are potentially promising to bring about such a decision and, hence, open a way to a well-founded understanding of the physical evolution of the earth's interior.

Unless the solid mantle theory is specifically mentioned, the subsequent interpretation of the density anomaly is strictly based on the fluid mantle hypothesis. In order to understand the density maps, one may visualize a fluid mantle heated from below. Thermally driven cellular convection currents have resulted in a density distribution which today has the pattern displayed by the maps in Figs. 7 and 8. If viewed from the earth's surface, each density low or high can be considered as a source or sink, respectively, provided the density maps are not significantly distorted by an overly sharp resolution of crustal irregularities. Since the density maps under consideration do not resolve such major massifs as the Himalayan and Kunlun Mountains or the Rocky Mountains and the Sierra Nevada as separate density highs, the maps presented can be considered with some confidence as void of treacherous resolution (see Sec. 7). Nevertheless, the full confirmation of this important presupposition is part of the necessary scrutiny of the physical meaning of the density maps.

As the sources feed their neighboring sinks the convective motions subject the plastic crust covering the mantle to vertical and horizontal forces. While the vertical forces tend to bend the plastic crust, the horizontal forces produce tensions and compressions through translation and rotation. The resulting deformations should generally be continuous (nonviolent) with gentle elevations or depressions as major tectonic effect . However, as stresses may accumulate at certain points up to critical values, abrupt releases can excite short-term discontinuous (violent, disastrous, or catastrophic) deformations effecting rough tectonic irregularities such as continental mountains and valleys, oceanic rises and deeps, fractures, faults, and folds.

Since thin plastic sheets resist deforming forces in a different manner than thick plastic layers, a proper translation of the density maps into terms of tectonic features must evaluate the thin oceanic floor and the thick continental crust according to their specific features. This is of particular importance in the transition regions between oceans and continents. The geometric arrangement of the sources and sinks (see Figs. 7 and 8) is also significant with respect to their distance and symmetry. For example, the thick continental crust may react to some extent just as the thin oceanic crust if the distance of two sources opposing each other is sufficiently large. Hence, every existent tectonic feature of the world must be considered individually and one must accept similar effects in spite of different causes. Vice versa, one must also allow for different effects from similarly seeming causes as they may have occurred at different times. Finally, since it is virtually impossible to predict the precise outcome of a discontinuous deformation, only major tectonic features can be expected to yield a physical explanation.

In spite of all the fascinating mystery of the evolution of the earth the following simple translation principles (T.P.) can be used to interpret the density anomalies into crustal tectonics up to many details (compare Sec. 1):

T.P. I : Moderate high-density sinks and low-density sources, in which horizontal stresses are negligible, cause a non-violent down-bending or up-bending of the crust under oceans as well as under continents (Fig. 2). The affected ocean floors or continental plains should be smooth with perhaps gentle depressions or elevations. In depth the crust should retain its original uniform layering.

T.P. II : Extreme high-density sinks and low-density sources in which critical horizontal compressions or tensions are of dominating strength, may deform the crust under oceans and under continents in an opposite manner which is characteristic for a fluid mantle.

T.P. IIa : Under the thin crust of the oceans critical horizontal compressions effected by a high-density sink should amplify the normal down-bending of the oceanic floor into a possible down-buckling (Fig. 3a). The resulting ocean deeps, basins, abyssal plains, or troughs should be marked by a more or less warped and fractured crust depending on the violence of the deformation.

T.P. IIb : Low-density sources in connection with horizontal tensions should tend to turn the normal up-bending of the ocean floor into a violent up-thrusting of oceanic rises with rough reliefs (Fig. 3b). The cellular motion under the rise should resemble a small water spout.

T.P. IIc : Under the thick continental crust a high-density sink with severe horizontal compressions causes a violent up-folding of mountains (Fig. 4a). The squeezing-up of a mountain system by two or more opposing low-density sources feeding one common sink must be considered as the most catastrophic event that affects the earth's crust and leaves behind the most spectacular reliefs of many unpredictable patterns. Through the ages of geologic time the physical evolution of a "mountain system" may be schematized as follows:

At the beginning, say, in Paleozoic time two or more low-density sources folded up a thick central "core" over their common sink (compare the Kuenen photographs of a floating plastic plate under compression in Heiskanen and Meinesz [2, p. 391]). Depending on the strength of the participating down-bending forces the folded core should be higher for closely arranged sources and deeper for distant sources. More recently, in Mesozoic time and perhaps again in Cenozoic time, new mountain "ranges" or "arcs" may have been folded up around the already thickly folded core. Being driven against the deeply rooted core the younger mountains in the nearer or farther outskirts may be expected to be higher than the core. In fact, in very violent cases narrow cores may be completely overthrusted with new fold belts. In general the thick core should resist the subsequent deformations with relatively small effects, although some warping or even thrust or normal faulting due to severe compressions and possible tangential tensions (see T.P. III) is acceptable. In this connection it may be mentioned that the up-folding of mountain ranges or arcs along the periphery of the core may be substantially aided by fractures effected by abrupt releases of frictional and thermal stresses (see T.P. IV, and Figs. 7 and 8). Furthermore, it is also possible that the thin oceanic crust can be folded into an ocean ridge similar to continental mountains. The core may be simply a stable piece of crust which is concave upward.

T.P. IId : Low-density sources with critical horizontal tensions may fracture the continental crust and lead to normal or block faulting (Fig. 4b). The latter, more symmetric case should by the major cause of rift valleys (see also T.P. III).

Along the continental shores a strong low-density source may tear apart a chunk of the continent and thrust it away against the thin oceanic crust.

T.P. III : Horizontal rotations effected by the asymmetric arrangement of density sources and sinks may produce considerable tangential compressions or tensions of the oceanic floor as well as of the continental crust. While tangential compressions should cause a warping or folding effect, severe tangential tensions might result into fracturing of the crust associated with normal, block, or wrench faulting. It may be pointed out that due to these tangential forces horizontal compressions and tensions can deform the same crustal area. Hence, rift valleys are compatible with mountains (see T.P. IIc).

T.P. IV : Another source for violent deformations of the earth's crust must be anticipated at points of large density changes which coincide (see Eq. (20)) with points of extreme temperature gradients. At such regions frictional and thermal stresses simultaneously attain their maximmm values and the fluid mantle may display its dual solid property by sudden stress releases effecting fractures associated with earthquakes. Because of the asymmetry of the convection currents across the fracture planes, faulting may occur in vertical and horizontal directions. Under the thin oceanic crust normal faulting may be associated with under-thrusting leaving behind an ocean trench and island arc as shown in Fig. 5. The uplift of the crustal arc generates probably a pressure low between the mantle and the crust which results in molten magma that breaks through the crust and builds up volcanic islands especially on the over-thrusting side (see Pacific 6e).

6. A Model of the Earth's Tectonic Evolution

In order to read off the information which an orbiting satellite has to tell about the earth's tectonic evolution from the world density maps (Figs. 7 and 8), it is best to follow the action of the convection currents from their low-density sources (light colors) to their high-density sinks (dark colors). This permits the viewer of the thermally active mantle to bring the sources and sinks, which participated in effecting the tectonic feature focused on, in the right perspective for a proper evaluation of the deforming forces exerted on the floating plastic continental and oceanic crust. By applying the appropriate translation principles most of which are compiled in Sec. 5, one should be able to reconstruct the development of the crustal structure of the earth of today at least to some extent.

If one visualizes the map of density sources and sinks (Fig. 7) as being overlayed by a transparent world relief map showing the major tectonic features of the earth, one envisions a rather frightening picture of the earth. One can imagine a mantle the thermally activated currents of which play at ease with the covering crust which man has yet to penetrate. One can see continents being pushed around and chunks of them being broken off to be thrust away. The thin ocean floors appear to be warped, folded, fractured, under-, over-, and up-thrusted, just as plates of glass or ice can be damaged by bending, pushing, tearing, and wrenching forces. Perhaps the most impressive effects of the mantle currents can be realized if one focuses on the world's spectacular mountains. Surge after surge coming from the mantle's low-density sources seems to have pushed together enormous mountain systems over the high-density sinks with majestic ranges or arcs folded up on the periphery.

During the discovery of all the geological evidence known today consequential evaluation and ingenious intuition led geophysicists to predict such seemingly incredible actions and reactions; and these predictions were made without the knowledge where the needed forces really originate. Hence, the importance of the information, which a satellite appears to relay to us, lies in the fact that it is trying to tell us the sofar unknown geographical location of the sources of the deforming forces together with their strengths and directions.

The following examination of this fantastic picture is intended as a guideline for a systematic analysis of its reality. No completeness can be claimed as many more well-established geophysical and geological facts must be brought into consideration. With the forthcoming construction of the entire flow and stress fields (see Sec. 3 and [19]) more and better substantiated results and conclusions can be anticipated.

The subsequent presentation is fully coordinated with Life's Pictorial Atlas [23] and with Reader's Digest Great World Atlas [24]. Both are very helpful in the discussions as they compile in excellent relief maps most of the major tectonic features of the earth. Approximate locations of the world's major earthquake centers (taken from

Gutenberg and Richter [26]) and trenches are directly shown in Fig. 7.

6a. THE AMERICAN CONTINENTS

The deforming forces of the North American continent (see Figs. 7 and 8) originate from two joint low-density sources located under the Canadian Shield and under the Gulf of Mexico with the connecting channel under the Central Plains. The existence of both sources confirms the up-rising and southwestward-drifiting tendency of the entire continent which has been observed by geological studies. In fact, North America seems to ride on an elongated water-spout-like flow. The considerably stronger and deeper Canadian source may well explain the rather rapid uplift of the Canadian area which can actually be observed today and which, when attributed exclusively to the retreat of an assumed large ice load, leads to controversial viscosity coefficients of the mantle (see Scheidegger [4, p. 345] and Broecker [25] and Sec. 7).

The North American double source supplies under the thick continental crust the western trough-like high-density sink, which lies completely under the Rocky Mountain and Sierra Madre Ranges (see [23, p. 42]). The largest discharge is obviously received by the almost circular center southwest of the dominant Canadian source. The flow under the continental crust which feeds the eastern high-density sink under the Appalachian Mountains is distinctly moderate. The flow to all other surrounding high-density sinks, which includes the discharge of the Canadian source supplying the strong sink under the North Atlantic and Greenland, is more or less without effect on the continent as it streams essentially under the thin ocean floor. The same can be said for all counteracting low-density sources under the surrounding oceanic crust. Thus, without the complete knowledge of the flow field (see Part II in [19]), one can visualize a resultant force which thrusts North America into southwesterly direction.

The drift of the North American continent has been conjectured by many researchers from the many damages which this movement afflicts on the neighboring thin ocean floors. The important accomplishment of this monstrous movement warrants a detailed investigation which also may expound the physical meaning of the density maps computed. Obviously the major damages must show up along the Pacific coast and along the Cayman and Puerto Rican Trenches where North America meets South America (see Figs. 7 and 8, and [24, p. 139]). Indeed, while there exists no severe effect (sec Atlantic 6f) at the eastern Atlantic shore, the southwestern border belongs to the well-known Pacific ring of fire.

As the continent drifts southwestward it pushes and wrenches the Pacific floor which seems to be turning counterclockwise due to a similar yet stronger wrench effect caused by the opposing southward drift of the Eurasian continent (see Eurasia 6b). The slip along the Pacific coast is evidenced by many wrench faults of which the San Andreas Fault is the most familiar one. The pushing, wrenching, and up-bending (for the latter see the two joint low-density sources) of the Northeast Pacific floor may well explain the mysteriously straight fracture zones which appear to originate here and traverse on great circles almost the entire ocean (see Pacific 6e, Gutenberg and Richter [28], Vine [27], Menard [28, 29], Hess [30], and [23, p. 427]).

In this connection one may compare the analogous splitting of glass or ice plates under similar forces. It is important to observe that the nearby strong low-density source seems to prevent an over-thrusting of the ocean floor by the continent along the San Andreas Fault system.

At the northern shore of the Pacific the drift of North America and the similar drift of Eurasia (see Eurasia 6b) is indicated by the presence of the Aleutian Islands and Trench. As both continents move southward and toward each other they force the northern oceanic crust to over-thrust the southern ocean floor. The formation of the trench and the island arc appears to follow precisely the principle explained in T.P. IV and Fig. 5.

At the southern border of the North American continent the south component of the drift is confirmed by the existence of three trenches (see [23, pp. 260 and 427]). Along the Cayman Trench the oceanic floor of the Caribbean Sea is bisected and the northern part under-thrusts the southern portion effecting the island arc between Jamaica and Honduras. The agreement of this tectonic feature with the principle of trench formation explained in T.P. IV and Fig. 5 is very remarkable in this region. Since the relatively small oceanic crust under the northern Caribbean Sea is spanned between the continental crust under the Island of Cuba and under the Yucatan Peninsula one might anticipate an over-thrust. However the remote uplifting force of the low-density source under the Gulf of Mexico appears to accomplish the under-thrust as shown in Fig. 5.

Farther to the east of the Cayman Trench the sliding North American continent forces the North Atlantic floor to under-thrust the oceanic crust of the Caribbean Sea which seems to be responsible for the Puerto Rican Trench and the associated island arc. Again the positions of the participating source and sink satisfy the condition of the principle of trench formation (see Fig. 5). Between the Cayman Trench and the Puerto Rican Trench the appendix of the North American thick continental crust cannot slip under the thin floor of the Caribbean Sea. Nevertheless, the Windward Passage between Cuba and Hispaniola, which connects both trenches, closes the gap in the discontinuity line between the Americas. The pressure of the North American crustal appendix against the floor of the Caribbean Sea is probably released through the strong uplift of the Islands of Hispaniola, Puerto Rico, and Jamaica south of the Windward Passage and the leading edge of Cuba in the north (see [23, p. 221]).

The separating line between the two Americas appears to be interrupted by the Middle American continent. The thrust of North America caused probably two displaced fractures which continue into the Pacific as the Clipperton and the Clarion Fracture Zones(see Menard [28] and [23, p. 427]). The entrances of both fracture zones into the continent are distinctly marked by a number of volcanos (see [23, p. 227] and Pacific 6e). Since both fracture zones are displaced with respect to the Caribbean discontinuity line (one to the south the other to the north), the North American pressure appears to be released by a "block joint". It is essentially this continental block (the geophysical

"Middle America") which slides over the thin Pacific floor and effects the Middle American Trench (see [23, p. 427]). This over-thrust is not inconsistent with the principle of trench formation described in T.P. IV and Fig. 5, which applies only to trenches with ocean floors on both sides. Here, the over-thrust is favored by the trough-like high-density sink which branches off from the sink under the Great Western Mountain system to connect up with the high-density sink under the Andes (Fig. 7). In support of the physical meaning of the computed density maps and their high degree of resolution it may be mentioned that the low-density sink along the Middle American trench is confirmed by the heat flow measurements of Bullard, Maxwell, and Revelle in [31, p. 167].

The actual slip of the North American continent occurs during sudden releases of critical stresses accumulated over a more or less long time. This is indicated by the associated earthquakes, which occur along the entire Pacific and Caribbean discontinuity line. One may observe (Fig. 7) that all earthquakes seem to be shallow along the entire San Andreas Fault system, along the East Aleutian over-thrust line, and along the Caribbean under-thrust line. Deep and violent earthquakes occur all along the Middle American block joint and at the joint between North America and Eurasia at the Aleutian Islands.

After having checked out the major damages of the drifting North American continent in the direction of the motion, there remains to investigate the countereffects in the opposite direction. Here one might be tempted to substantiate the continental drift theory from one urcontinent as it was ingeneously envisioned by Wegener so early in 1912. The drift-causing density sources and sinks seem to be in the right positions to effect such a tremendous split of a joint continent consisting of North America and Eurasia somewhere over the Arctic and North Atlantic region (see Scheidegger [4, p. 239]). Nevertheless, this important question may be left to future investigations when also the timing of the event can be safely estimated in order to follow the drift over such a long distance.

The more local damage caused by the strong Canadian low-density source appears to be quite obvious. As is evidenced by the crustal fractures in the northeast, the strong Canadian source seems to have torn off (see T.P. IId) Greenland and some of the Canadian islands and is thrusting them away toward the strong high-density sink under the North Atlantic (see Fig. 7 and [24, p. 139]). Of course, this has been conjectured by Wegener (see Scheidegger [4, p. 239]) and other geophysicists but the origin of the forces needed to accomplish this gigantic feat remained subject to very specific hypotheses. For another example of the same kind one may compare the discussions of the African Rift Valleys under Africa 6c.

The analysis of the North American continent may now turn to the immediate continental deformations which may be caused by the two coupled low-density sources under Canada and the Gulf Plains. Since the beginning of geological studies the many lakes and rivers of the area over the source pair have been attributed exclusively to the retreat of the great glaciers which covered a large part of the same region. It is now (see Fig. 7) equally plausible that the low-density source pair participated in the formation of lake and river beds at least to some extent. For example, the violent separation of Greenland from North America must have been preceded by a slow plastic stretching and attenuation of the crust under Canada. The large Hudson Bay and the many other lakes, channels, sounds, etc., of Canada can certainly be used in support of this effect. If Greenland has really been torn off also from the Eurasian continent, the North and Baltic Seas both are readily explained by the same process.

The low-density sources must most probably be held responsible for the uplifting of the major mountain systems of the world (see below). Hence, an attenuation of the crust around the mountain systems and perhaps over the low-density sources should be evidenced by large lakes and river systems. In North America (see Fig. 7 and [23, pp. 42 and 74]) there are so many lakes at the foot of the Canadian Rocky Mountains and there are also the Great Lakes and the Mississippi-Missouri River system right above the low-density source between the western and eastern highlands. Of course, they all represent now the vital drainage system of the continent and the participation of the drained water masses in the construction of the lake and river beds cannot be debated.

As the low-density source pair feeds the shallow eastern high-density sink (see Figs. 7 and 8), it stands in opposition to the counteracting flow coming from the elongated low-density source under the Northwest Atlantic floor. Thus, if one invokes the principle of mountain building described in T.P. IIc and Fig. 4a it is not difficult to envision in "time-lapse motion" the successive up-folding of the Appalachian Mountain ranges back in Paleozoic age, provided one reverses adequately the slight southwesterly drift of the continent which has occurred since that time. In spite of erosion one still can see how the parallel fold belts are winding between the participating low-density sources shown in Fig. 7 while yielding gently to their strength (see [23, p. 75]). Indeed, the southern and central ranges appear to have been effected by the sources under the Gulf Plains and Canada, respectively. As the large source under the thin Atlantic floor extends under the thick continental crust to join the Canadian source, the northern fold belts assume abruptly their distinct direction. An accurate evaluation of the continental displacement with respect to the sources may lead to an estimate of the continental drift distance since the creation of the mountain system in Paleozoic time. The absence of foldings of more recent time can be explained by the continental shift which made the Atlantic source ineffective under the continent. If one follows the drift and observes the lifting effects of the approaching sources, of the dragging crustal mountain roots, and of the southwestward slanting continent one can understand the uplift of the Appalachian Mountains and of the Florida Peninsula in Cenozoic time.

When turning to the Pacific side one can again envision in time-lapse motion the evolution of the Great Western Mountain system from Paleozoic time through Cenozoic time. Participating in this construction (see Figs. 7 and 8 and [23, p. 43]) were obviously the two opposing double sources on the continent and in the ocean and the trough-like high-density sink under the mountain system. The slight northeasterly displacement of the sources and sinks appears to confirm again the southwestward drift of North America.

Perhaps the most typical uplift of a mountain system as described in T.P. IIc and Fig. 4a can be visualized at the central part, the Rocky Mountain-Sierra Nevada system (see [23, p. 74] and [24, p. 140]) in the triangle between the Canadian, the Gulf, and the large Pacific low-density sources. The eccentric appearance may easily be explained by the asymmetric arrangement of the three sources under the continental and oceanic crust. In Paleozoic time strong opposing currents repeatedly folded up the core of the system which is now known as the Great Nevada Basin. Then in Mesozoic age and again in Cenozoic time the high Rocky Mountain Ranges, the Sierra Nevada and the California Coastal Ranges were folded on along the outskirts of the core.

The already compressed crustal masses under the Nevada Basin resisted these repeated violent deformations with more or less effect. The dominant Canadian source displayed its strength by crushing and grinding the crust rather than folding it. This may explain the rather scrambled appearance of the Central Rocky Mountains. It is especially visible in the mountains north of the Snake River which virtually seem to have been driven into the Paleozoic Nevada Basin. The core appears to have released the normal compressions and tangential tensions received from these violent currents by (see T.P. III) thrust faulting and normal faulting, the rich evidence of which captivates the geologist and the sight-seer of today.

The elongated low-density source under the Gulf Plains counteracted the Canadian and Pacific sources by folding up the Southern Rocky Mountains in Mesozoic time. The weaker strength of the source is reflected in the less compressed fold belts which cover a large area.

The strong Pacific source, which opposes the two eastern sources essentially under the thin ocean floor, folded up the less rugged Sierra Nevada in Mesozoic age and the lower California Coastal Ranges in Cenozoic time. The Great California Valley makes it look as if the Coastal Ranges have just been flipped up by the strongly up-coming currents from the nearby source. The neighboring Cenozoic Northern Coastal Ranges and the California Peninsula, which was created together with the Gulf of California in Mesozoic time, appear to belong to the same type of mountain uplift. It is also here along these coastal ranges that the Pacific floor breaks the continental thrust of North America by wrench faulting and not by under-sliding as elsewhere (see above and below).

To the north and to the south of the central Rocky Mountain-Sierra Nevada system the Great Western Mountain system continues with essentially the same structure but adjusts to the changing strength of the participating low-density sources. In the northern continuation the source under the Gulf Plains is no longer participating and the Canadian source opposes more and more the weaker source of the Pacific source pair (see [23, p. 42] and [24, p. 140]). The Paleozoic core attenuates between the North-Central Rocky Mountains and the Cascade Ranges and seems to disappear completely farther north. This interesting feature can probably be explained by the continental drift since Paleozoic time. A slight shift of the continent in northesterly direction makes the Canadian and Pacific sources ineffective with respect to mountain building because the source under the ocean holds no grip on the continental crust in this area. Promptly, when the Canadian source loses its strength as the continent approaches the low-density source north of Northeast Asia, the mountain ranges turn into east-to-west direction.

In the south of the Rocky Mountain-Sierra Nevada system the Gulf source and the directly counteracting large Pacific source folded up the Sierra Madre Cordilleras and the California Peninsula. The Paleozoic core attenuates here too and can again be explained by a slight northeasterly shift of North America which makes the Pacific source ineffective under the continent. Cenozoic folding and the presence of shallow but notable earthquakes on the side of the Sierra Madre Oriental shows that the Gulf source is quite active today (see Fig. 7 and [24, p. 140]). Though the Sierra Nevada and Baja California were folded up by the same Pacific source during the same Mesozoic age, they are not perfect continuations of each other. The break in continuity in the Los Angeles area can probably be explained as follows: During the up-folding of the Sierra Nevada the Pacific source faced essentially the Canadian source. During the uplift of the Peninsula of California and the creation of the Californian Gulf the Pacific source counteracted directly the source under the Gulf of Mexico. Furthermore, as it was pointed out above the uplift of Baja California resembles more the uplift of the Coastal Ranges in the north. The almost west-to-east oriented mountain ranges in the Los Angeles break appear to be the southern spurs of the California Coastal Ranges which have been uplifted in Cenozoic time against the Canadian source.

In the earlier stages of geophysics the Great Western Mountain system was considered as the natural continuation of the Andes. With the advancing exploration of the oceans recently geophysicists

(Vine [27] and Menard [29]) invoked the continental drift theory and conjectured that the East Pacific Rise continues under the Rocky Mountains. From the viewpoint of topography both conceptions may be acceptable. However, as the world density map (Fig. 7) discloses, from the standpoint of geophysics the Great Western Mountain system of North America continues into the Pacific as an ocean deep which parallels the East Pacific Rise on its western side. Indeed, the East Pacific Rise (see [23, pp. 426-429]) is resolved in full agreement with the density interpretation T.P. IIb and Fig. 3b and with the heat flow measurements by Bullard, Maxwell, and Revelle [31, p. 166] as a channel-like low-density source. The crossover from a topographic high on the continent to a topographically analogous high under the ocean, which is accomplished by a reversed crossover from a density high under the continent to a density low under the ocean, is perhaps the most important evidence in favor of the fluid mantle hypothesis. Indeed, this contrasting feature, which is so impressively demonstrated at the Middle American Pacific coast, can hardly be explained by a mechanism based exclusively on a solid mantle theory.

As the East Pacific Rise diminishes toward Middle America the low-density source under it opposes the source under the Gulf of Mexico. Both sources supply the trough-like high-density sink under the Middle American Trench (see above) which connects the long sink of intermediate depth (see Fig. 8) under the Great Western Mountain system with the deep, strong, and also elongated high-density sink under the Andes. The mountain ranges of Middle America, which display no Paleozoic folding, assume clearly the proper direction with respect to their effecting sources (see [23, p. 220], and [24, p. 139]). It looks as if the sources under the Mexican Gulf and under the East Pacific Rise may have helped to establish the Middle American block joint between the Americas which eases the North American drift thrust (see above). The same sources must also be held responsible for the rippled Pacific floor between the Middle American Trench and the East Pacific Rise which is so clearly emphasized in the artistic version of this area shown on the relief map in [23, p. 427].

The geophysical implications of the distribution of the density sources and sinks under and around the South American continent are essentially the same as in North America. Clearly the dominating low-density source sits under the Brazilian Highlands (see Figs. 7 and 8 and [23, pp. 234, 262, 428]). It gives the South American continent a considerable thrust in a westerly direction which is evidenced by the damages it inflicts on the Pacific floor. In fact, the westward drift of South America has been suspected by many geophysicists from the existence of the Chile-Peru Trench, where the continent is overriding the Pacific floor, and from the many earthquakes which cover the whole seismic scale in depth and violence. The effects along the Caribbean discontinuity line between the Americas have been analyzed in detail above. As in North America no severe consequences of the westward drift of South America are known at the immediate Atlantic coast line (see Atlantic 6f). However, if one looks farther east, one can see three large low-density sources which could have easily torn off South America from Africa somewhere over the Southern Mid-Atlantic and pushed it westward into the position of today just as Wegener had envisioned it in 1912 (see Scheidegger [4, pp. 204, 239]). As was mentioned in connection with the North American drift a more substantiated investigation of this long-distance movement must be left to the future.

The eccentric position of the Brazilian low-density source may well explain the strong uplift of the Highlands of Brazil (see T.P. I and Fig. 2b) which has been known from geophysical and geological studies. The Highlands of Guiana may also be explained by a similar uplift accomplished by the low-density source pair northeast of Guiana. The eastern sources, which appear to be loosely connected, must also be held responsible for the great drainage system of the continent, that is, they prepared the beds of the large river systems such as those of the Amazonas and Parana at least in their basic layout (see [23, pp. 234, 262]).

If one focuses on the Andes, one can visualize again in time-lapse motion how its spectacular cordilleras were successively folded up by currents coming from the surrounding sources and subsiding in the very deep (see Fig. 8) trough-like high-density sink under the mountain area. Within the margin of a small westward (perhaps somewhat southerly) drift of the continent since Mesozoic time one can imagine the precise influences of the participating sources on the Mesozoic fold belts of the Central and Northern Andes. This is particularly impressive at the "fan-like" northern cordilleras which must be attributed to the source under the East Pacific Rise, to the source pair northeast of Guiana and perhaps also to the distant source under the Gulf of Mexico. As the trough-like sink under the Mesozoic Andes continues southward under the Southern Andean Cordilleras, which are of Paleozoic age (see [24, p. 193]) it loses rapidly its strength until it joins the high-density sink under the Palmer Peninsula of Antarctica.

6b. THE EURASIAN CONTINENT

After having gained some understanding of the geophysical meaning of the world density maps from the detailed discussions of the American continents, it may now suffice to examine the tectonic features of the Eurasian continent in their correlation to the density anomaly computed in a more comprehensive fashion. The same may apply to the subsequent discussions of the continents of Africa, Australia, and Antarctica as well as to the Pacific, Atlantic, and Indian Oceans. Of course, new and unfamiliar phenomena which might occur especially in the oceans will be discussed as thoroughly as possible.

The Eurasian continent appears to float on four low-density sources located under the European, Turan, Siberian, and Chinese Lowlands. The Asian source triplet is considerably stronger than the isolated European U-shaped source. Since none of the major high-density sinks, which these sources supply, lie in northerly direction, one concludes that a strong resultant force thrusts Eurasia southward. The dominating Asian source triplet seems to subject the continent also to a torque which turns Eurasia in clockwise direction. The rotation against the African continent might produce a small easterly drift component; but this is a rather intuitive conclusion which needs further investigation.

The continental drift of Eurasia has also been conjectured by many geophysicists from the tectonic evidence which they gathered all around the continent. Along the North Atlantic and Arctic coast line the drift is evidenced by many fractures (see [24, p. 139]) which tend to confirm Wegener's conception of an urcontinent (see America 6a). In spite of the strong southward drift of Eurasia there seems to exist no serious problem in the mechanical interaction between the continental crust and the Indian Ocean floor. It appears that the ocean floor avoids the continental pressure by simply sliding southward (see Indian Ocean 6g). The low-density "supersource" under the southern tip of India, which is roughly 60 per cent stronger than any other source and 40 per cent stronger than any sink, prevents probably an overriding of the ocean floor by the continental crust. The Mid-Indian Ocean Ridge, which begins almost as a continental appendix at the southeastern tip of India, may also help to accomplish a smooth transmission of the continental pressure on the ocean floor.

The fractures around the coast of India (see [24, p. 139]) must possibly be attributed to the tension-effecting Indian supersource. Indeed, it looks as if this source was once just in the right place to tear off a united Australia-Antarctica from Eurasia as envisioned by Wegener (see Scheidegger [4, p. 239]). When floating rather rapidly toward the dominating high-density sink pair under the Indonesian and

Melanesian Archipelagos, Antarctica may well have been separated from Australia somewhere over the low-density sources which they had to override. Finally, the mantle flow toward the strong sink under todays Enderby Land might have brought Antarctica into the present location (see Antarctica 6d). It is almost needless to say that the existence of the Indonesian and Melanesian Archipelagos as well as of New Zealand could also be explained by the same process. Nevertheless, it must be emphasized again that such large-scale projections require much deeper investigations than those considered here.

The interaction between the drifting Eurasian continent and the Pacific floor represents the most violent portion in the Pacific ring of fire (see Figs. 7 and 8). In contrast to the "wrench fault system", which transmits the North American drift on the Pacific floor, the mechanical transmission of the Eurasian drift on the other side of the Pacific floor may be called a "wrench gear system". It consists of a western trench chain (Philippine Trench and Nansei-Shoto Trench) and an eastern trench chain (West Aleutian Trench, Kuril-Kamchatka Trench, Japan Trench, and Marianas Trench), both of which are associated with island arcs representing the "teeth" in the gear system. The oceanic floor under the Philippine Sea appears to act as a kind of gearing wheel in order to reduce the rigidity of the transmission. It may be noted that along both trench chains the west side always over-thrusts the eastern side. The positions of the locally participating sources and sinks facilitate the tranch and island arc formations in the manner described in T.P. IV and Fig. 5. The only exceptions are the Philippine and Japan Trenches which must be considered as continental over-thrusts. Through the wrench gear system, which allows almost no tangential slip, the southward drifting Eurasian continent transmits a strong torque on the Pacific floor which turns it counter-clockwise (see Menard [28]) in spite of the adversely slipping North American continent (see America 6a). The damaging effect, which this rotation inflicts on the Pacific floor itself, may be carried on under Pacific 6e.

On the Indonesian Archipelago the southward drift of Eurasia and the currents of the surrounding sources appear to exert a southeast·ly resultant force. It may be noted, that Meinesz (see Heiskanen and Meinesz [2, Map 10C-2, p. 388-389]) arrived at the same result from his extensive gravity measurements in this area. This strong thrust may explain the long Sumatra-Java Trench where the continental crust overrides the Indian Ocean floor (see also Australia 6d).

On the continent itself the four Eurasian low-density sources must be held at least partly responsible for preparing the important drainage system which includes the Persian Gulf, the North, Baltic, Aegean, Black, Caspian, and Aral Seas, the Lakes Ladoga, Balkhash, and Baykal as well as the great European, Siberian, Chinese, and Indian river systems (see Fig. 7 and [23, pp. 264 and 338]). The same four sources can also be visualized to have built up over the ages the mountains of Eurasia in cooperation with their opposing low-density sources located around the continent. It is particularly amazing to find a satellite's sensitivity detecting what no human eye appears to have ever seen before, namely that the mighty Alpine-Himalayan Mountain chain consists of four loosely connected mountain systems.

There is the largest continental irregularity of the world, the Himalayan-Kunlun Mountain system, which together with the Tebetian Plateau resembles closely the North American analogue the Rocky Mountain-Sierra Nevada system (see America 6a). After a small continental drift adjustment this system fits between the Indian supersource (effecting the Himalayas) and the sources under the Chinese and Siberian Lowlands. It may be observed how the Indian and Chinese sources in direct opposition turned the fold belts into the proper direction (see [23, p. 338]). After a narrow ridge separating the Indian and Siberian Lowlands one recognizes the Eastern Middle East Mountain system comprising the mountains of Iran, Afghanistan, and West Pakistan around the Plateau of Iran. The corresponding high-density sink under this system is supplied by the sources under the Lowlands of Siberia and Turan and by the western extension of the Indian supersource. After a second narrow ridge between the Persian Gulf and the Lowlands of Turan, one finds the Western Middle East Mountain system. It consists of the mountains of Asia Minor including the Caucasus and of the ancient highly eroded mountains of Western Arabia and Northeast Africa (see [23, p. 264]). In its creation participated the western extension of the Indian supersource, the sources under the Lowlands of Turan and Europe, and the source under the Sahara. The southern portion of this compression area is sliced by the tension-effected rift valley which originates in Southeast Africa (see Africa 6c).

The fourth link in the Alpine-Himalayan Mountain chain is the somewhat isolated European Mountain system comprising the Apennine, the Alpine, the Carpathian, and the East Atlas Mountain arcs (see [23, p. 264]). The high-density sink under the Tyrrhenian Sea is supplied by the U-shaped source under the European Lowlands and by the joint sources under the Sahara and the Southeastern North Atlantic. The eastern branch of the European source is connected with the Sahara source under the Aegean and Black Seas. A narrow connection between the western branch of the European source and the Southeastern North Atlantic source exists also under the Rhone Valley and under the fracture zone which separates the East Atlas from the West Atlas (see [24, p. 139] and below). The European Mountain system is distinguished from all other major mountain systems by its oceanic core. Furthermore, the entire mountain area together with the Mediterranean Sea seems to be under the influence of the Asian source triplet which turns Eurasia clockwise (see above). This may well produce tension forces which interact with the local compression forces in various ways (see T.P. III). For example, as the western branch of the European source supplies the high-density sinks under the Northern North Atlantic and the Iberian Basin, it counteracts the clockwise rotation of Eurasia. Thus, one can conceive of a tension force which may have effected the Rhine Valley that cuts through mountain arcs at blunt and sharp angles.

The absence of deep earthquake foci in the Alpine-Himalayan Mountain chain (Fig. 7) indicates that all four high-density sinks should be more or less shallow. This conjecture is closely confirmed by Fig. 8 and by earlier gravity studies (see [21]), which failed to resolve, for instance, the Himalayan-Kunlun Mountain system. One can see in Fig. 8 that the density anomaly under the world's largest topographic irregularity has vanished at one quarter of the mantle depth. It may also be observed that with the exception of few isolated cases most of the earthquake foci accumulate on the far outskirts of the high-density sinks (see T.P. IIc), where the density variation is largest.

The deepest high-density sink occurs under the Western Middle East Mountain system which has spurs under the Ural Mountains and under the East African Mountains including Mount Kilimanjaro. The Western Atlas Mountains and their continuation on the Iberian Peninsula (see [23, p. 264]) as well as the Pyrenees seem to be continental mountain arcs on the periphery of the high-density sink under the Iberian Basin. They must probably be attributed to currents coming from the elongated Southeastern North Atlantic source and from the western branch of the European source. The mountains of Northwest (Scotland and Scandinavia) and Northeast Eurasia (see [23, p. 40]) can obviously be explained by similar currents between the corresponding sources and sinks shown in Figs. 7 and 8.

6c. THE AFRICAN CONTINENT

The mantle currents under the African continent display no distinctly preferred direction which would indicate a clearly noticeable continental drift. This is also supported by the absence of major damages which such a large movement would inflict on the surrounding ocean floors (see America 6a, Eurasia 6b, and Australia-Antarctica 6d). However, this does not exclude the possibility of a large continental drift as envisioned by Wegener (see Scheidegger [4, 239]) prior to the time when Africa arrived at the present more or less stable position (see America 6a).

In spite of Africa's relatively stationary location it receives a strong westward directed torque from the low-density source which is situated precisely under the Southeast African origin of the world's most awesome rift valleys (see [23, p. 386] and [24, p. 139]). While it cannot cause a major continental drift, it seems to wrench Africa apart from the large Eurasian continent. Thus, with the density interpretations given in T.P IId and T.P. III one can easily resolve the secret (see Heiskanen and Meinesz [2, p. 389]) of the East African Rift Valleys the major branch of which has virtually sliced the entire continent from south to north all through the Red and Dead Seas and up the Jordan River to the foothills of the mountains of Asia Minor. Indeed, it is evidently the East African source which has first cracked the covering continental crust (Fig. 4b), and then continued the fractures in the now visible fashion by the wrench action described above. It is particularly interesting that the major branch of the tension-effected African Rift Valleys runs mostly through mountainous areas which are locally under compression. One has here obviously the same phenomenon as along the Rhine Valley (see Eurasia 6b) and along the Pacific Fracture Zones (see America 6a). The resemblance in appearance of, for instance, the Murray Fracture Zone and the rift valley of Central East Africa has been already observed by Menard [28]. Both fractures were probably associated with great pressure lows between the mantle and the crust which produced molten magma and subsequently the large volcanos visible today (see Pacific 6e).

The frightening strength of the East African low-density source is also reflected in the creation of the Island of Madagascar. As was conjectured by Wegener (see Scheidegger [4, p. 239]), it has undoubtedly ripped off Madagascar from the African continent which now seems to be floating toward the adjacent high-density sink (see Fig. 7 and [24, p. 129]).

A quick survey of the other low-density sources confirms their meaningful locations under the Congo River system and under the Sahara Desert the latter of which is known as a rising area (see Fig. 7 and [23, p. 386]). In addition to the Atlas and East African Mountains, which have been already discussed under Eurasia (6b), one finds the mountains of Southwest Africa and along the Guinea Coast correctly resolved as high-density sinks.

6d. THE AUSTRALIAN AND ANTARCTIC CONTINENTS

The strong low-density source under Australia (see Fig. 7) subjects the continent to a northeasterly thrust which opposes the counterclockwise rotation of the Pacific floor and the southeasterly drift of the Indonesian Archipelago (see Eurasia 6b). The interference with the Pacific rotation is evidenced by the long Kermadec-Tonga Trench and by several smaller "gaps" along the entire northeastern side of the Melanesian Archipelago (see [24, p. 78]). It may be noted that the overthrust along the Kermadec-Tonga Trench is governed by the local sources and sinks in the manner described in T.P. IV and Fig. 5. In contrast to the formation of trenches the fine structure of the considerably smaller gaps is obviously not controlled by the local sources and sinks. However, there may well exist an analogous correlation between ocean gaps and oceanic fold ridges (see Pacific 6e) which seem to exist so abundantly in the Melanesian area. On the northwestern side the Australian drift has probably participated in the formation of the Sumatra-Java Trench and of the gap in the Banda Sea. The interactions of the Indonesian and Australian drifts are also in agreement with the diverging drift directions of the Indonesian Archipelago which Meinesz (see Heiskanen and Meinesz [2, Map 10C-2, p. 388]) concluded from his gravity measurements.

The fractures along the Great Australian Bight, which cut also deep into the continent (see [24 139]), can easily be explained by the presence of the large low-density source (see T.P. IId). The Great Dividing Ranges on the eastern side and the lower mountain ranges on the west side are both adequately resolved as high-density sinks (see [23, p. 424]). According to its appearance the Island of New Guinea on the continental appendix of Australia seems to have been stretched away. This may be supported by the distinct uplift of its leading edge against the southward pressing Pacific floor.

The two low-density sources under Victoria Land and Queen Maud Land of Antarctica (see Fig. 7 and [23, p. 438]) appear to be responsible for the mountain ranges which connect the high-density sinks under Enderby Land and under the Palmer Peninsula. The dominant source under Victoria Land and the major sink under Enderby Land may indicate a slight drift of the Antarctic continent toward the Indian Ocean with perhaps a small westward turning component. Though both components are probably very weak and, hence, need more precise justification (see Part II [19]), the latter may have taken part in the creation of the South Sandwich Trench in the South Atlantic, which agrees with the principle of trench formation explained in T.P. IV.

6e. THE PACIFIC OCEAN

The tectonic features of the ocean floors are only partly determined by the regional mantle currents. In fact, as was pointed out during the discussions of the continents major damages and deformations of the ocean floors must be attributed to the monstrous movements of the continents. This applies not only to the ocean shores, where severe discontinuities have been explained by continental drifts, but also to the inner ocean floors which may be warped, folded, fractured, etc. Such large-scale deformations may interact with the local deformations due to the subcurrents in various ways, for instance, they may amplify each other or they may interfere with each other. Hence a proper evaluation of the density anomalies under the oceans must pay attention to the fact that a known particular feature of the oceanic crust may have been effected by local mantle currents, by global forces due to continental drifts, or by both causes together.

Due to the adverse movements of America (6a), Eurasia (6b), and Australia (6d) with respect to the Pacific Ocean, one must suspect that the Pacific floor should display the greatest variety of crustal deformations. This is impressively demonstrated by the numerous volcanic irregularities in the Pacific which resemble goose pimples and eczema of an irritated skin (see [23, pp. 426-429]) except that they appear to follow some ordering principles (see also [24, p. 78]). Indeed, it is known that the temperatures inside the mantle are so high that molten magma should form and trigger volcanic activity if by some kind of mechanism the mantle pressure, which is considerably above the atmospheric value, could be sufficiently reduced. Since the earth crust appears to be movable over the mantle, it is conceivable that pressure lows between the mantle and the crust can be accomplished by the following crustal deformations:

(A) through folding and uplifting of the crust,

(B) through fracturing and faulting of the crust,

(C) through fracturing and over-thrusting of the crust.

Obviously in all three cases cavities can be produced between the mantle and the crust which result in sufficiently low pressures.

This can especially be anticipated under the oceanic crust of the Pacific which is subject to enormous compression and tension forces due to continental drifts.

The possibility that condition (C) might be a cause of volcanic activity has been already mentioned in connection with the principle of trench formation explained in T.P. IV and Fig. 5. A quick review of the trenches in the Pacific as well as in the Atlantic and Indian Oceans verifies that particularly along ocean-to-ocean trenches volcanic islands occur in abundance on top of the over-sliding crustal arc. During the preceding discussions of the Northeast Pacific Fracture Zones (see America 6a) and of the East African Rift Valleys (see Africa 6c) condition (B) has also been named as a probable cause of volcanic activity (see Menard [28]). Indeed, the numerous fracture zones of the Northeast Pacific, which were attributed to the continental drifts of North America and Eurasia, are paralleled by a yet unknown number of volcanic irregularities (see [23, pp. 426-429]). Moreover, the volcanos exist along the tension-effected east-to-west running fracture zones as well as along the compression-effected southeast-to-northwest directed fractures, the latter of which seem to continue the San Andreas Fault system into the Pacific.

It may be noted that the local under-currents remained without noticeable effects on the straight course of the fractures. This important property characterizes the fracture zones as brittle deformations of the crust (see Menard [28]). Of course, the local mantle currents should determine the direction of vertical slips succeeding the fractures. In fact, the major fault directions of the fracture zones should be controlled by the same rule as the overthrusts along trenches (see Fig. 5). For example, according to Menard [28] the major escarpments of the (northern) Mendocino and the (southern) Murray Fracture Zones face each other. As Fig. 7 shows the Mendocino Escarpment has a sink to the north and a source to the south. In contrast to that the Murray Escarpment has a sink to the south and a source to the north.

The observation that volcanic activity is quite frequently associated with folded continental mountain areas, tends to confirm condition (A) as a third major cause of volcanic crustal irregularities. During the preceding discussions it was found that the southerly Eurasian drift (see Eurasia 6b), which produces a counterclockwise rotation of the Pacific floor, is opposed by the northeasterly Australian drift (see Australia 6d). Consequently, in contrast to the tension-effected Northeast Pacific Fracture Zones one must expect compression-effected "oceanic fold ridges" in the Western Pacific. This conjecture receives ample support by the numerous ridges which occur in the entire West Pacific including the Philippine Sea and the Eastern Indonesian Archipelago. Particular attention may be given to the strong crowding of fold ridges in the Melanesian Archipelago, which appear to be more or less normal to the Australian drift direction.

Though the West Pacific Fold Ridges display well-defined directions, they are not as neatly aligned as the straight fracture zones of the Northeast Pacific. The pattern of the fold ridges indicates a compression-induced continuous (plastic) deformation of the crust which yields considerably to the local forces exerted by the mantle currents. In this connection one may compare the extensive experimentally supported investigations of plastic deformations by Bijlaard and Meinesz (see Heiskanen and Meinesz [2, pp. 326-343] and Menard [28]). The plastic formation of the fold ridges can be expected from the fact that the strong Eurasian and Australian thrusts are continuously transmitted onto the West Pacific floor. As was pointed out under Eurasia (6b) the wrench gear system, by means of which the counterclockwise rotation of the Pacific floor is accomplished, appears to prevent major sudden slips in tangential direction.

The West Pacific Fold Ridges are virtually occupied by volcanic irregularities (see [23, pp. 426-429] and [24, p. 78]), and many of them constitute the numerous small and large volcanic islands of the so-called South Sea. In fact there is no other place in the world which is plagued with so many and so huge volcanic structures as the West Pacific floor. This can readily be explained by condition (A). An uplift of the ocean floor from the mantle by folding without opening the crust may well produce a cavity with an associated pressure reduction far below the surface pressure and, hence, ignite a tremendous volcanic activity. The development of cavities under oceanic fold ridges should be amplified by local high-density sinks and decreased by low-density sources. Accordingly, the maximum volcanic creations should occur on fold ridges over(or at least over the outskirts of)high-density sinks. As can be seen in Fig. 7 the large volcanic Islands of Hawaii on the Hawaiian Fold Ridge occur within the ocean deep which extends to the Aleutian Islands (see [23, p. 426] and [24, p. 78]) and which is correctly resolved as a high-density sink (see T.P. IIa and Fig. 3a). The same applies to all the large volcanic islands of the Indonesian and Melanesian Archipelagos as well as to the Islands of Japan all of which occupy fold ridges over high-density sinks.

The Eastern and Southern South Pacific exhibits considerable less volcanic irregularities. The major tectonic feature is here the East Pacific Rise which is correctly resolved as an up-thrusted ocean floor over a low-density source (see T.P. IIb, Fig. 3b, and America 6a, also Scheidegger [4, p. 94], Hess [30], Bullard, Maxwell, and Revelle [31, p. 166], and LePichon, Houtz, Drake, and Nafe [32]). It is important to observe that the East Pacific Rise appears to be a unique example of its kind. Indeed, all other known major elevations of the oceans can be classified as oceanic fold ridges due to continental drifts (see West Pacific above) or due to opposing low-density sources (see Atlantic 6f). For instance, the South Pacific-Antarctic Ridge, which connects the East Pacific Rise with the Mid-Indian Ocean Ridge seems to be a fold ridge as the Mid-Atlantic Ridge. The change of type is evidently indicated by a slight easterly displacement of the South Pacific-Antarctic Ridge with respect to the East Pacific Rise at their junction (see [23, p. 425], and [24, p. 79]). In this connection one may compare the smooth junctions between the Mid-Indian Ocean Ridge and the South Pacific-Antarctic Ridge and also the Mid-Atlantic Ridge.

6f. THE ATLANTIC OCEAN

The principal tectonic feature of the Atlantic Ocean is the Mid-Atlantic Ridge which begins in the Arctic Ocean in the north and continues as the Mid-Indian Ocean Ridge in the south. In contrast to the East Pacific Rise the Mid-Atlantic Ridge evolved obviously by a totally different process. While the former rise is precisely resolved as an essentially up-thrusted ocean floor over a low-density source (see T.P. II b and Fig. 3b), the latter ridge follows nowhere the contours of a low-density source (see Fig. 7 and [23, pp. 260-263]).

One can follow the Mid-Atlantic Ridge, if one considers it as a folded ridge between low-density sources just as the mountains of continents (see America 6a and Eurasia 6b). The folded structure is most distinctly visible along the South Atlantic portion of the ridge which exhibits ranges winding gently between two pairs (one on each side) of low-density sources. The pronounced winding of the ridge in the Middle and North Atlantic is clearly determined by the sources under the Northwestern South Atlantic, under the Southeastern and Southwestern North Atlantic, under the Central North Atlantic, and under the European Lowlands. The branch ridges of the South Atlantic such as the Guinea, Walvis, Rio Grande, and Trinidad Ridges can also be explained by the same fold process.

It may be noted that the major elevations of the Mid-Atlantic Ridge occur on the outskirts of the participating high-density sinks. The same phenomenon has also been pointed out for continental mountain ranges. The nearer the fold ridge approaches a high-density sink the more it tends to increase in seismic and volcanic activity (see Fig. 7). An explanation for the latter phenomenon was given in connection with the discussion of the similar West Pacific Fold Ridges which were attributed to continental drifts (see Pacific 6e). The pronounced volcanic activity around the Islands of Jan Mayen, Iceland, Azores, Ascension, Tristan da Cunha, and Gough has been already pointed out by Hess in [30]. The especially large volcanic activity around Iceland is readily explained by the fact that the fold ridge is so close to the center of the strong North Atlantic-Greenland low-density sink.

The fundamental difference between the East Pacific Rise and the Mid-Atlantic Ridge is further evidenced by two important experimental observations. Seismic measurements (see Hess [30] and LePichon, Houtz, Drake, and Nafe [32]) revealed that the East Pacific Rise is filled by the mantle as shown in Fig. 3b. The covering oceanic crust behaves as an ordinary ocean floor without any thickening. In contrast to this characteristic feature of up-thrusted ocean rises, the folded ridge of the Mid-Atlantic is filled by the crust (see Gutenberg [1, p. 58], Scheidegger [4, p. 53], and Bullard, Maxwell, and Revelle [31, p. 168]). Moreover, the folding has displaced the mantle and the ridge has deep roots just as folded continental mountains (see T.P. IIc, and Fig. 4a). As is characteristic for an ocean rise over a low-density source, heat flow measurements along the East Pacific Rise yielded distinctly high heat flows (see Scheidegger [4, p. 94], Hess [30], and Bullard, Maxwell, and Revelle [31, p. 166]). Measurements along the Mid-Atlantic ridge yielded high and low (even very low) heat flows in a rather random fashion (see also Vacquier and Herzen [33], Nason and Lee [34], Langseth and Grim [35] and Langseth, LePichon, and Ewing [36]). Only the measurements near the rift valley of the Mid-Atlantic Ridge appeared to produce high heat flows. This, however, confirms just the tension-effected fracture of the Atlantic which runs along the entire ridge and which must probably be attributed to the opposing drifts of the adjacent continents. Indeed, the large opening of the locally folded crust seems to have triggered (see Pacific 6e) a considerable volcanic activity and, hence, itensified the heat flow along the rift valley of the ridge.

The Puerto Rican and the South Sandwich Trenches of the Atlantic have been already discussed under America (6a) and Antarctica (6d). There remains to be mentioned the Romanche Trench at the equat portion of the Mid-Atlantic Ridge. The direction of the trench and the under-thrust property, which is in agreement with T.P. IV and Fig. 5, verifies the existence of a low-density source in the south (under-thrusting side) and a high-density sink in the north.

6g. THE INDIAN OCEAN

From seismic and heat flow observations it is known that the crust of the Indian Ocean behaves as the Atlantic floor (see Hess [30]). This is closely confirmed by the result that the Mid-Indian Ocean Ridge can be traced as a fold ridge winding between low-density sources just as the Mid-Atlantic Ridge (see Atlantic 6f) of which it is the smooth eastward continuation. Farther to the east the Mid-Indican Ocean Ridge is continued as the South Pacific-Antarctic Ridge, which has been considered under Pacific 6e.

The branching elevations as the Carlsberg, Seychelles-Mauritius, South Madagascar, South Tasmanian, Southwest Auckland, and Amsterdam

Ridges must also be considered as folded. The folding of the Seychelles-Mauritius Ridge, which is occupied by numerous volcanic irregularities, may be supported by the drift-thrust of Madagascar (see Africa 6c). Finally, it may be mentioned that the Diamantina, Amsterdam, and Malagasi Fracture Zones can probably be attributed to an analogous wrench effect as the Northeast Pacific Fracture Zones (see Pacific 6e). Here one has to evaluate the northeasterly drift of Australia and the slight westward motion of Antarctica (6d).

7. General Geophysical Implications

The foregoing discussion of the world density maps (Figs. 7 and 8) concentrated on the question of how the tectonic evolution of the earth's crust may have been effected by thermally driven convection currents in the mantle. At the same time detailed tectonic features were scrutinized in order to examine the presupposed theoretical simplifications and the accuracy of the empirically obtained satellite gravity coefficients, both of which were needed in the computations of the density anomalies.

With respect to the empirical basis of the results one can probably say that the satellite data used yielded just the right resolution of the density anomalies of the mantle. In fact, it appears that every density anomaly computed has played some role in the mechanical deformation of the crust of today. This tends to confirm again the presupposition (see Sec. 5) that the density maps presented do not suffer from overly sharp resolutions which would expose exclusively crustal density anomalies. It also supports the seismically discovered phenomenon of crustal compensation according to which large accumulations of crustal masses rise as mountains over the average topographic level and simultaneously displace the mantle in the form of roots (see, for instance, Gutenberg [1, p. 55] and compare T.P. IIc and Fig. 4a). However, it must be pointed out that this principle may be somewhat violated by some oceanic irregularities. For instance, because the East Pacific Rise (see Pacific 6e and Atlantic 6f) has no crustal roots in the mantle, its true density anomaly must be expected to be a little larger than the computed value.

Since every essential tectonic feature of the crust appears to be explainable by just the computed density anomalies it seems that no major density anomaly of the mantle remained undetected. Certainly, future improvements of the satellite gravity data will produce better density maps. For example, the U-shaped low-density source under the European Lowlands can probably be expected to yield a resolution into more pronounced secondary centers, but their effective unity as a single source should remain unchanged. The completeness of the computed density lows and highs of the mantle is especially evidenced by their geometric structure which matches closely the geometric dimensions of the relevant tectonic features. For instance, one may compare again the shapes of the four Eurasian Mountain systems with those of their corresponding high-density sinks. Furthermore, the horizontal and vertical dimensions of the individual density highs and lows are of the same order of magnitude, which is a characteristic property of cellular convection flows.

From the standpoint of the simplifications applied in Sec. 2 it is important to examine the decay property of the density anomaly ρ' with the mantle depth. Indeed, since the density anomaly ρ' is fitted to the observed gravity field of today, a substantial error, which could be the consequence of the neglected terms of heat convection and of heterogeneous heat sources in the heat equation (5), should manifest itself in the behavior of ρ' with depth. By comparing Figs. 7 and 8 one concludes that the density anomaly ρ' attenuates rather rapidly. For instance, at only 25% of the mantle depth the density anomaly ρ' is generally more than 50% below the surface value and many highs and lows are no longer noticeable. This is a satisfactory confirmation of the empirically supported general opinion of geophysicists of today (see Sec. 2 and Heiskanen and Meinesz [2], MacDonald [7], and McKenzie [18]), according to which significant convection currents and, hence, density anomalies should not penetrate into the lower mantle. It may be noted that the rapid decay of the density anomaly ρ' is essentially due to the governing equation (24) and not to the boundary condition $\rho'(b,\theta,\varphi) = 0$ (Eq. (21)) at the inner surface of the mantle. If one would assume, say, $\rho'(b,\theta,\varphi) = 2\rho'(a,\theta,\varphi)$ then the density anomaly $\rho'(r,\theta,\varphi)$ would approach the inner value in a similar fashion (see Fig. 6).

Another substantial error could possibly result from the neglect of the time dependence of the thermal activity in the mantle (see Sec. 2). However, during the preceding discussions it was repeatedly pointed out that even Paleozoic fold belts of mountains appear to have been effected by the same low-density sources as the younger foldings of Mesozoic or Cenozoic ages. The older fold belts require only larger readjustments of the continents due to continental drifts. Moreover, the possibility was also indicated that the present low-density sources may well have accomplished the global continental drift from one urcontinent as it was envisioned by Wegener. The almost stationary behavior of the density anomalies is also physically plausible within the slow-motion regime. If convection currents have been initiated at some time, then they continue to exist unless the driving heat supply is subject to large intensity variations. Furthermore, even if one allows for some changes in the heat supply it is very unlikely th ascending currents change into descending currents and vice versa. Since the Grashof number at which convection starts or dies is not zero, one can expect that renewed convection currents follow the pattern of previously extinguished flows.

During the discussion of the North American continent (6a) it was shown that the strong low-density source under the Canadian area exerts a considerable lifting force on the covering crust. Hence, a proper evaluation of the uplifts of Canada, Fennoscandia, and other rising areas of the world for the purpose of determining realistic estimates of the mantle viscosity must take into account the lifting forces of the relevant under-currents as well as those due to the removal of glacial ice loads. With the forthcoming construction of the complete flow and stress fields (see Part II [19]) it should be possible to improve the present estimates of the mantle viscosity. Since the strength of the individual low-density sources varies considerably from area to area, it seems probable to find a viscosity which is uniformly valid for the entire mantle (see Scheidegger [4, p. 345] and Broecker [25]). Moreover, it is not excluded that the consideration of the additional lift forces might produce a viscosity coefficient which is large enough to support the nonhydrostatic equatorial bulge (see MacDonald [7], and McKenzie [18]).

The explanation of the uplifts of Canada, Fennoscandia, etc. as an exclusively postglacial isostatic readjustment has been questioned by several geophysicists for some time (see Scheidegger [4, pp. 46 and 345], and Broecker [25]). As is mentioned by Scheidegger a scrutiny of geological evidence led Luystikh and others to maintain that Fennoscandia has been rising even before the last ice age and that, therefore, some other phenomenon must be the cause of the uplift. It has also been observed that there exist areal uplifts in the world, such as the Highlands of Brazil (see America 6a), the Sahara Desert (see Africa 6c), etc., which can hardly be explained by postglacial readjustment, by up-folding, or by some other mechanism invoking the solid mantle theory. The satellite-detected low-density sources, the shapes of which are congruent to the uplifted areas, seem to provide the missing cause of the uplift phenomenon under consideration. In fact, it is not impossible that the warm undercurrents have contributed to the retreat of glaciers which sofar has been attributed only to solar radiation. On the other hand, the cold mantle currents under the Northern North Atlantic may help to bind the large ice load over Greenland which is so strikingly far south.

The discussion of the world density maps may be concluded with a brief remark concerning the Indian supersource, the unusual strength of which (see Eurasia 6b) appears to be safely established by the present computations and by earlier gravity studies. It seems rather strange that this deficiency of mass could have been produced by pure thermal activity in an originally more or less homogeneous mantle layer. If one neglects the shallow density highs under the Himalayan-Kunlun Mountain system and under the Eastern Middle East Mountains (see Figs. 7 and 8), then the Indian, Turan, Siberian, and Chinese density lows unite to a circular hole which matches roughly the dimensions of the moon. Thus, one may be tempted to return to the abandoned theory of G. H. Darwin (see Scheidegger [4, p. 188])that perhaps the earth's natural satellite, the moon may have once been ejected from here and left the earth behind with this tremendous wound which is still not closed. Whether one can pursue this fantastically sounding idea in the future or not, one must certainly be concerned about the origin of the Asian lack of mass.

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APPENDIX A

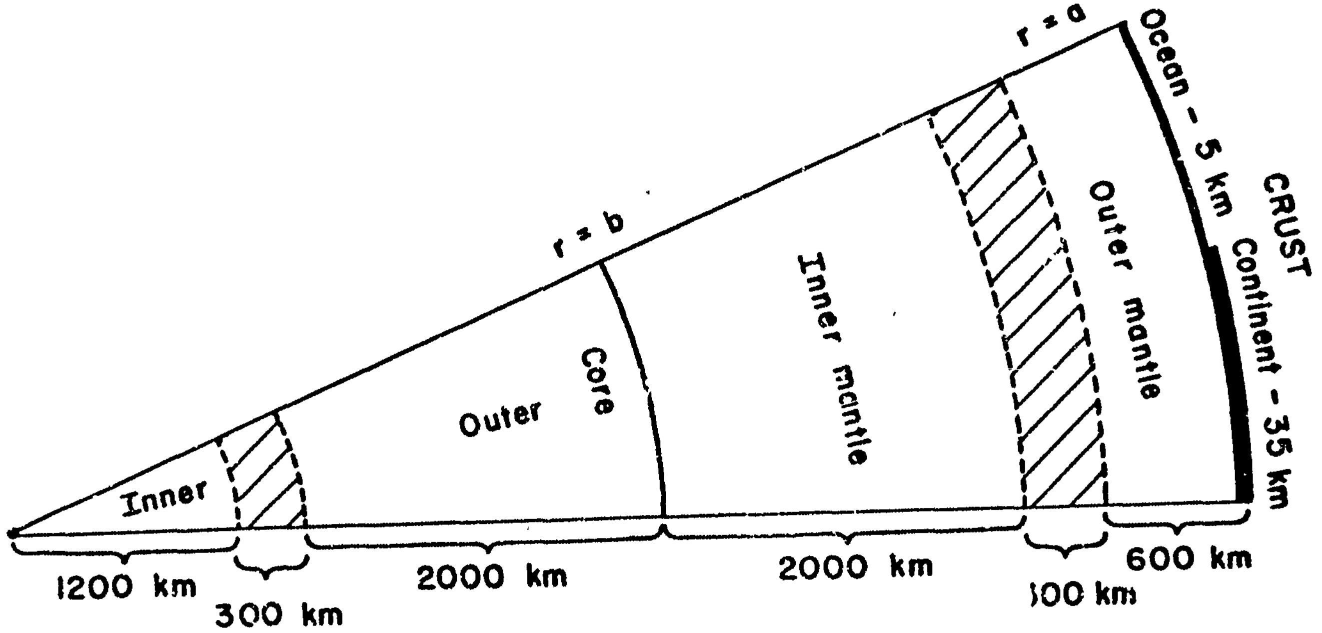


Fig. 1: Layering of the earth's interior

▨ : Transition Layers

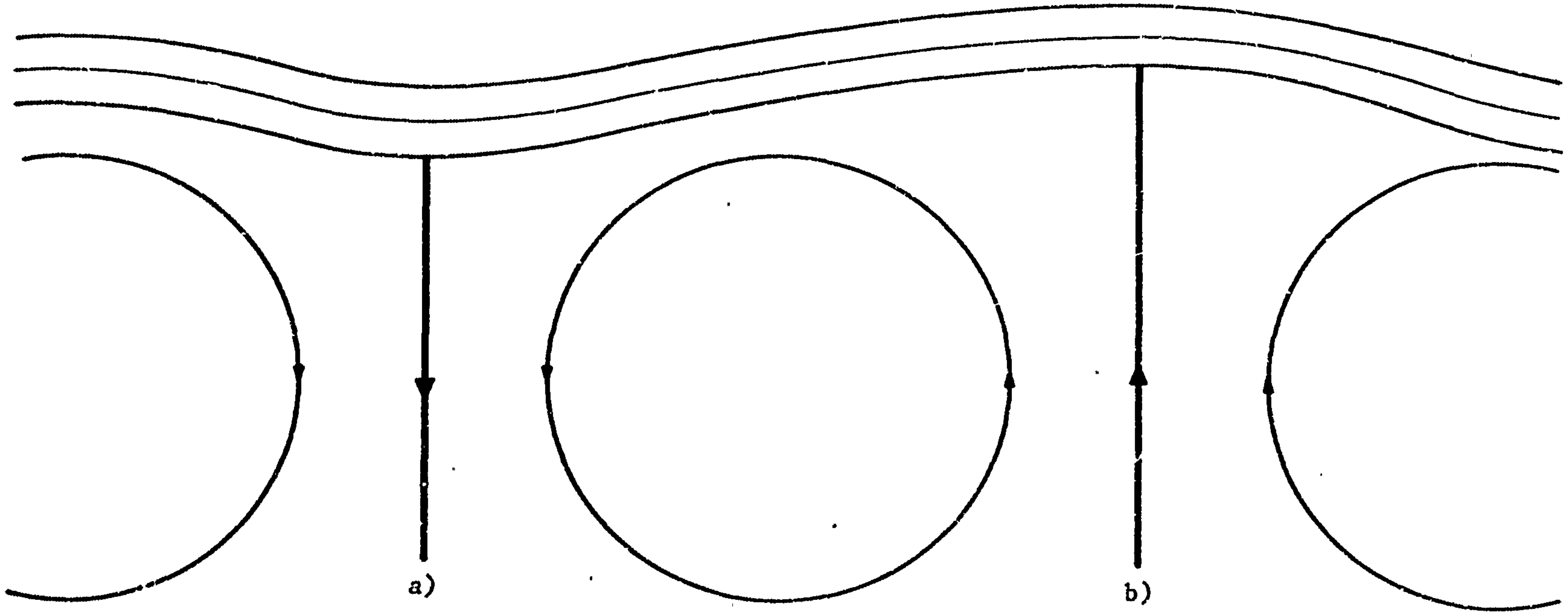


Fig. 2: Sketch of gentle deformations of the oceanic or continental crust

a) Down-bending over a high-density sink.

b) Up-bending over a low-density source.

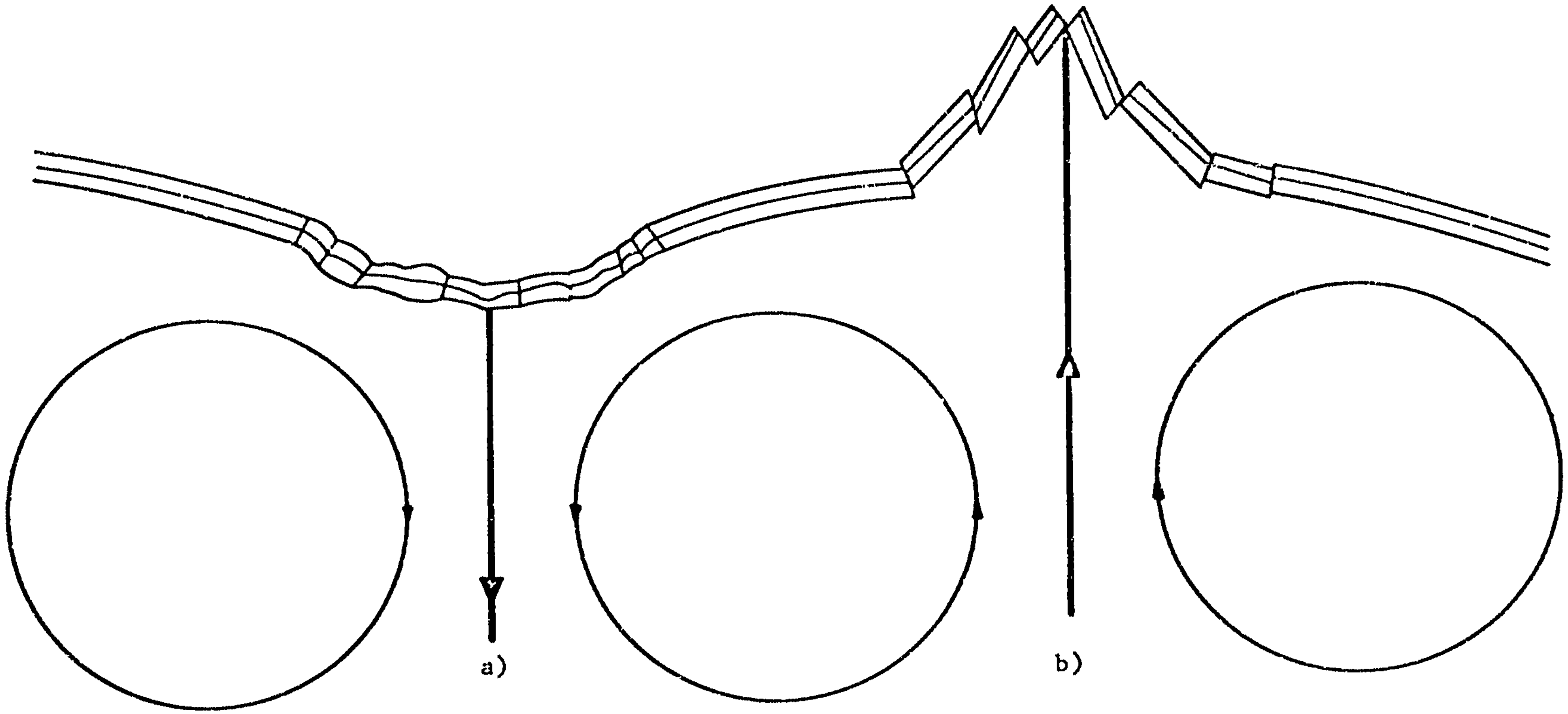


Fig. 3: Sketch of violent deformations of the thin ocean floor

a) Down-buckling over a high-density sink with compression effecting ocean deeps, basins, abyssal plains, or troughs.

b) Up-thrusting over a low-density source with tension causing ocean rises.

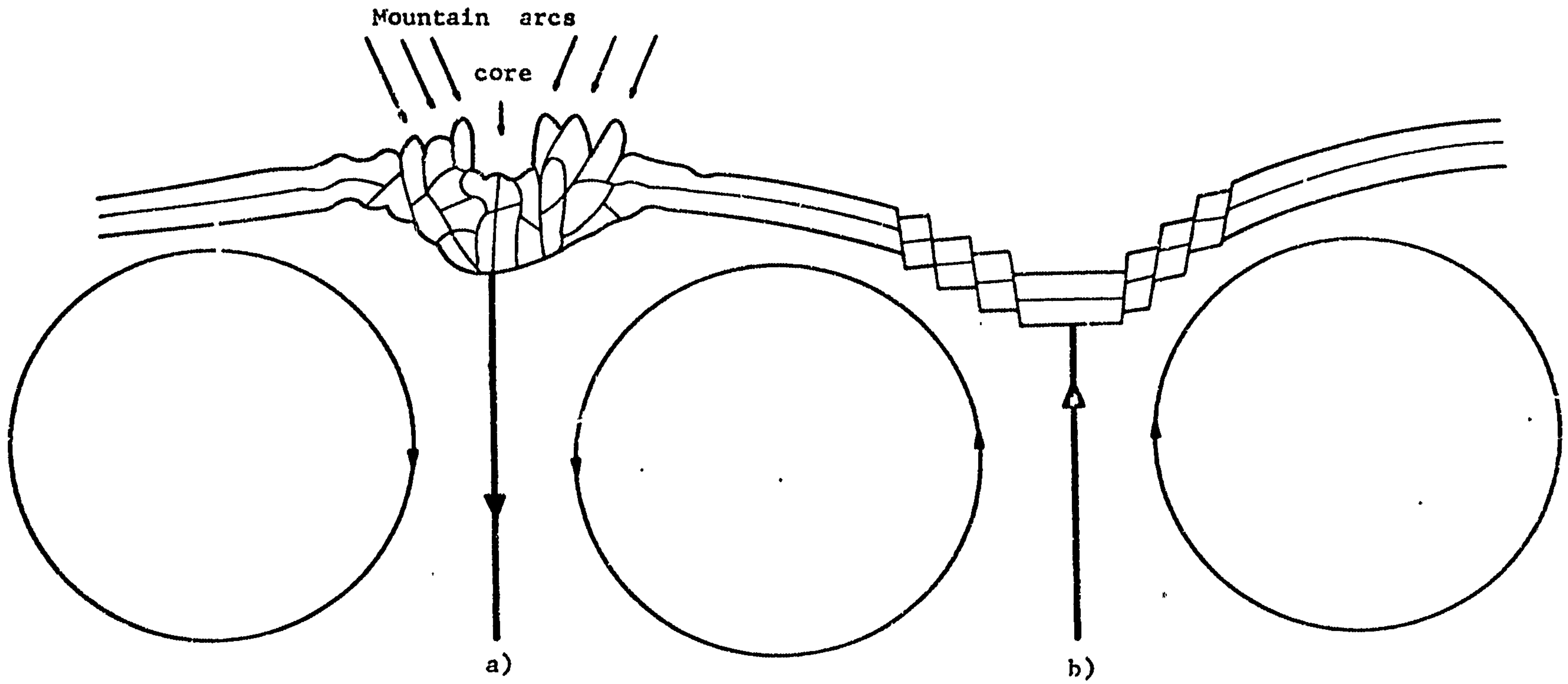


Fig. 4: Sketch of violent deformations of the thick continental crust

a) Up-folding of a mountain system (old core plus new mountain arcs or ranges) over a high-density sink by compression.

b) Block-faulting of a rift valley over a low-density source through tension.

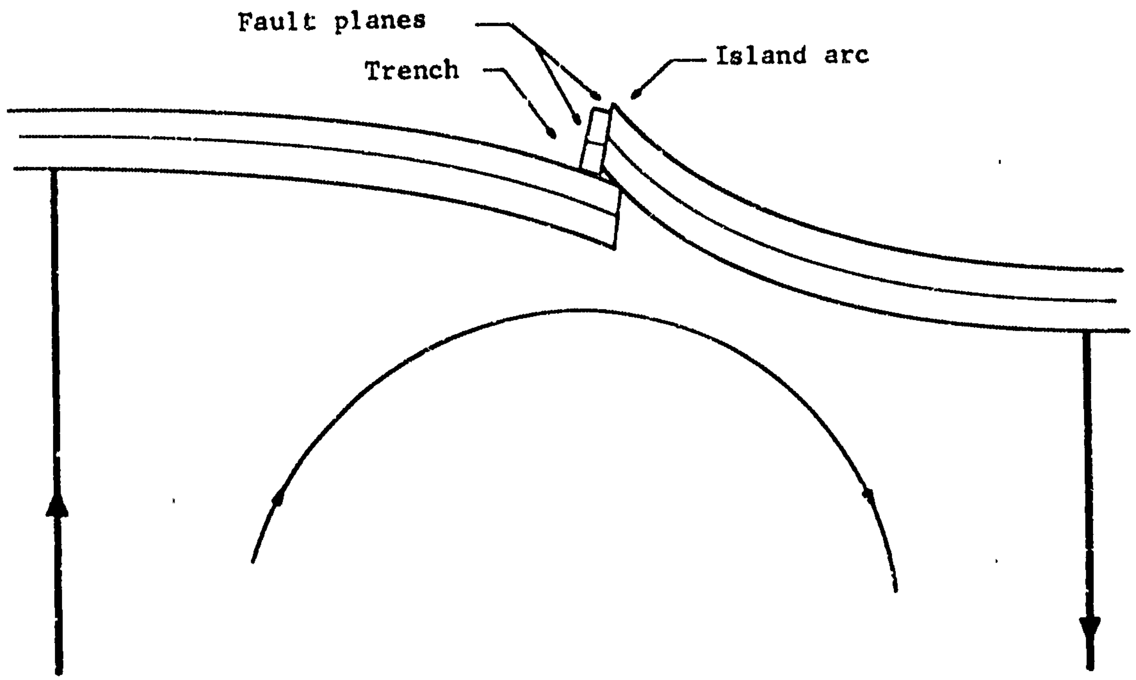


Fig. 5: Sketch of violent deformation of the thin oceanic crust through sudden release of critical friction and thermal stresses between density lows and highs. Asymmetric mantle flow results in faulting associated with under-thrusting effecting trenches with volcanic island arcs.

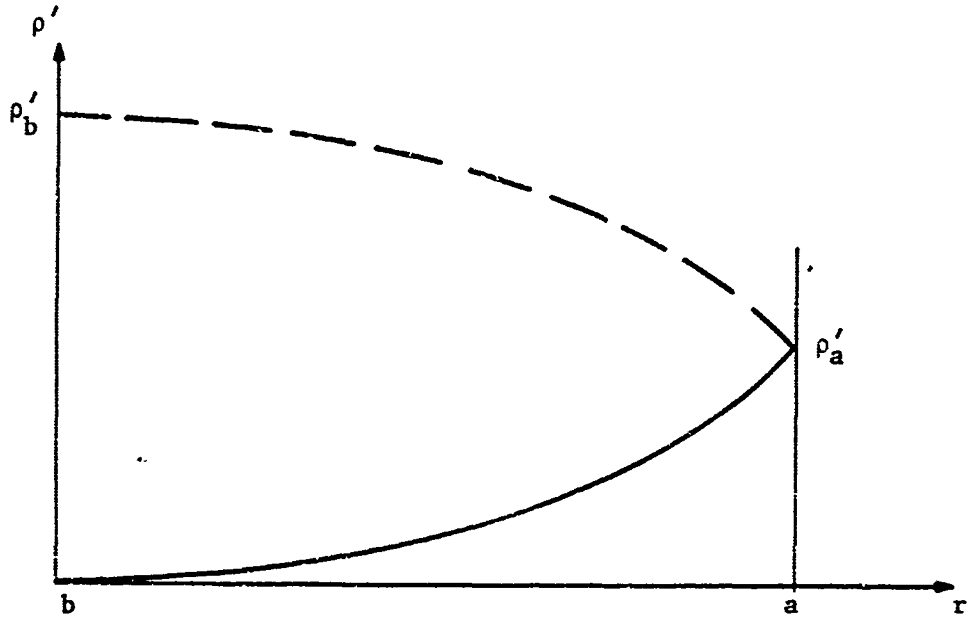
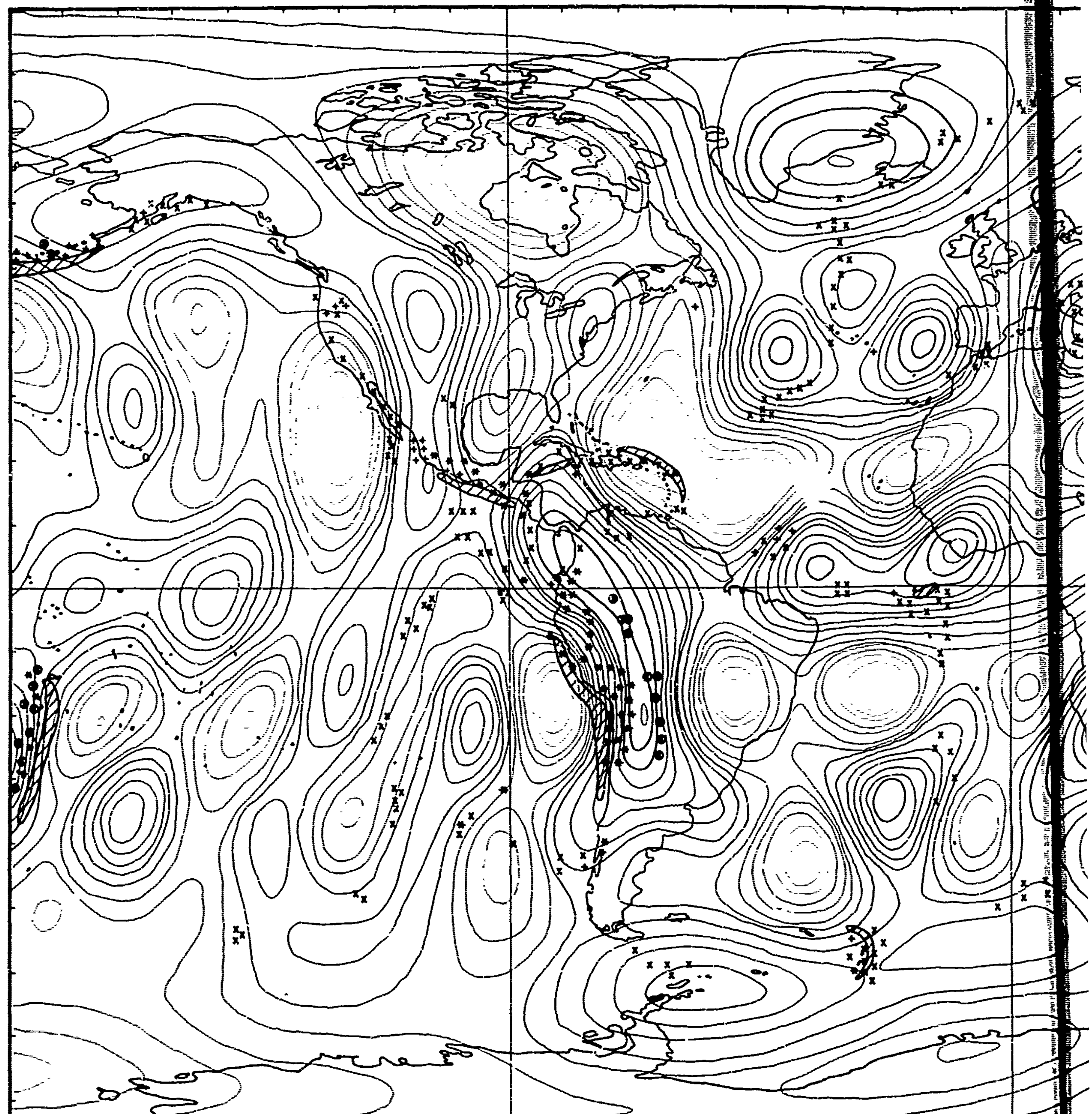


Fig. 6: Rapid attenuation of the density anomaly ρ' with the mantle depth (a - r)

———————— Sketch of present model with $\rho'_b = 0$.

- - - - - - - - Sketch of comparable model with $\rho'_b = 2\rho'_a$.



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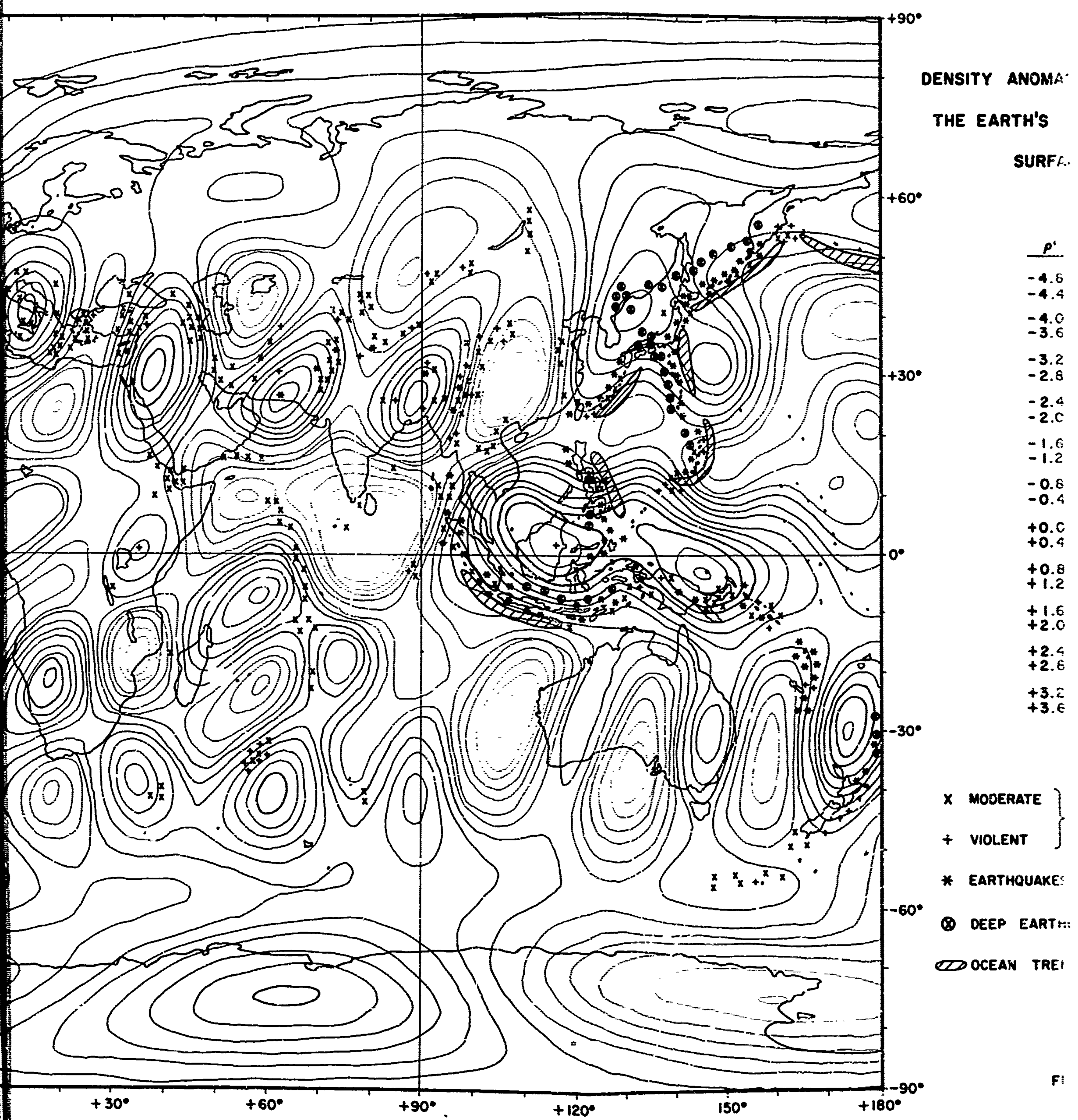
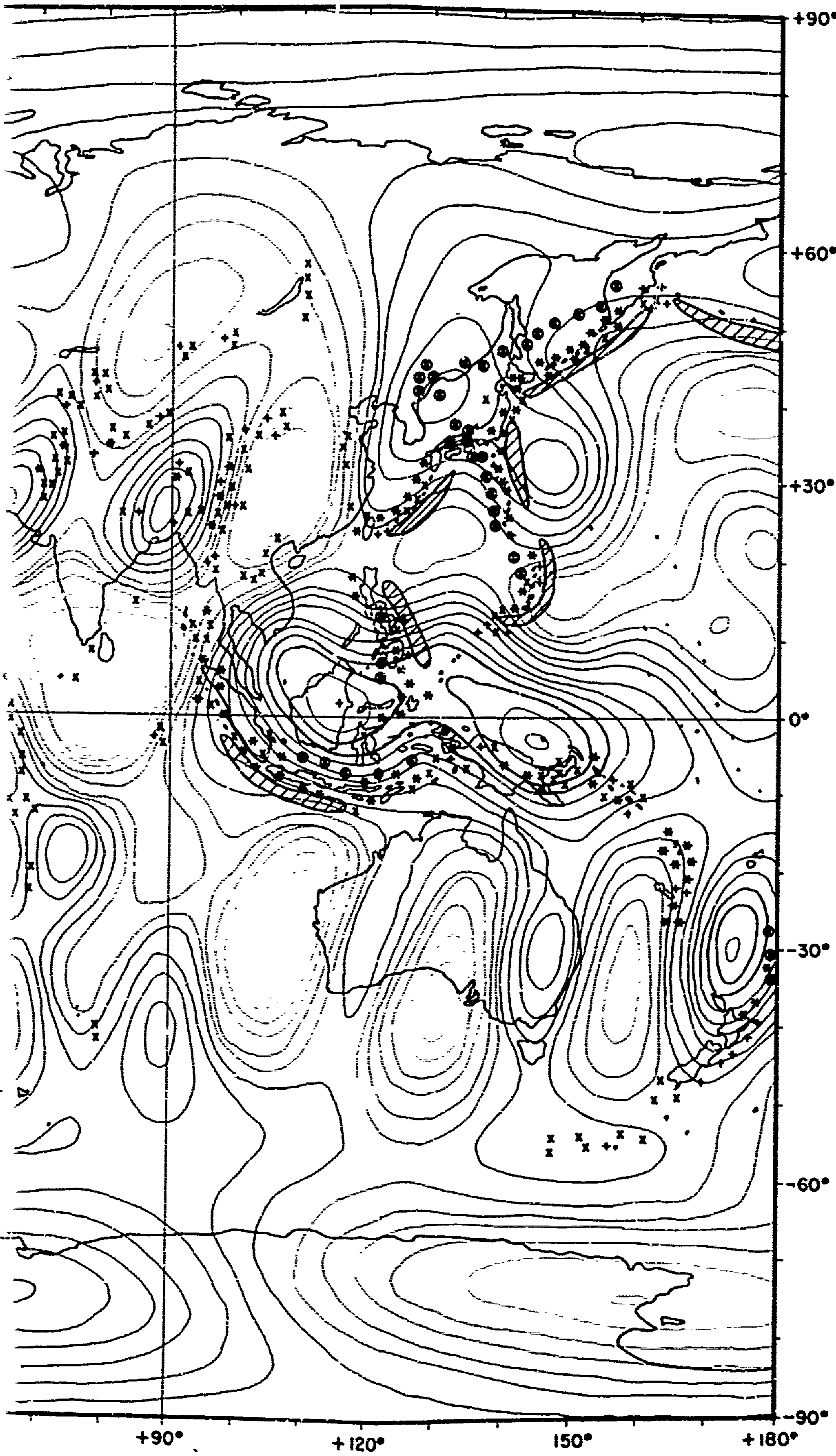


DENSITY ANOMA
THE EARTH'S
SURFA

FI

b

c



DENSITY ANOMALY ρ' (in g/dm^3) OF THE EARTH'S MANTLE AT THE SURFACE ($r_0 = a$)

ρ'	COLOR
-4.8 -4.4	
-4.0 -3.6	
-3.2 -2.8	░
-2.4 -2.0	▒
-1.6 -1.2	▒
-0.8 -0.4	▓
+0.0 +0.4	█
+0.8 +1.2	█
+1.6 +2.0	█
+2.4 +2.8	█
+3.2 +3.6	█

X MODERATE } SHALLOW EARTHQUAKES
+ VIOLENT } SHALLOW EARTHQUAKES

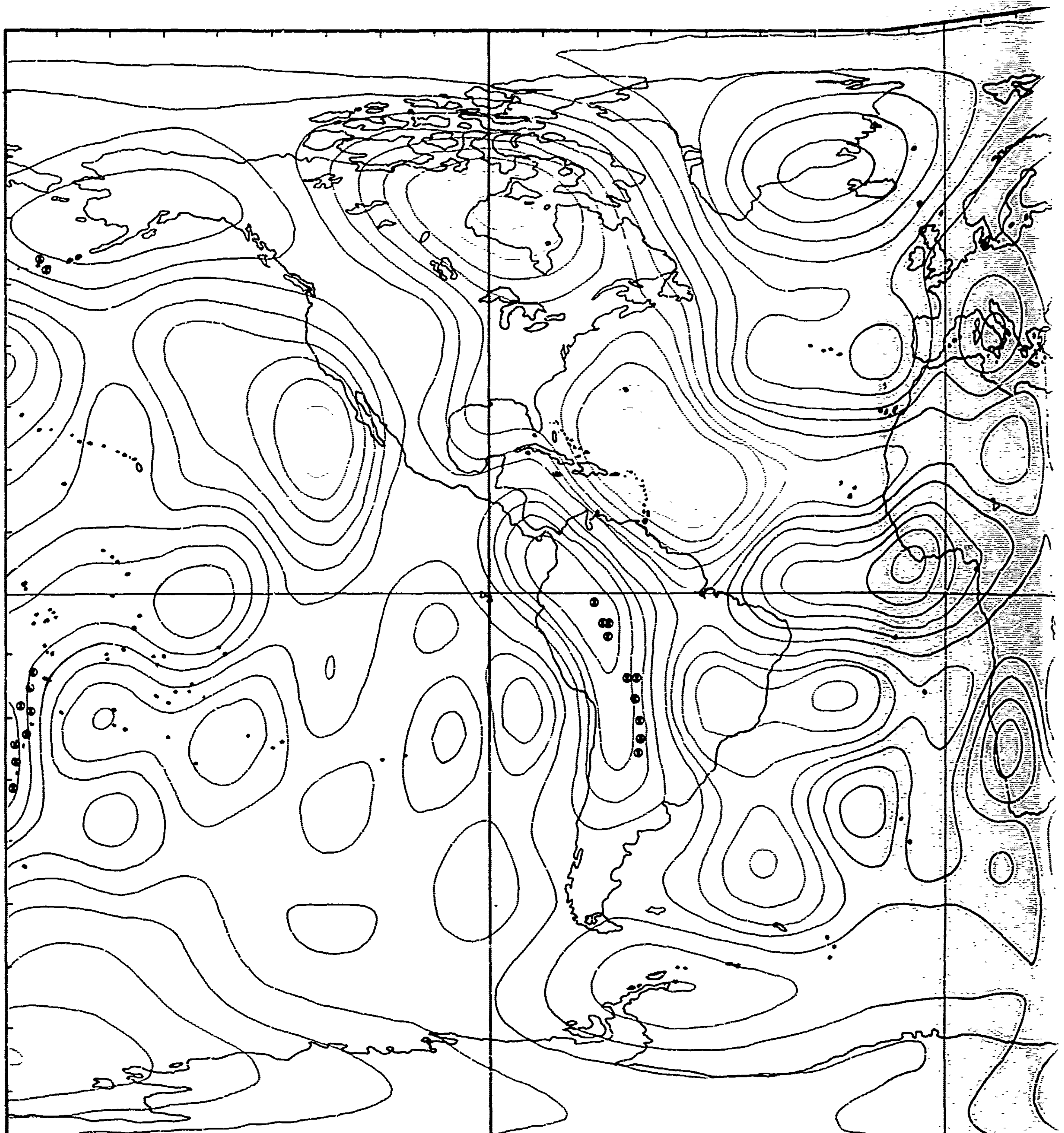
✱ EARTHQUAKES OF INTERMEDIATE DEPTH

⊗ DEEP EARTHQUAKES

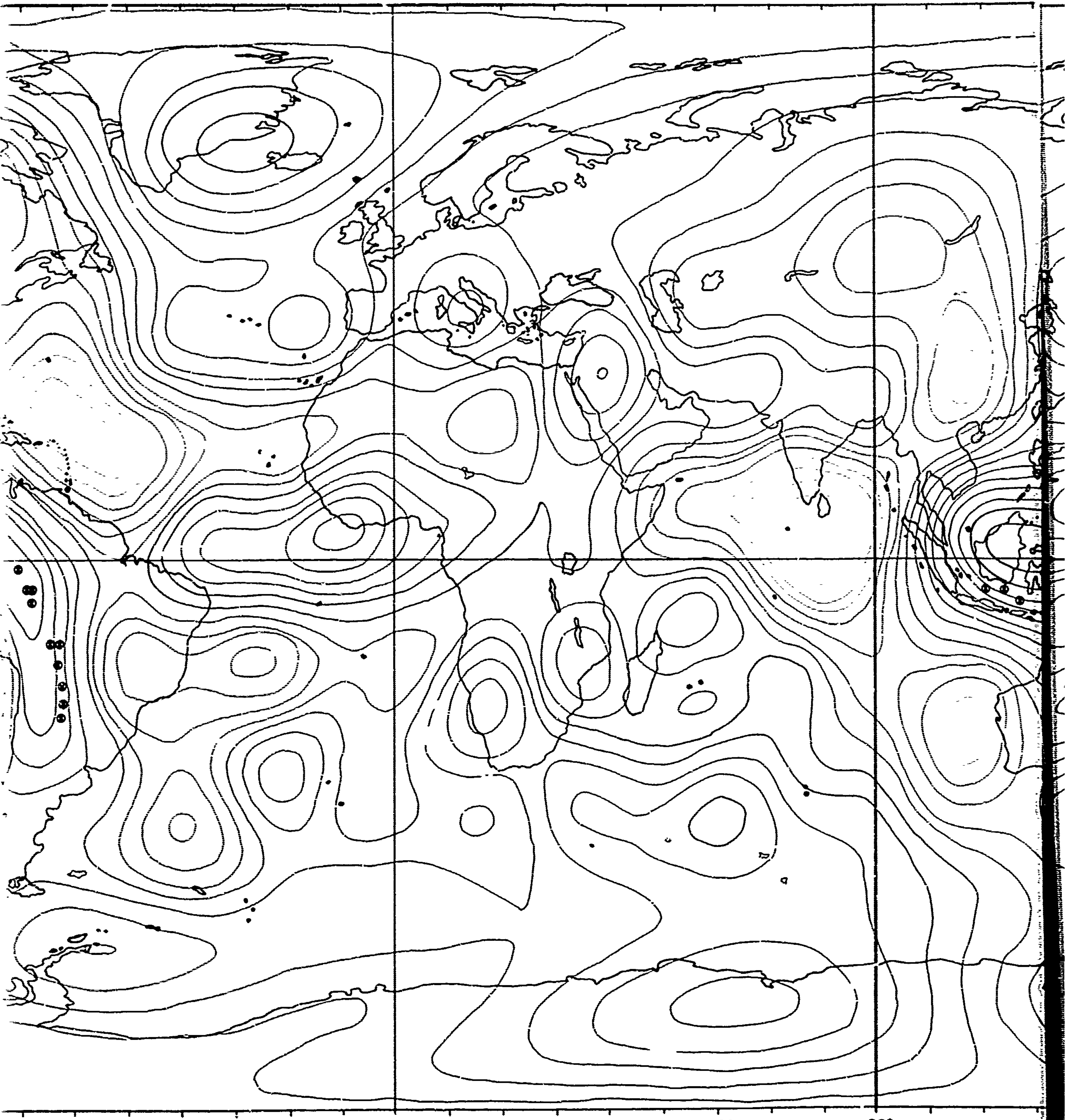
▨ OCEAN TRENCHES

FIGURE 7

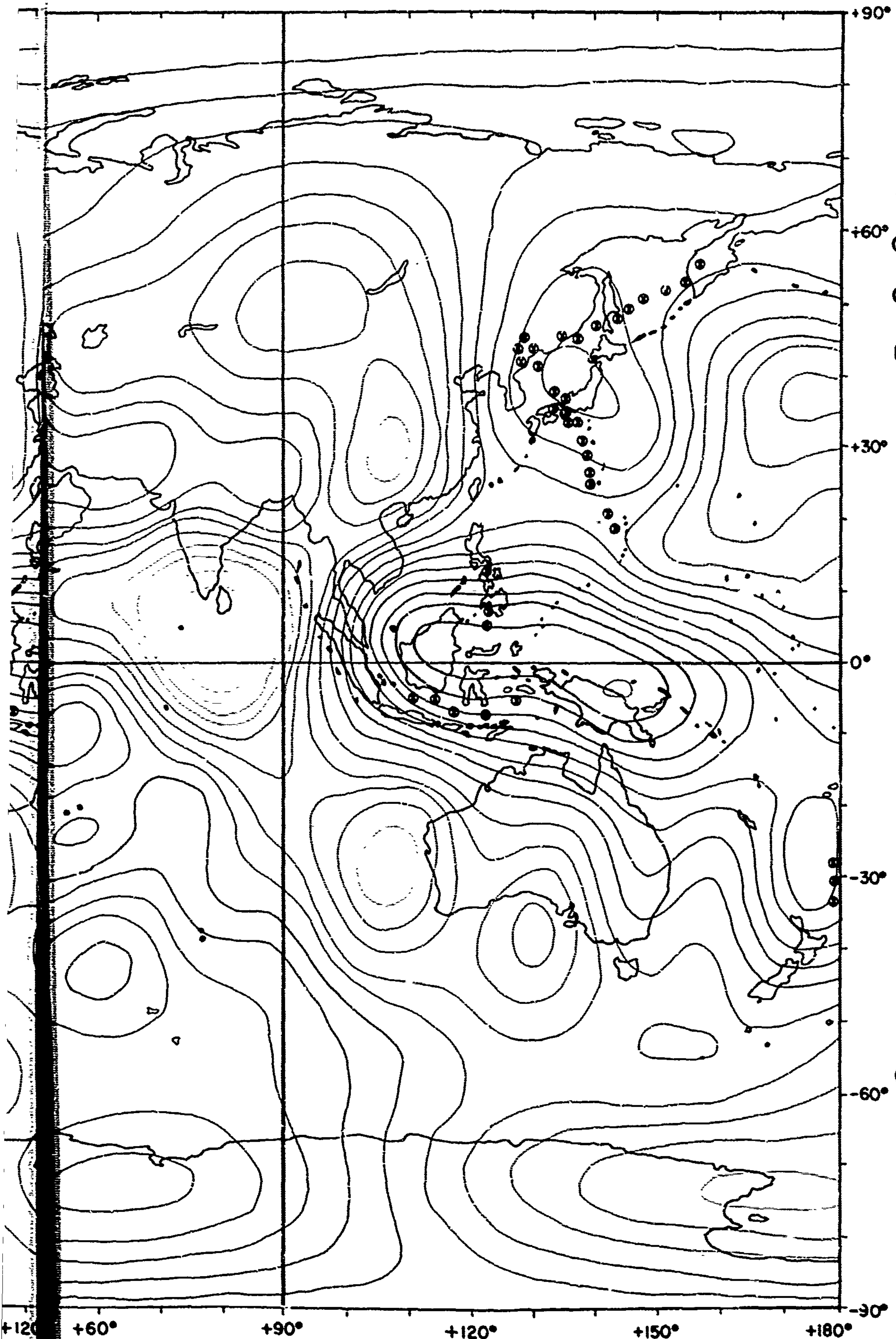
C



A



B



DENSITY ANOMAL ρ'(in g/(dm)^3) OF THE EARTH'S MANTLE AT ONE QUARTER OF THE MANTLE DEPTH (≈720km, $r_1 = a-(a-b)/4$)

ρ'	COLOR
-2.0 -1.8	
-1.6 -1.4	░
-1.2 -1.0	▒
-0.8 -0.6	▓
-0.4 -0.2	▓
+0.0 +0.2	■
+0.4 +0.6	■
+0.8 +1.0	■
+1.2 +1.4	■
+1.6 +1.8	■

⊗ DEEP EARTHQUAKES

FIGURE 8

C

APPENDIX B

UNCLASSIFIED
Security Classification

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13. ABSTRACT

A model of a fluid mantle is described which retains the significant features of the earth's interior and is adjustable to the outside gravity field. It is shown that the density anomaly is within the order of approximation governed by Laplace's equation regardless of a fluid or solid mantle hypothesis. The density anomaly is numerically evaluated on the basis of the most recently available satellite-sensed gravity data. While it is virtually impossible to interpret the computed world density maps in terms of tectonic features of the earth's crust on the grounds of a solid mantle assumption, the fluid mantle theory permits such an interpretation which is consistent up to many small details. Since every density anomaly computed seems to have played some role in the evolution of the crustal tectonics of today and, vice versa, because every major tectonic feature appears to be explainable by just the computed density anomalies, it is concluded that the gravity data used yielded a resolution of all essential density anomalies of the mantle. While it seems almost incredible that a satellite is sensitive enough to feel all those little density variations of the mantle, it must be hailed as a triumph of modern science and technology to read off such an enormous amount of information from the path of a satellite.

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