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A Schematic Model of Development of Active Continental Margins as Inferred from Particular Features of Global-Scale Geoid Undulations

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Abstract

The global-scale geoid undulations have been attributed mostly to the densiy variations within the upper half of the lower mantle. Based on this, a schematic model of development of active continental margins has been proposed. Then, simple numerical calculations were carried out in order to investigate the characteristic features of upper mantle flows predicted by the schematic model, with a special reference to the Meso-Cainozoic development of the East Asiatic continental margin.

1. Introduction

It has been generally accepted that the geoid anomalies are due to the lateral density variations within the earth's interior, though the depths of the sources of the anomalies have remained a subject of controversy: as for the global-scale geoid anomalies, in which we are primarily interested, one side postulates that they originate from lateral density variations in the upper mantle while the other side attributes them to an irregularly shaped core-mantle boundary. In the present paper, first of all, an attempt will be made to provide a constraint on the depth range of major sources of global-scale geoid undulations by referring to sundry papers, and then it will be suggested that the undulations can be attributed mostly to the lateral density variations within the upper half of the lower mantle. It will also be suggested that the most likely reason for the density variation is compositional heterogeneity of mantle material possibly resulting from unequal development of differentiation processes in the earth's interior.

On the other hand, the lateral density variation within the mantle can be considered to be the cause as well as the result of deep processes occurring in its interior, since the widely accepted rheological property of mantle material renders itself incapable of statically sustaining significant deviatoric stresses due to the density variation over geologically long periods of time and therefore the compositional heterogeneity responsible for the density variation can be envisaged to be eventually adjusted by dynamic processes in the mantle. Thus it seems reasonable to expect some manifestation of these processes as correlated with the geoid anomalies reflecting the lateral density variations within the earth. However, the global-scale geoid anomalies do not exhibit any excellent correlation with the surface tectonic features such as the geographical distribution of continents and oceans or that of mountain chains and ocean ridges. In the present paper, taking into consideration that the deep-focus seismic zones called Benioff zones are the only tectonic features penetrating deep into the mantle, a spatial relationship between the configuration of the seismic zones and the particular features of the global-scale geoid undulations will be examined, and then a schematic model concerning the development of active continental margins including the Benioff zones will be proposed. By means of simple numerical calculation based on a two-dimensional viscous layer model, the characteristic features of upper mantle flows will be investigated in order to interpret some of the peculiar features pointed out by geological studies concerning the Meso-Cainozoic tectonic development of transition zone from the East Asiatic Continent to the Northwest Pacific Ocean.

2. An Examination of the Global-Scale Geoid Undulations

Recent improvements in geoid models attained by using satellite and surface gravimetric data have made it possible to investigate geoid anomalies based on new methods. For example, the new concept of isostatic geoid anomaly proposed by Haxby and Turcotte (1978)[1], representing the perturbation in the earth's gravitational potential caused by the density variations within a thin isostatically compensated layer, has played an important role in the development of investigation of relatively short-wavelength geoid anomalies. This concept has been applied in numerous papers aimed at investigating the correlations between the regional detailed geoid anomalies and the near-surface features such as the topography of the earth's surface and the variations of thickness of the lithosphere[2)~4)]. It should be noted, however, that the geoid anomalies hardly can be attributed solely to these features, since the total amplitude of geoidal effects of the latter could not exceed some 15% of that of the observed geoid anomalies amounting to 180 m or so in height. Certainly, as can be seen from **Fig. 1**, the corrections of the geoid height for the effect of near-surface topography and for that of the so-called subducting lithosphere do not make any significant change in the global pattern of geoid anomaly. Therefore it seems reasonable to ascribe the large-scale geoid anomalies to the density variations in the deep mantle.

With respect to the large-scale geoid anomalies, Tarakanov et al. have proposed a new method of interpretation[6)~8)]. They obtained a number of gravity vectors by means of numerical differentiation carried out directly on the geoid surface and then they found the regions in the mantle within which the gravity vectors intersect one another. According to their estimation, the large-scale geoid anomalies, such as the Indian Ocean anomaly, that of east off Australia and others characterized by densely drawn closed contours of geoid height, can be ascribed to the lateral density variations below the second boundary of the mantle's transition zone at the depth of 790–900 km. It is important to note that the geoid anomalies investigated by Tarakanov et al. have the characteristic wavelengths of several thousand kilometers.

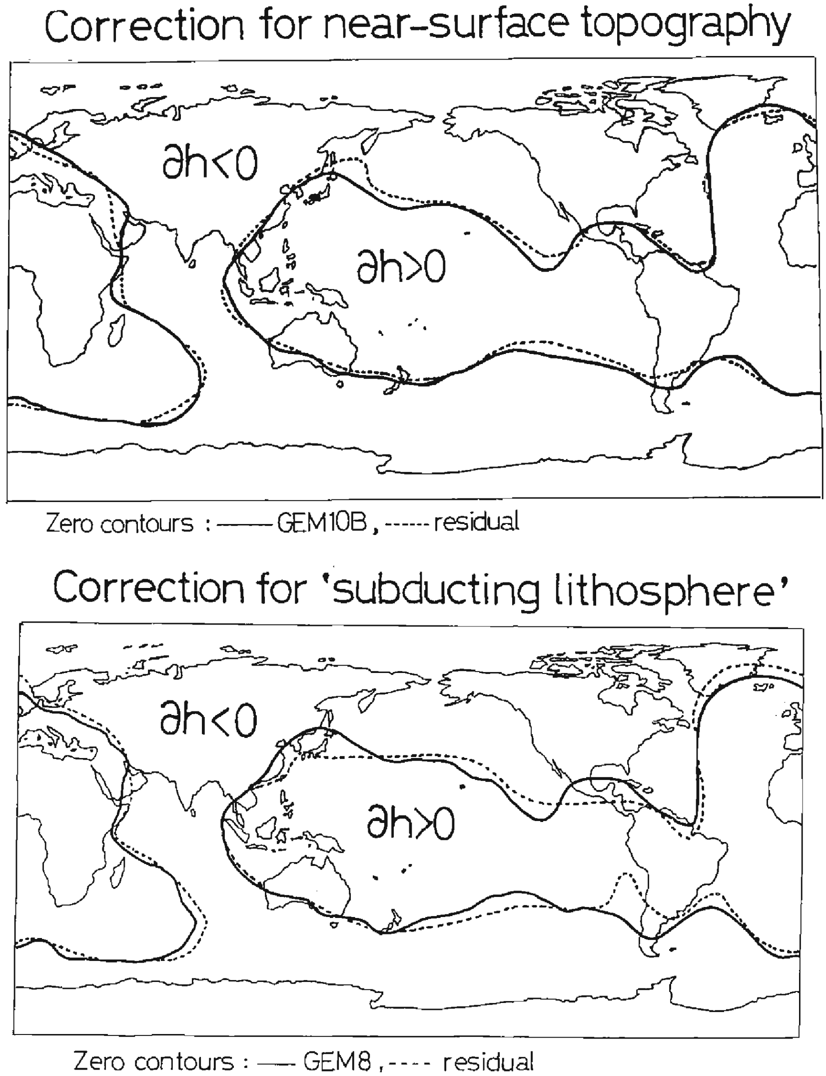

Fig. 1 Comparison of global pattern of geoid undulations with the corresponding patterns of two kinds of residual geoid, reproduced after Chase (1979)[5] and Chase and McNutt (1982)[4].

Thus it seems reasonable to attribute the global-scale undulations, characterized by longer wavelengths, to the density variations within the deeper part of lower mantle.

As for the global-scale undulations, Malin and Hide (1982)[9] have attributed them to the bumps on the core-mantle boundary by investigating the correlation between the pattern of long-wavelength geoid anomalies and the corresponding pattern of anomalies in the geomagnetic field. However, according to the estimation carried out by them, the gravitational effect of the bumps on the boundary seems fairly small as compared with that of the density variations associated with mantle convection which was supposed so that the bumps might be maintained against the tendency for gravity to smooth them out. Such being the case, it seems possible to consider that though the topography of the core-mantle boundary could be partly responsible for the global-scale geoid undulations, the latter should be ascribed mostly to the density variations within the lower mantle above the boundary.

On the other hand, a clear indication of wide-spread heterogeneities residing in the lower mantle came from the statistical study of P-wave travel times carried out by Dziewonski et al. (1977)[10]. They discerned global-scale P-wave velocity anomalies in the mantle, especially in the lower mantle. They also pointed out a negative correlation between the long-wavelength gravity anomalies and the P wave velocity anomalies within the lower mantle. But, in their study, a proportionality was assumed between the spherical harmonic coefficients of the gravitational potential and those of the velocity potential defined by them, and then a statistically estimated value of proportionality coefficient was used to modify the original solutions of velocity anomalies. In the present paper, the original solutions obtained by Dziewonski et al. for each shell within the mantle were examined without any assumption, and then it was found that they could be utilized in order to provide a constraint on the depth range of major sources of global-scale geoid undulations. In **Fig. 2** the global pattern of geoid anomaly is compared with that of velocity anomaly found for the shell located in the lower mantle at the depth range of 1100 to 1500 km. Within the above depth range, the both anomalies can be thought to correlate with each other to a remarkably

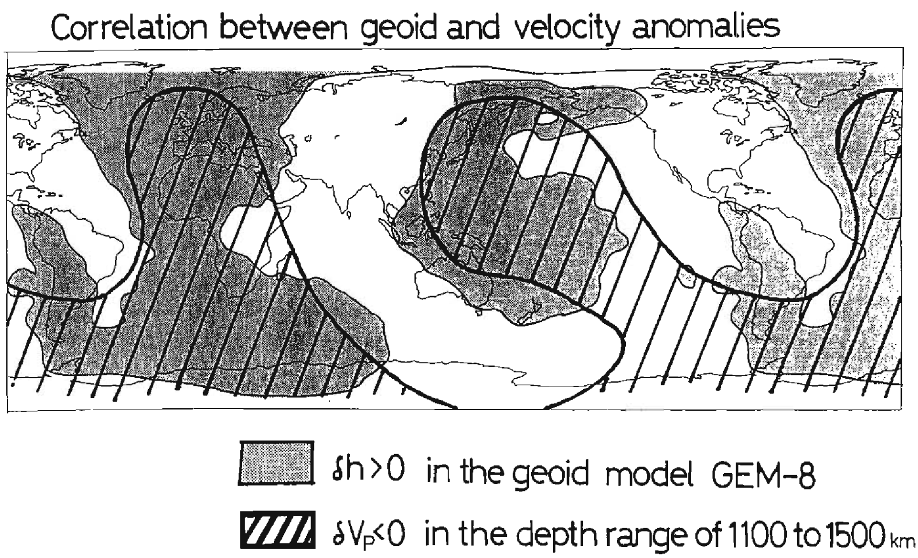

Fig. 2 A map showing a negative correlation between the global-scale geoid undulations given by GEM-8 model[11] and the P wave velocity anomalies found for the shell located in the depth range of 1100 to 1500 km[10].

high degree. In the other depth ranges, however, such an excellent correlation is never found. This means that it is possible to infer that the global-scale geoid undulations are mostly due to the density variations within the above-mentioned shell of the lower mantle. This inference seems concordant with the result obtained by Allan (1972)[12], who investigated the spectra of mean square values of the gravity coefficients and came to the conclusion that the lower order parts of the gravity field correspond to the density variations at the effective depth ranging from 1300 to 1700 km.

Another observation in **Fig. 2** is a negative correlation between the velocity and density anomalies: the regions appointed to higher velocity almost coincide with those appointed to lower density and vice versa. It seems impossible to explain the correlation simply in terms of lateral temperature variations within the mantle, because they would provide a rather positive correlation. Dziewonski et al.[10] offered one possible explanation that the velocity and density anomalies might be related to large-scale mantle convection. They suggested that the velocity anomalies are due to temperature differences associated with mantle-wide convection and, on the other hand, the density anomalies are due to perturbations of the earth's free surface and core-mantle boundary also associated with the convection. However, even if these effects were taken into account, it seems difficult to explain the fact that, as seen from **Fig. 2**, both the western part of the Pacific Ocean and major part of the Atlantic Ocean belong to the regions appointed to higher velocity and lower density, since, in the widely accepted pattern of mantle convection, to the former is assigned the descending flows and to the latter the ascending one.

Accordingly, in the present paper, we prefer to invoke the compositional heterogeneities in the lower mantle in order to explain the above-mentioned negative correlation. **Fig. 3** represents the shock wave experiment data of two dunites in the pressure range of 0.2 to 1.2 Mbars corresponding to the depths of the lower mantle. The original data obtained by McQueen et al. (1967)[13] were arranged by taking the chemical composition into account. As can be seen from the figure, a Mg-rich dunite exhibits higher bulk sound velocities and lower densities than an Fe-rich one. Assuming that the pressure dependence of P wave velocity is analogous to that of bulk sound velocity, this tendency can be taken as a basis of interpretation of the negative correlation observed in **Fig. 2**. Thus it might be considered that the higher velocity and lower density implies a high Mg/Fe ratio in the composition of the matter within the lower mantle and, conversely, the lower velocity and higher density implies a low Mg/Fe ratio. It is important yet difficult to specify the cause of the compositional heterogeneities supposed in the lower mantle, though one possibility is that unequal development of differentiation processes within the earth, such as Fe-Mg partitioning for perovskite and magnesiowustite[14] and subsequent upward removal of Fe-rich materials during the evolution of the earth[15], is responsible for the heterogeneities. The chemical plumes proposed by Anderson (1975)[16] might have brought about the heterogeneities within the lower mantle.

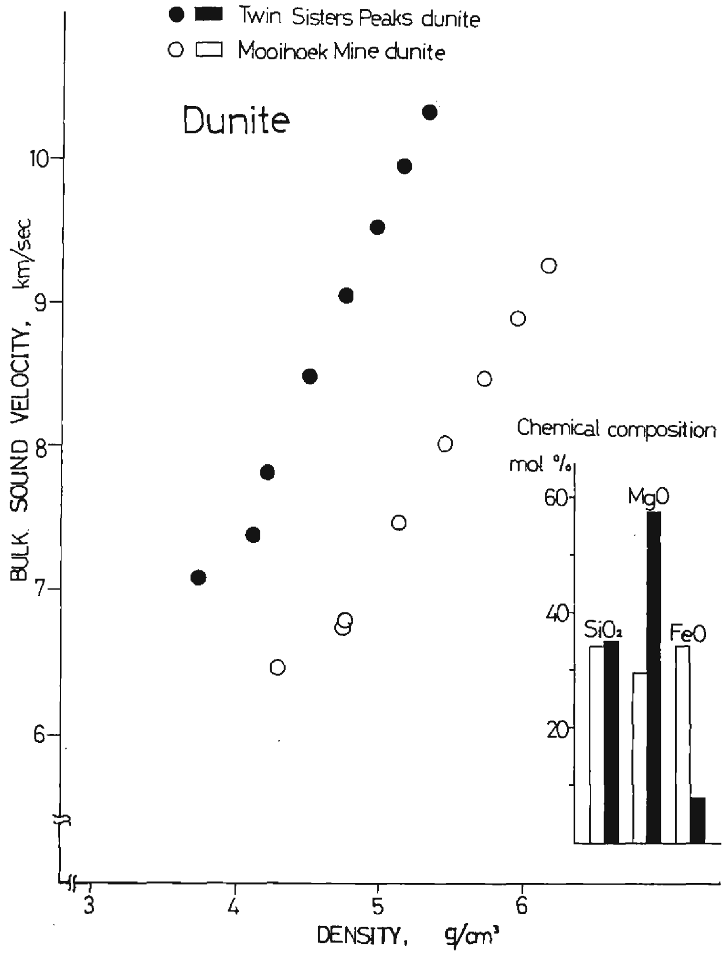

Fig. 3 Shock wave experiment data of two dunites in the pressure range of 0.2 to 1.2 Mbars arranged by taking the compositions into account. Original data are from McQueen et al. (1967)[13].

After all, though the considerations presented above are highly qualitative, it seems possible to suggest that the global-scale geoid undulations are mostly due to the lateral density variations within the upper half of the lower mantle possibly reflecting compositional heterogeneities, which are envisaged to be an eventual consequence of differences in the degree of depletion of the mantle material.

3. A Schematic Model of Development of Active Continental Margins

Generally speaking, the lateral variation of the physico-chemical properties of the matter within the earth is the cause as well as the result of deep processes occurring in its interior. In this sense the density variations investigated above seem to have a significant implication with regard to dynamic processes in the mantle. It should be discussed here that the depletion of the mantle material in Fe-rich constituents, for example, generating compositional heterogeneities as suggested in the previous section, would not result in any significant density decrease, if the compositional heterogeneities could be compensated by the lateral temperature variations. However, the heating of the previously depleted material by conduction from its periphery, by internal heat sources or by diapiric intrusion from below seems to render the compensation incapable of surviving for very long periods. Therefore, the lateral density variations involved with the compositional heterogeneities can be envisaged to be eventually adjusted by dynamic processes occurring in the earth's interior.

According to the estimation of the state of stress within the earth carried out by Kaula (1963)[17], the density distributions corresponding to spherical harmonics of the gravitational field up to the 4th order harmonic could cause a stress difference exceeding the creep strength or the yielding point of the matter within the mantle. Thus it seems possible to assume that the regions within the mantle characterized by large lateral density contrast are in a state in which creep flow is taking place due to large stress differences. In the present paper, as shown in **Fig. 4**, an attempt was made to find some outward manifestation of such a specific state in the upper half of lower mantle. The hatched zones on the upper map in the figure indicate particular belts characterized by steepest descent on the relief of global-scale geoid undulation corresponding to abrupt transition from positive to negative geoid anomalies and possibly reflecting large lateral density contrast within the upper half of the lower mantle. It is below the belts that the creep flow is most likely to occur. On the other hand, it is important to note that the deep-focus seismic zones called Benioff zones are the only tectonic feature penetrating deep into the mantle up to the depth of about 700 km. Thus it seems reasonable to examine a spatial relationship between the seismic zones and the above-mentioned particular belts. As shown on the lower map in **Fig. 4**, it is noticeable that most of the zones extend near along the ocean side of the particular belts. This relationship was considered as indicative of a genetic interrelation between the both, and then a schematic model was proposed relating the formation of the seismic zones to the creep flow supposed within the upper half of the lower mantle.

Fig. 5 illustrates the proposed model. In this model the creep flow in the lower mantle is considered as similar to a density current in the gravitational field and the seismic zone is thought to be a kind of weak zone which might be formed as a result of upper mantle differential flow induced by the density current. In order to resolve a question whether or not the density current is responsible for the processes occurring in the upper mantle, a tentative estimation of the order of density current velocity was made with the use of two-dimensional viscous layer model composed of two semi-infinite horizontal layers in contact with each other at a vertical interface. Taking into account that the high viscosity of the matter within the mantle enables us to treat the current as a steady-state flow and assuming that main streams are

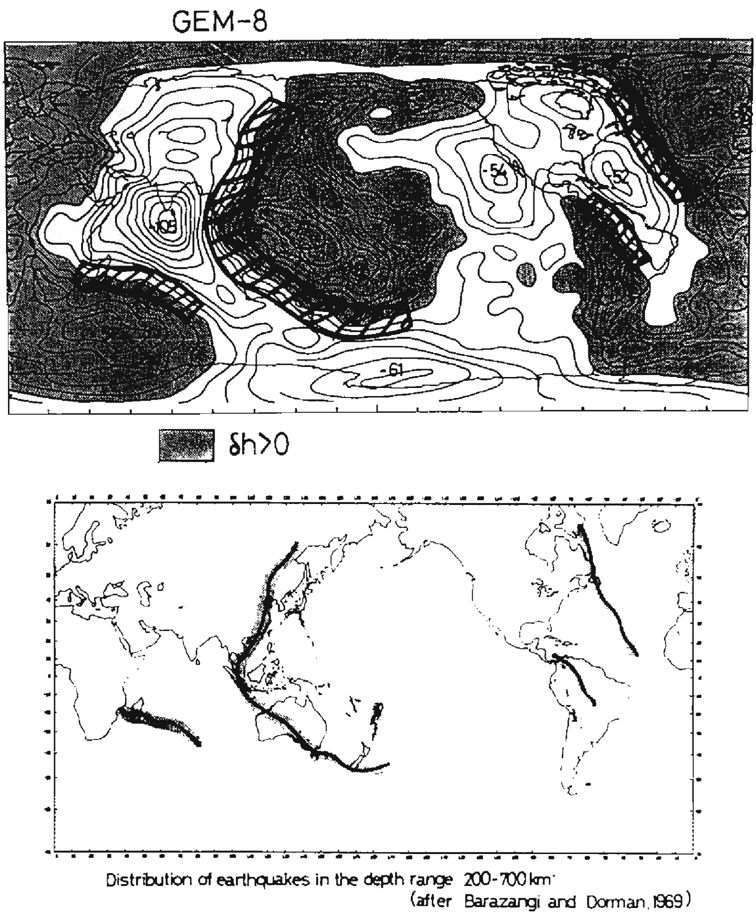

Fig. 4 The upper map showing the belts characterized by steepest descent on relief of the geoid surface and the lower showing a spatial relationship between the above-mentioned belts and the epicentral distribution of deep-focus earthquakes reproduced after Baragangi and Dorman (1969)[18].

concentrated within a narrow portion near around the interface, the velocity of the current can be crudely estimated as follows:

$$v \sim \frac{gH^2}{\nu} \cdot \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

where g is the gravitational acceleration, H is the thickness of the layer, ν is the kinematic viscosity and ρ_1, ρ_2 $(\rho_1 > \rho_2)$ represent the densities of the semi-infinite layers. Making use of adequate values: $H \sim 10^3$ km, $\nu \sim 10^{24} - 10^{26}$ cm^2/sec, $(\rho_1 - \rho_2)/(\rho_1 + \rho_2) \sim 10^{-2}$, the velocity of the current was estimated to be the order of $10^{-1} - 10^1$ km/my, which seems sufficient for the density current to have a significant effect on the processes occurring within the upper mantle during the Meso-Cainozoic tectonic cycle of the earth's evolution.

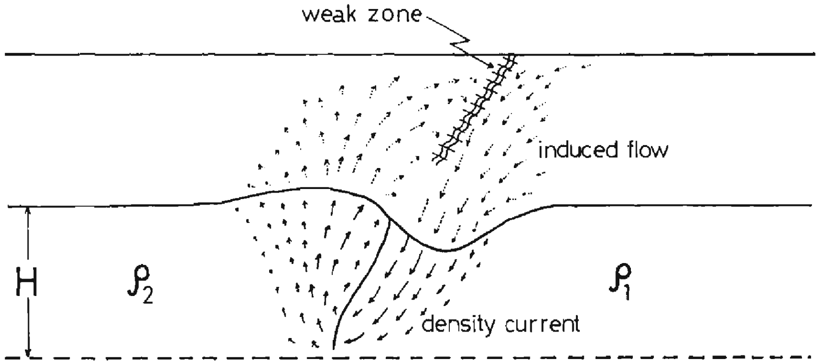

Fig. 5 A schematic model illustrating the formation of a weak zone corresponding to the Benioff zone as a result of upper mantle differential flows induced by density currents in the upper half of the lower mantle.

The characteristic features of the upper mantle flows induced by the density current was investigated by means of simple numerical calculation. A two-dimensional model used for calculation is shown in **Fig. 6**, in which the upper 1000 km of the mantle is assumed to be composed of five homogeneous viscous layers and the distributions of density and viscosity are assumed analogous to those comprised in widely accepted models including an asthenosphere-like layer. For simplicity, the effect of the density current was assumed to be equivalent to a vertical differential

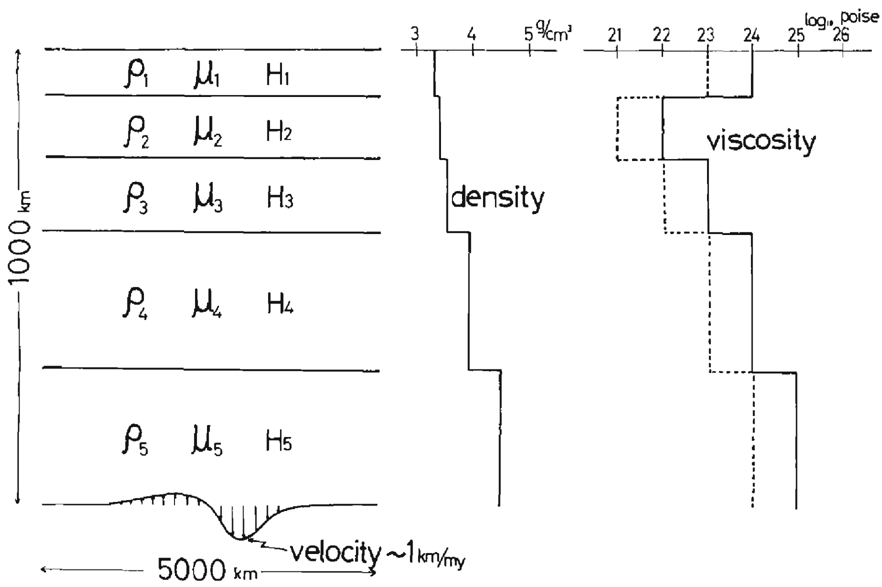

Fig. 6 Two-dimensional viscous layer model with the distributions of density and viscosity, used for calculation of the velocity field of upper mantle flows induced by the differential movement applied on the bottom surface.

movement applied on the bottom surface as a boundary condition and, judging from the above estimation, the maximum velocity of movement was assumed to be the order of 1 km/my and to remain constant for a sufficiently long time, as shown in the figure. Mathematical formulation of the model was obtained based on the treatment of Ramberg (1968)[19], with a slight modification so that the velocity field can be represented as a summation of many sinusoidal components by a suitable choice of the phases and amplitudes (see **Appendix**). Numerical calculation was carried out step by step in time by taking into account the temporal variation of topography of the free surface and interfaces, which were assumed to be initially parallel to the equipotential surfaces. Except for the initial stages of calculation, the successive solutions changed so gradually with time that the resultant flow could be considered as nearly stationary during the time interval of at least several tens of million years.

Fig. 7 illustrates a typical example of solution, the arrows indicating the velocity field of the resultant flow. As it can be seen from the figure, the velocity field exhibits a circulative nature in the middle part of the model and the horizontal stream is remarkably intensified in the asthenosphere-like layer. Another observation in the figure is the abrupt change of stream lines on the both sides of the model; namely, on the left-hand side the horizontal stream goes apart from the obliquely ascending stream and on the right-hand side it encounters the descending one. Although the present model is still quite primitive and a more precise analysis is desirable, the salient features observed in the figure seem to have a significant implication with regard to the tectonic development of active continental margins. In the present paper, bearing in mind that one of the particular belts as mentioned above extends near along the inside of the eastern margin of the Asiatic Continent (see **Fig. 4**), a special reference was made to the Meso-Cainozoic development of the transition zone from the East Asiatic Continent to the Northwest Pacific Ocean and some recently proposed diagrams were inserted in **Fig. 7** for comparison. It was firstly noticed that the intensified horizontal stream observed in the present model can be compared to the eastward upper mantle flow which is often supposed by geologists in order to explain the peculiar features of tectonic development of the East Asiatic Continent, as schematized, for example, in the inserted diagram of Tan and Zhang (1983)[20]. A similar flow was also supposed by Nagibina et al. (1981)[21] as responsible for the lateral migration of the specific tectono-magmatic process called revivation. In the figure is also inserted another diagram proposed by Meyerhoff and Meyerhoff (1978)[22], relating the formation of island arcs in the active continental margins to the upper mantle surge current involved with the differential contraction of the earth. It is interesting to note that, apart from the global contraction of the earth supposed by Meyerhoff and Meyerhoff, the physical nature of the surge currents seems identical to that of the intensified horizontal stream encountering the descending one in the present model. Moreover, the oliquely ascending stream observed on the left-hand side of the model can be compared to the uprise of the anomalous mantle material supposed by Zamarayev and Ruzhich (1978)[23] to be

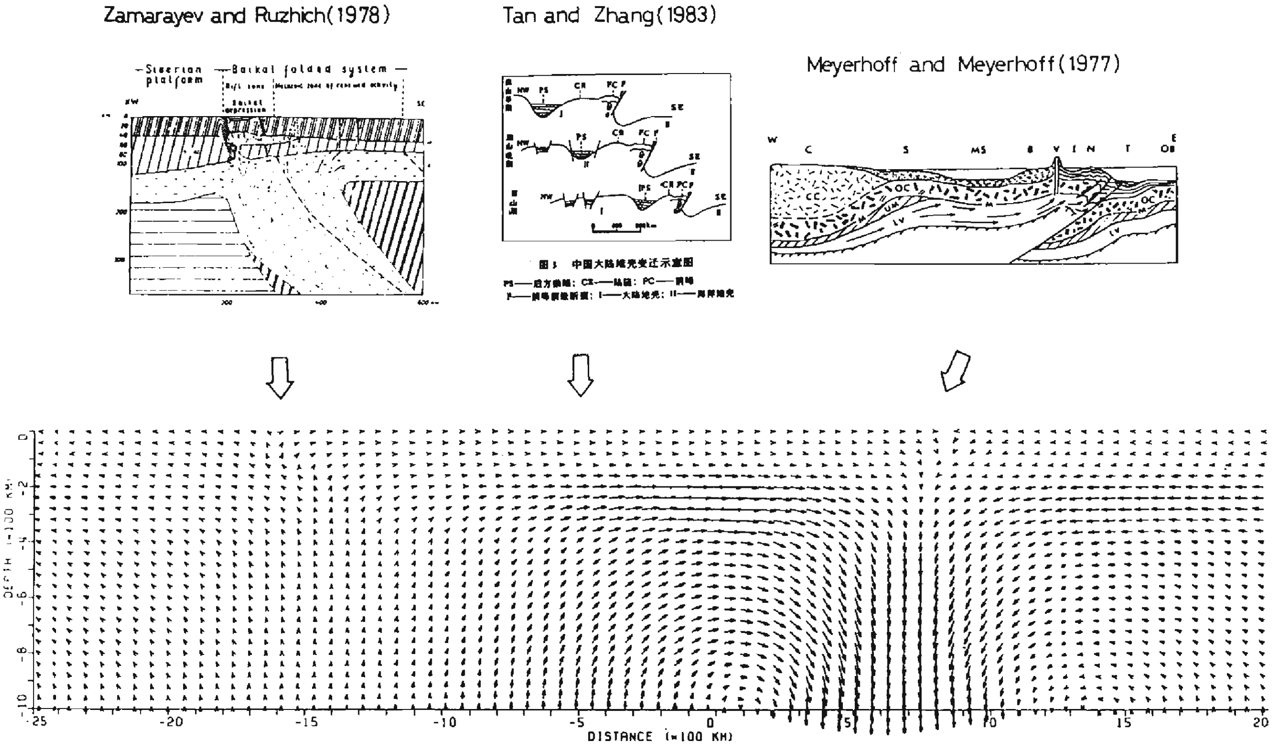

Fig. 7 A solution of the resultant flow, arrows indicating the velocity field, and its implications with regard to the peculiar features of tectonic development of the East Asiatic Continent as schematized in the inserted diagrams.

responsible for the Meso-Cainozoic development of the anomalous upper mantle strucrure below the Baikal rift zone.

In summary, it seems possible to suggest that the upper mantle flow induced by the density current within the lower mantle could be responsible for the peculiar features of regional tectonic development of the East Asiatic transition zone during the Meso-Cainozoic cycle of the earth's evolution.

4. Concluding Remarks

In the present paper, the global-scale geoid undulations were attributed mostly to the density variations residing in the upper half of lower mantle, and then taking into consideration a spatial relationship between the characteristic features of the undulations and the configuration of the deep-focus seismic zones called Benioff zones, a schematic model of development of active continental margins including the Benioff zones was proposed. It was suggested that the upper mantle flow induced by the density current within the upper half of lower mantle could be responsible for the peculiar features of Meso-Cainozoic development of the transition zone from the East Asiatic Continent to the Northwest Pacific Ocean.

It should be mentioned here that the schematic model presented above is in a sense similar to that of Van Bemmelen (1972)[24], in which the regional tectonic development of the East Asiatic Continent was also related to the movement in the lower mantle; namely, the upper mantle flows induced by "a spreading mega-undactory upwelling of the lower mantle causing the Tibet-Mongolian Mega-Undation" (p. 110) were supposed to be responsible for the tectonic features of the East Asiatic continental margin including the island arcs. It seems, however, that the characteristic features observed in the gravitational field precludes us from supposing solely an upwelling of the lower mantle located below the East Asiatic Continent, since, as mentioned above, one of the particular belts characterized by large density contrast extends near along the inside of the East Asiatic continental margin, which seems rather to support the density currents as supposed in the present paper. On the other hand, Beloussov (1982)[25] has recently proposed a new interpretation of formation of the Benioff zones, according to which the Benioff zone was formerly a vertical deep fault and its inclination is of secondary nature, that is, a result of upper mantle differential flows caused by lateral temperature difference on the both sides of the fault. It is noteworthy that, if referred to the Benioff zones penetrating deep into the mantle up to the depth of about 700 km, the schematic model of Beloussov seems necessitated to assume large-scale differential flows involving the whole upper mantle and mantle's transition zone, the pattern of which can be envisaged to be similar to that of the flows observed in the present model, though the thermal aspect of the latter has not been investigated as yet.

Finally, it should be also mentioned that some problems remain unsolved. At this time it is difficult to explain the reason why the density current supposed in the lower mantle does not result in formation of the Benioff zones near around the middle parts of the Indian Ocean and the Atlantic Ocean, where the above-mentioned particular belts were traced, as shown in **Fig. 4**. It is also difficult to explain why the individual Benioff zones do not necessarily extend in parallel to the particular belts. In a future study, these problems should be examined by taking into consideration the actual conditions in the upper mantle, such as lateral heterogeneities and pre-existing deep faults, in addition to the mantle-crust interactions, since these factors would bring about a significant modification in the schematic model proposed in the present paper. Certainly, more questions have been raised than have been answered, but it is hoped that new insights into the problem of mantle dynamics have been gained in this study.

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Appendix

Equations for dynamics of a five-layered viscous model in the gravitational field as illustrated in **Fig. 6** were derived based on the treatment of Ramberg[19].

Assuming Newtonian viscosity, small amplitude-to-wavelength ratio, negligible inertial forces and two-dimensional flow, the velocity field in the i-th layer can be obtained by summing the sinusoidal velocity components, each of which is assigned with the characteristic wavenumber $k(=2\pi/\lambda$, where λ is wavelength).

$$\left.\begin{aligned} U_i(x,y) &= \sum u_i(x,y;k) \\ V_i(x,y) &= \sum v_i(x,y;k) \end{aligned}\right\} \quad \text{(A-1)}$$

where $U_i(x,y)$ and $V_i(x,y)$ are the horizontal and the vertical velocity components, respectively, in an orthogonal coordinate system, y being the vertical direction reckoned positive upward. The sinusoidal velocity components, $u_i(x, y; k)$ and $v_i(x, y; k)$, can be written as follows:

$$\left.\begin{aligned} u_i(x,y;k) &= [A_i(k)e^{ky}+B_i(k)e^{-ky}+C_i(k)kye^{ky}+D_i(k)kye^{-ky}]\cos(kx+\phi(k)) \\ v_i(x,y;k) &= [A_i(k)e^{ky}-B_i(k)e^{-ky}+C_i(k)\cdot(ky-1)e^{ky}-D_i(k)\cdot(ky+1)e^{-ky}] \\ &\qquad \sin(kx+\phi(k)) \end{aligned}\right\} \quad \text{(A-2)}$$

where $A_i(k)$, $B_i(k)$, $C_i(k)$ and $D_i(k)$ are coefficients to be determined by the boundary conditions and $\phi(k)$ represents the phase to be given by resolving the velocity profile of the differential movement applied on the bottom surface into many sinusoidal components.

The boundary conditions that both the normal and shear stresses and the horizontal and vertical velocities are all continuous at the four interfaces in the model give the following sixteen equations:

$$\left.\begin{aligned}
&a_i(k)\bar{A}_i(k)+\bar{B}_i(k)/a_i(k)-kH_ia_i(k)\bar{C}_i(k)-kH_i\bar{D}_i(k)/a_i(k)=0\\
&a_i(k)\bar{A}_i(k)-\bar{B}_i(k)/a_i(k)-(kH_i+1)a_i(k)\bar{C}_i(k)-(kH_i-1)\bar{D}_i(k)/a_i(k)=0\\
&a_i(k)\tilde{A}_i(k)-\tilde{B}_i(k)/a_i(k)-kH_ia_i(k)\tilde{C}_i(k)+kH_i\tilde{D}_i(k)/a_i(k)=0\\
&a_i(k)\tilde{A}_i(k)+\tilde{B}_i(k)/a_i(k)-(kH_i+1)a_i(k)\tilde{C}_i(k)-(kH_i-1)\tilde{D}_i(k)/a_i(k)=\\
&\qquad\qquad(\rho_{i+1}-\rho_i)gy_i(k)/2k\\
&\qquad(i=1\sim4)
\end{aligned}\right\}\quad\text{(A-3)}$$

where μ_i and ρ_i are the viscosity and the density of the i-th layer, respectively, and g is the gravitational acceleration. $H_i=\sum_{j=1}^{i} h_j$, where h_j is the thickness of the j-th layer. $a_i(k)=\exp(-kH_i)$ and

$$\left.\begin{aligned}
&\bar{A}_i(k)=A_i(k)-A_{i+1}(k), && \tilde{A}_i(k)=\mu_iA_i(k)-\mu_{i+1}A_{i+1}(k);\\
&\bar{B}_i(k)=B_i(k)-B_{i+1}(k), && \tilde{B}_i(k)=\mu_iB_i(k)-\mu_{i+1}B_{i+1}(k);\\
&\bar{C}_i(k)=C_i(k)-C_{i+1}(k), && \tilde{C}_i(k)=\mu_iC_i(k)-\mu_{i+1}C_{i+1}(k);\\
&\bar{D}_i(k)=D_i(k)-D_{i+1}(k), && \tilde{D}_i(k)=\mu_iD_i(k)-\mu_{i+1}D_{i+1}(k)\\
&\qquad(i=1\sim4)
\end{aligned}\right\}\quad\text{(A-4)}$$

$y_i(k)$ on the right-hand side of the last equation in (A-3) represents the amplitude of inflection of the lower boundary of the i-th layer. The boundary conditions at the free surface give the following two equations:

$$\left.\begin{aligned}
&A_1(k)=B_1(k)\\
&\mu_1(A_1(k)+B_1(k)-C_1(k)+D_1(k))=-\rho_1gy_0(k)/2k
\end{aligned}\right\}\quad\text{(A-5)}$$

where $y_0(k)$ is the amplitude of inflection of the free surface. Finally, the boundary conditions at the bottom surface give the following two equations:

$$\left.\begin{aligned}
&a_5(k)A_5(k)+B_5(k)/a_5(k)-kH_5a_5(k)C_5(k)-kH_5D_5(k)/a_5(k)=u_b(k)\\
&a_5(k)A_5(k)-B_5(k)/a_5(k)-(kH_5+1)a_5(k)C_5(k)+(kH_5-1)D_5(k)/a_5(k)=v_b(k)
\end{aligned}\right\}\quad\text{(A-6)}$$

where $u_b(k)$ and $v_b(k)$ represent the amplitudes of the horizontal and the vertical sinusoidal velocity components, respectively, obtained by resolving the velocity profile of the differential movement applied on the bottom surface.

Accordingly, twenty coefficients $A_i(k)$, $B_i(k)$, $C_i(k)$ and $D_i(k)$; $(i=1, 2, \ldots, 5)$ can be determined by solving the twenty equations given in (A-3) to (A-6). Substituting them into (A-2) and then the sinusoidal components $u_i(x, y; k)$ and $v_i(x, y; k)$ into (A-1), the resultant velocity field in the whole model can be obtained.