NUMERICAL SIMULATION OF THE MUTUAL INTERACTION BETWEEN A TRENCH AND A SEAMOUNT

Takeshi MATSUMOTO and Yoshihumi TOMODA

Ocean Research Institute, the University of Tokyo, Tokyo, Japan

(Received October 21, 1983; Revised January 26, 1984)

Lithospheric deformation at a subduction zone due to the collision and the consequent interaction between a trench and a seamount on the oceanic plate is examined using numerical simulation of the motion of viscous fluid. The results show that the slab-pull force at the trench cannot disappear even if a seamount collides against it. In the case of a small seamount the subduction motion continues, while in the case of a large seamount the motion of subduction terminates temporarily and another subduction takes place at the seaward edge of the seamount.

1. Introduction

The place of collision of a trench and an obstacle like a seamount on an oceanic plate is known to be a junction point of the trench. There are many such places in the Western Pacific. The Bonin Rise, Amami Plateau, Kashima No. 1 Seamount, Erimo Seamount, and Caroline Ridge are obstacles which are colliding against a trench. Here, topographic depression is quite different from that of the normal trench and anomalous structure of topography appears around the trench.

The Bonin Ridge is placed landward of the collision point of the Bonin Rise and the Izu-Bonin Trench. The maximum free-air anomaly of the arc is more than 380 mgal (ISHIHARA et al., 1981). Recently a small-scale seamount placed between the Bonin Ridge and the trench was found, and petrological research concerning the seamount was carried out (KOBAYASHI, 1981, 1983). The seismicity around the ridge is lower than that of areas to its north and south.

Amami Plateau is in the northwestern part of the Philippine Sea, where it is in contact with the Ryukyu Trench. Results of a geophysical survey of the plateau were compiled (KOBAYASHI, 1983), and a detailed topographic map was completed, showing some bending and discontinuity of the trench axis.

Kashima No. 1 Seamount is near the junction point of the Japan and Izu-Bonin Trench. In the published results of the topographic survey, it is pointed out that a depth offset of about 1,500 m splits the seamount into eastern and western halves, suggesting the breakdown of the seamount due to the subduction motion of the trench (MOGI and NISHIZAWA, 1980).
The region off Urakawa is known as a low gravity zone. It is near the junction point of the Kuril and Japan Trench, and Erimo Seamount is situated on the trench axis. The low gravity zone has the possibility of being a relic of a submerged seamount which belongs to the same chain as the Erimo Seamount (TOMODA and FUJIMOTO, 1981).

Yap Trench presents very sharp depression of topography and close spacing from the Yap Arc. HAWKINS and BATIZA (1977) explain that such topography is related to the termination of subduction at the trench due to the blocking of the Caroline Ridge. Yap Islands are known to be an old volcanic arc. The volcanic activity ceased in middle Tertiary (HAWKINS and BATIZA, 1977), which coincides with the time of the opening of Parece Vela Basin (MROZOWSKI and HAYES, 1979). However the free air anomaly in Yap Islands is about 200 mgal, higher than that of the typical volcanic island arc.

Detailed geophysical and geological observations of the collision zone have been carried out. However, a general theory about the mechanism of such a tectonic movement has not been presented so far.

The driving force of subduction at a trench is the slab pull due to the density contrast between lithosphere and asthenosphere (ELSASSER, 1971). Provided that the two materials behave as viscous fluid, the contacting of the two causes horizontal as well as vertical stress, which may induce the deformation of the crust and the upper mantle. Whether or not the slab-pull force remains at a trench in case of the existence of such an obstacle has yet to be investigated.

In this work, numerical simulation of the deformation of lithosphere given the existence of such obstacles was undertaken. Some of the above-mentioned phenomena in the region of the collision zone can be explained and the characteristics of the tectonics common to all these areas derived from the result of the simulation. All the materials considered in this work are assumed to be viscous fluid. Lithosphere is a fluid of density 3.3 g/cm³ and viscosity $10^{23}$ poises. Several cases classified by parameters concerning the quality of the crustal and asthenospheric materials are examined to obtain a general theory of such a problem.

2. Method

Materials of the crust and the upper mantle are assumed to behave as a viscous fluid, therefore the basic equations governing the phenomena are like those of the motion of fluid on the rotating earth. In the situation being addressed here, stress terms are predominant due to the large viscosity, while inertia terms and Coriolis terms are negligible. If the two-dimensional calculation is available, stream function $\psi(x, z)$ can be defined and the equations are written as

$$-4\pi \frac{\partial^2 \psi}{\partial x \partial z} \left( \mu \frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial x \partial z} \right) - \left( \frac{\partial^2 \psi}{\partial z^2} - \frac{\partial^2 \psi}{\partial x \partial z} \right) \left( \mu \left( \frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial x \partial z} \right) \right) + K \frac{\partial \rho}{\partial x} = 0,$$

(1)

where $\mu$ is the viscosity of the materials. Variables in Eq. (1) are non-dimensional.
Numerical Simulation of the Mutual Interaction

\[ K = \frac{\rho_0 L^2}{\mu_0 g} \]  \hspace{1cm} (2)

where \( \rho_0 \) is reference density, \( \mu_0 \) is reference viscosity, \( L \) is reference length, \( U \) is reference velocity, and \( g \) is vertical acceleration of gravity.

Equation (1) is expressed by the finite difference scheme and is solved by SOR (successive over relaxation) method:

\[ \psi_{\text{NEW}} = \psi_{\text{OLD}} + \omega(\psi - \psi_{\text{OLD}}) \]  \hspace{1cm} (3)

\( \psi \) is obtained by the finite difference form of Eq. (1). The value \( \omega \) must be not less than 1.0 and less than 2.0. It is necessary to select \( \omega \) so that Eq. (1) rapidly converges.

When \( \psi \)'s are obtained, velocity field is calculated by the definition of stream function. The new density field is obtained by use of MAC (marker and cell) method (HARLOW and WELCH, 1965), in which marker particles with proper density and viscosity are removed according to the velocity field in each time step.

In calculation, the area is assumed to be closed. Then the boundary condition is

\[ \psi = 0 \]  \hspace{1cm} (4)

Another condition is that the shear stress is zero at the boundaries of the calculation area, so the boundary conditions

\[ \frac{\partial^2 \psi}{\partial x^2} = 0 \]  \hspace{1cm} (5)

and

\[ \frac{\partial^2 \psi}{\partial z^2} = 0 \]  \hspace{1cm} (6)

are to be held.

The time increment \( \Delta t \) of each step must be defined so as to satisfy the relation

\[ \Delta t < \frac{\min (\Delta x, \Delta z)}{V_{\text{max}}} \]  \hspace{1cm} (7)

where \( \Delta x \) and \( \Delta z \) are the horizontal and vertical lengths of each computational cell respectively, and \( V_{\text{max}} \) is the maximum of absolute values of velocities at cell boundaries. In this work, \( \Delta x \) is set at 20 km and \( \Delta z \) at 10 km. \( \Delta t \) is 3/4 of the value of the right side of Eq. (7) in each time step.

Marker particles are moved according to the velocity field defined by the velocities at cell boundaries. The new position \((x_{\text{NEW}}, z_{\text{NEW}})\) is calculated by using the horizontal velocity \( u(x_{\text{OLD}}, z_{\text{OLD}}) \) and vertical velocity \( w(x_{\text{OLD}}, z_{\text{OLD}}) \) at the old position, which is interpolated by the velocities at cell boundaries. Their relation is expressed as

\[ x_{\text{NEW}} = x_{\text{OLD}} + u(x_{\text{OLD}}, z_{\text{OLD}}) \times \Delta t \]

\[ z_{\text{NEW}} = z_{\text{OLD}} + w(x_{\text{OLD}}, z_{\text{OLD}}) \times \Delta t \]  \hspace{1cm} (8)
Fig. 1. Initial state of the crustal, lithospheric, and asthenospheric materials for calculation. The area is 1,200 km (horizontal) \times 300 km (vertical). As for the other parameters in each case, see the text and Table 1. 1 indicates the oceanic lithosphere, 2 is island-arc lithosphere, 3 is asthenosphere derived from ocean, 4 is asthenosphere derived from island arc, 5 is seamount, 6 is oceanic crust, and 7 is island-arc crust.

In calculation, the density and viscosity coefficients of each cell are determined by averaging the values of all the particles in each cell.

3. Results

The initial state is shown in Fig. 1. The calculation area is composed of lithosphere, asthenosphere, oceanic crust, island-arc crust, and sea water. Oceanic crust is assumed as viscous fluid of density 2.8 g/cm\(^3\) and the same viscosity as lithosphere, while island-arc crust is viscous fluid of density 2.6 g/cm\(^3\) and the same viscosity as lithosphere. The thickness of each layer is assumed as follows: oceanic lithosphere, 100 km (left side) and 90 km (right side); island-arc lithosphere, 30 km; oceanic crust, 5 km; island-arc crust, 10 km; sea water, 5 km. They are selected as a standard value of each material at the plate boundary. The seamount body is assumed to be in isostatic equilibrium, and the thickness is set at 21 km. Its density is assumed to be 2.8 g/cm\(^3\), while its viscosity is \(10^{25}\) poises, as in Ito's (1972) discussions of the oceanic crust around guyots and atolls.

The initiation of subduction occurs if two blocks of different density structure contact with each other. The case of Mendocino Fracture Zone was examined, and the possibility of the initiation of a trench a few tens of million years after the contact of the two different blocks was pointed out (Tomoda et al., 1983; Matsumoto and Tomoda, 1983). For the convenience of calculation, therefore, the initial state is assumed as the contacting of two different structures like Mendocino Fracture Zone, and the seamount, which is in isostatic equilibrium, is placed 150 km away from the boundary of the two blocks in order to collide against a forthcoming well-developed trench due to the difference in lithospheric structure.
Table 1. Labels to represent the parameters for calculation.

<table>
<thead>
<tr>
<th>Case a-b-c</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a: Density contrast</td>
<td></td>
</tr>
<tr>
<td>1: $=3.2/3.3$</td>
<td></td>
</tr>
<tr>
<td>2: $=3.25/3.3$</td>
<td></td>
</tr>
<tr>
<td>b: Viscosity contrast</td>
<td></td>
</tr>
<tr>
<td>1: $=10^{-1}$</td>
<td></td>
</tr>
<tr>
<td>2: $=10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>3: $=10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>c: Seamount size</td>
<td></td>
</tr>
<tr>
<td>0: no seamount</td>
<td></td>
</tr>
<tr>
<td>1: 50 km</td>
<td></td>
</tr>
<tr>
<td>2: 100 km</td>
<td></td>
</tr>
<tr>
<td>3: 200 km</td>
<td></td>
</tr>
</tbody>
</table>

In this work, the upper mantle is assumed to be composed of two different materials—lithosphere and asthenosphere—on the basis of RGA distribution (TOMODA and FUJIMOTO, 1981). Actual density and viscosity of the sub-bottom materials depend on their thermal state. However, accurate temperature distribution has not been observed yet. Therefore, several cases of different density contrast and lithosphere and asthenosphere viscosity contrast are examined. These parameters are limited to reasonable values for actual materials of crust and upper mantle. In addition, several cases of seamount size are selected for calculation. These cases are labeled to represent these parameters; the first number indicates density contrast code, the second, viscosity contrast, and the third, seamount size. The meaning of these numbers is shown in Table 1.

3.1 Effect of seamount sizes

Case 1-2-1 and Case 1-2-3 are compared. Figure 2 shows the result of the first case (small seamount) and Fig. 3 shows the second (large seamount). In these figures, state (a) expresses the distribution of the materials immediately after the collision of the seamount against the trench.

In the case of the small seamount, the shape of the subducting slab changes when the seamount reaches and collides against the trench. That is, lithospheric thickening is temporarily interrupted at the point below the seamount and the front part of the thinned slab continues to subduct. However, the lithosphere under the seamount becomes thick soon after the collision, and the motion of subduction seems to continue without any intermittence.

Both the seamount and the trench exhibit seaward motion. The moving speed of the trench axis is greater than that of the seamount. Therefore, the topographic depression of the seaward edge of the seamount after the collision suggests that the trench axis jumps to this position and that the seaward motion
continues. The seamount does not subduct because its density is smaller than that of the upper mantle.

Figure 4 shows the distribution of the stream function obtained in Case 1-2-1. The pattern is quite similar to that of Case 1-2-0, the stream function of which is shown in Fig. 5, though its value is 10–20% smaller than that in Case 1-2-0 after the collision of the seamount.

Case 1-2-3 presents quite a different pattern, as shown in Fig. 3. The dip angle of the frontal zone of the subducting slab (corresponding to the Benioff Zone) is about 60 degrees if the seamount is not near the trench. However, after the collision of the large scale seamount, the seaward motion of the trench axis stops and the subducting slab stands normal to the horizontal direction of the calculation area. If the asthenosphere is underlain by denser material or bounded by free-slip surface, the subducting lithosphere is torn off and the lithospheric material accumulates on the surface.

At the seaward edge of the seamount, lithospheric thickening and downward motion appear after the collision of the two. This result of Case 1-2-3 means
that a new subduction occurs and the old subduction ceases its activity about 15 million years after a large-scale seamount collides against a trench. In other words, a trench jumps from the landward side of the seamount to the seaward edge of it, and the seamount becomes attached to the continental plate.

Figure 6 shows the distribution of the stream function of Case 1-2-3. At first, one only zone of downgoing motion is found, but after the collision there are two zones of downgoing motion, which correspond to the initiation of a new vortex at the seaward edge of the seamount. The strength of the seaward vortex gradually becomes greater. The result expresses clearly the initiation of a new subduction seaward of the seamount.

Thus, the results of the two cases present quite different patterns from the viewpoint of the shape of the subducting slab. However, there is an important point common to both cases: the lithospheric thickening is interrupted under the seamount immediately after the collision of the seamount against the trench and the lithosphere thickens at the seaward edge of the seamount.

In the case of a large seamount, the seaward side of it is quite apart from
Fig. 4. Stream functions in Case 1-2-1 (unit in $10^{-1}$ cm$^2$/sec). (a) 12.3 Ma., (b) 17.9 Ma., (c) 21.3 Ma.
Fig. 5. Stream functions in Case 1-2-0 (unit in $10^{-1}$ cm$^2$/sec). (a) 12.4 Ma., (b) 18.0 Ma., (c) 21.0 Ma.
Fig. 6. Stream functions in Case 1-2-3 (unit in $10^{-1} \text{cm}^3/\text{sec}$), (a) 23.7 Ma., (b) 28.6 Ma., (c) 38.4 Ma.
Numerical Simulation of the Mutual Interaction

3.2 Effect of density contrast

Asthenosphere is the low velocity layer from the seismological viewpoint as well as the layer of partial melting from the petrological viewpoint. Therefore, the density of the asthenospheric material is considered to be less than that of lithosphere (Yoshii, 1973). However, it is difficult to estimate the density contrast of lithosphere and asthenosphere because of the uncertainty of the model of the two layers of different density. Two cases are examined and compared for density contrast: Case 1-1-3 and Case 2-1-3.

The results are shown in Fig. 7 (Case 1-1-3) and Fig. 8 (Case 2-1-3). In Case 1-1-3, in which density contrast is twice as large as that in Case 2-1-3, the falling speed of the subducting slab is about twice that in Case 2-1-3. This is
the result expected from dimensional analysis. Even if cases including a smaller seamount or without a seamount are examined, the result is almost the same as that in these cases.

3.3 Effect of viscosity contrast

Viscosity of the upper mantle is expressed as

$$\mu = a \exp \left( \frac{bT_m}{T} \right)$$

if the variable viscosity model is assumed (Toksoz and Hsu, 1978). In Eq. (9), $T$ is local absolute temperature, $T_m$ is absolute melting temperature of pyroxene with 0.1% water content, and $a$ and $b$ are constants. In the simple two layer model used in this work, the viscosity of lithosphere is $10^4$–$10^5$ times as large as that of asthenosphere, although the value depends on the selection of the constants $a$ and $b$. Three cases are examined for various viscosity contrasts of lithosphere and asthenosphere. Figure 7 (Case 1-1-3), Fig. 3 (Case 1-2-3), and Fig. 9 (Case 1-3-3) are the results.
The falling velocity of the slab in Case 1-1-3 is about half that of Case 1-2-3, if the figures of the same age in these cases are compared. In Case 1-3-3, the falling velocity of the slab is about 1.5 times as large as that in Case 1-2-3. The result is almost the same, even if the cases without a seamount are examined. If the viscosity of the lithosphere is the same, higher viscosity contrast between the lithosphere and the asthenosphere presents larger velocity of deformation.

4. Discussion

The results described in the previous section show that the lithospheric deformation and the behavior of the seamount at a trench depend on the parameters. Density contrast of lithosphere and asthenosphere effects the velocity of the subducting slab. Viscosity contrast also contributes to the velocity of the subducting slab. Seamount size effects whether or not the form of subduction changes (continuous subduction occurs or new subduction appears).
In the cases of a large seamount, a new subduction occurs about 15–30 million years after the collision irrespective of the density and viscosity contrast of lithosphere and asthenosphere, as far as their values examined in this work are considered and \(10^{23}\) poises is assumed as viscosity of lithosphere. Reference viscosity \(\mu_0\) is inversely proportional to the reference velocity \(U\) if the value \(K\) in Eq. (2) is constant. Therefore, if the materials behave as fluid of 10 times higher viscosity, it takes 10 times as long as in the present results for the same state to be realized. Lithospheric viscosity is estimated as \(10^{22}-10^{24}\) poises by several authors, so the time scale of the phenomena should have uncertainty of this degree.

When the results of the case of a small seamount and that of a large seamount are compared, the ultimate shape of the lithosphere is apparently quite different. But the results of the two different cases can be explained by the same tectonic mechanism. The origin of subduction is the slab-pull force due to the density difference for the horizontal direction. Lithospheric thickness is relatively small under the seamount compared with the surrounding region, even though isostatic compensation is attained. So, the edges of a seamount are the places where pressure discontinuity due to the density difference exists and the horizontal as well as the vertical movement of the lithosphere takes place. The place of the lithospheric thickening in the nearest future after the termination of the subduction due to the collision of the seamount against a trench is thus the edge of the seamount.

At the collision zone, quite different structures of topography and lithosphere are found compared with the typical trench. The origin of these kinds of structures summarized in the introductory section can be explained by the results of the numerical simulation. Figure 3 (the result of Case 1-2-3—collision of a large-scale seamount against a trench) shows a sharp slope of the trench suggesting the characteristics of topography of the Yap Trench, although quantitative estimation of desirable accuracy is not available because the cell for calculation is not so small. If this result is accepted, it can be concluded that the topographic depression will be unable to recover even if the motion of subduction ceases and the slab-pull force disappears.

Figure 3 also shows a breakdown and accumulation of the subducting lithosphere. This result corresponds to the distribution of hypocenters of the Izu-Bonin-Mariana Region where the Wadati-Benioff Zone stands at right angle or discontinues and appears again at the depth of 400–600 km, where the dip angle of the zone is much lower than that near the trench axis.

Figure 2 (the result of Case 1-2-1—collision of a small-scale seamount against a trench) shows that, even if a seamount is small, unlike the subducting slab, it will not be absorbed into the trench. This is due to the assumption that the seamount has smaller density than the lithosphere, and that it has higher viscosity and hardly deforms its shape. The sedimentary and crustal materials at the subduction zone are drawn into the trench with the motion of the subducting slab (Murauchi and Ludwig, 1980). If the breakdown of the seamount actually
takes place like in the case of Kashima No. 1 Seamount, it would be concluded that the seamount suffered from the downward pulling force at the trench, some normal faults formed due to this force, and the deformation of the seamount took place due to the apparent decrease of its viscosity.

According to Fig. 2, topographic depression appears at both sides of the seamount. Such a topography corresponds well to the case of Kashima No. 1 Seamount, which has a topographic moat at its western and eastern sides. It suggests the downward force at the edge of the seamount for the origin of subduction, though accurate quantitative estimation is not available in this case either.

Stress distribution is also calculated from the velocity field obtained by the space differentiation of stream functions. For example, Fig. 10 is the result of Step 70 (38 million years after the initial state is given) of Case 1-2-3.

In Fig. 10, maximum is found at both edges of the seamount, along the front zone of the subducting lithosphere shallower than 150 km, and at the lithospheric wedge which fell down to the bottom of the calculation area. The maximum of the front zone of the lithosphere corresponds to the pulling force due to its falling
motion, whereas that of the bottom is the result of the accumulation of the subducting lithosphere.

In the cases without seamounts, maximum is found at two areas, front zone and bottom. These distribution of the two maximum along the subducting lithosphere might explain the distribution of Benioff Zone shown at plate boundaries like Izu-Bonin-Mariana region.

The two-dimensional approximation of the seamount in this work easily applies to the cases of the seamount of large horizontal extention. In the actual three-dimensional cases, the pulling force of the trench is dominant at the flank of the seamount, rather than at the opposite side from the trench. So the bending of the trench axis would occur at the collision point, which would result in the junction point of the trench as with Kuril-Kamchatka, Japan-Izu, and Mariana-Yap Trenches.

In the Southwestern Pacific, the distribution of plate boundaries is more complicated. One of the most remarkable features of this region is the existence of the plate of eastward convergence unlike the Pacific, such as New Britain, Solomon, and New Hebrides Trenches. On the other hand, the obstacles which could possibly block the motion of subduction, such as Caroline Ridge and Ontong Java Plateau, are placed on the eastern side of the plate boundaries. The mechanical process of the formation of these inverse plate convergences could be detected by use of the same method of numerical simulation if boundary conditions are adequately selected. Especially in these cases, three dimensional calculation will be required for accurate estimation of the lithospheric deformation in such a complicated region.

5. Conclusion

The effect of the existence of a seamount at a trench is summarized as follows. In the cases of a small seamount (50 km or less), the trench axis jumps to its seaward edge, and the subduction motion continues without any intermittence.

In the cases of a large seamount (200 km or more), the seaward motion of the trench terminates, and new subduction appears at its seaward edge about 15-30 million years after the collision occurs.

Both of these results are explained by the continuation of slab-pull force at the trench despite the existence of the seamount.

REFERENCES


KOBAYASHI, K., Preliminary report of the Hakuyo Maru Cruise KH-80-3, Ocean Research Institute, the University of Tokyo, Tokyo, 1981.

KOBAYASHI, K., Preliminary report of the Hakuyo Maru Cruise KH-82-4, Ocean Research Institute, the University of Tokyo, Tokyo, 1983.


