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**Evolution of Attached and Detached Slabs and Their Associated Mantle Dynamics**

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## Summary

Over the two years of the NASA grant, this project has produced a significant amount of research results related to the plate subduction process and the surface crustal deformation at convergent boundaries (i.e. above subduction zones). While some research objectives are completely accomplished, other research tasks remain active and continue to be investigated at present. A steady state analytic thermal model for subducting slabs was used to examine the torques acting on a descending slab. It is found that gravitational torque vanishes when a slab is dipping either vertically or horizontally, unlike previous studies indicating that the magnitude of gravitational torque decreases as dip angle increases. Subsequently, a new time-dependent, analytic thermal model for a subducting slab was developed. The new model enable us to study transient phenomena associated with plate subduction analytically. On the basis of this model, the nature of slab dip angles was evaluated. Slab dip angles are found to be transient features. As they penetrate into the mantle and increase their lengths, the associated gravitational torque also increases resulting in a downward pulling of the slab to a steeper dip angle. This is especially true once a slab penetrates the olivine-spinel phase boundary at about 400 km depth. However, if the phase transformation does not follow the equilibrium condition, the gravitational torque may have a different behavior. This problem was investigated. Except for fast descending slabs, non-equilibrium phase transformation can only slow down the transient increase of slab dip angles discussed earlier. Its effect is not sufficiently strong to reverse the downward pulling for most of the slabs. However, when slabs subducting at 10 cm/yr or faster, a sufficient amount of metastable olivine can exist beneath 400 km. Because of its low density compared with the surrounding spinel, an upward buoyancy is produced resulting in an upward bending of the slab and possibly an upward rotation of the slab such that smaller dip angles are formed. Seismic studies of the Japanese Slab seem to support this interpretation. The development of oroclinal geometries at convergent boundaries was also examined to study plate obduction which is an important ingredient to the initiation of plate subduction. Although the study suggests that surface features are better modelled by block models, the large scale deformation can be adequately studied by viscous models. Such a model is now under development to complete our original objective to study the initiation of plate subduction. Finally, a three-dimensional, finite element, spherical convective model is developed to study dynamic plate subductions. The model development is now complete and it is being tested to ensure its proper operation. The model is able to generate convection results with a viscosity contrast of about 100. Our research continues to push the viscosity contrast to a level that is appropriate for a subducting slab. Research results derived from this project are expected to continue appearing in literature over the next few years.

### Articles and Abstracts Resulted from this Research Project :

Hsui, A. T., Are slab dip angles steady or transient features?, EOS, Trans. Am. Geophys. Un., 71, 1574, 1990.

Hsui, A. T., Metastable Olivine and Its Gravitational Effects on a Subducting Lithosphere, EOS, Am. Geophys. Un., 72, No. 17, 288-289, 1991.

- Hsui, A. T., Bending of a subducting slab, EOS, Trans. Am. Geophys. Un., 72, 513, 1991.
- Hsui, A. T., Bending of a Subducting Lithosphere, Earth and Planet. Sci. Lett., in review, 1993.
- Hsui, A. T., K. Rust and G. deV. Klein, A Fractal Analysis of Quaternary, Cenozoic-Mesozoic and Late Pennsylvanian Sea-Level Changes, J. Geophys. Res., in review, 1993.
- Hsui, A. T., X-M Tang and M. N. Toksöz, On the dip angle of a subducting plate, Tectonophysics, 179, 163-175, 1990.
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- Yang, W. S., A. T. Hsui and J. R. Baumgardner, On energy partition within a dynamic spherical mantle, EOS, Trans. Am. Geophys. Un., 73, No. 43, 575, 1992.

## Introduction

As stated in the original proposal, the objectives of this research project (sponsored by the Crustal Dynamics Program of NASA under Grant NAG 5-1312) are the following:

1. to develop an analytic thermal model for a subducting plate with finite length, so that the effects of a leading edge can be studied, and the various forces acting on a descending slab can be evaluated meaningfully,
2. to understand the initiation and subsequent evolution of plate subduction, and the role of various phase transformations play in these processes, and
3. to simulate numerically the process of finite amplitude, dynamic plate subduction.

As of August this year when funding of the project ended, two of the objectives were met and one objective remained in progress. Details of the research results are summarized below.

### Development of an Analytic Slab Thermal Model

An analytic thermal model was successfully developed. Associated dynamic torques acting on a slab and their balances have been examined. Results of this aspect of the investigation are either published in refereed journals or presented in national scientific conferences. On the basis of a steady state thermal structure of a subducting slab, the gravitational and fluid dynamic torques acting on a slab are evaluated. While the fluid dynamic torque is found to decrease exponentially with slab dip angles as pointed out by many previous investigators (Stevenson and Turner, 1977; Tovish et al., 1978), the gravitational torque is found to have a somewhat different behavior (Hsui and Tang, 1988). Tovish et al. (1978) showed that gravitational torques are decreasing with slab dip angles ranging from  $0^\circ$  (horizontal) to  $90^\circ$  (vertical). Our study (Hsui and Tang, 1988) showed that the gravitational torque vanishes at both the horizontal and the vertical positions, and reaches a maximum at a dip angle between  $35^\circ$  to  $45^\circ$ . This behavior is produced because at  $90^\circ$ , the moment arm vanishes, and at  $0^\circ$ , the thermal anomaly of a slab vanishes. This finding further enhance the possibility for a shallow dipping slab to remain shallow-dipping because of the overwhelming dynamic pressure torque associated with shallow-dipping subducting plates.

Subsequent to the development of the steady thermal model discussed above, a new, time-dependent, thermal model for a subducting slab was developed (Hsui et al., 1990a). In this model, the evolution of a slab as it penetrates into the mantle can be studied analytically through a Laplace transform. This provides a convenient way to consider the thermal evolution of a subducting slab. Because of the transient nature of the model, many time-dependent phenomena associated with a descending slab can now be

investigated. This includes the possible transient nature of slab dip angles.

### Initiation and Evolution of Plate Subduction

To understand the evolution of slab subduction, it is important to understand how plate subduction is initiated. Two theories have been suggested: (1) boundary layer instability (McKenzie, 1977), and (2) plate puncture theory (Turcotte et al., 1977). The boundary layer theory treats surface plates as viscous systems such that when they are sufficiently cooled, gravitational instability will naturally cause them to follow a descending trajectory. The plate puncture theory, on the other hand, requires active volcanism prior to the descending of an oceanic plate. Observations, however, do not appear consistent with either theory completely. Instead, initiation of plate subduction appears to require the collision of two plates such that one plate is forced downward by the obducted plate.

We hypothesize that plate subduction is initiated by obduction of one plate over another. When the crustal layer thickness is thin such as that of an oceanic plate, a basalt-eclogite phase transformation may cause the underlying plate to delaminate and start the subduction process. This view has been suggested by Anderson (1989). To test the validity of this hypothesis, we first examine how crustal layers deform mechanically over geological time scales. Thus, an attempt to model crustal deformation under tectonic stresses has been carried out. To test if the model can indeed describe geological processes accurately, a well constrained observation is desirable. The model has been applied to study the development of pinned oroclinal curvatures. It is found that pinned oroclinal curves can be understood in terms of this model (Hsui et al., 1990b). To understand if oroclinal curvatures can be formed by other processes, we have also studied laboratory sand models using different driving mechanisms (Marshak et al., 1991). Laboratory model studies seem to suggest that while the curvature of oroclinal fronts can be modeled as viscous flow fronts, deformation behind the fronts may be better understood in terms of block rotations instead of continuum rotations. In any case, a flow model seems appropriate for our study, although details of mechanical structure at the surface may be better modeled as tectonic deformation of rigid blocks. Consequently, efforts to develop a three dimensional crustal deformation model was initiated, and it is an appropriate model to investigate the thermal-mechanical consequences of plate obduction. The model is complex, and its development continues at present.

Simultaneously, I also investigated the evolution of slab dip angles after plate subduction was initiated. Our study suggests that slab dip angles are probably not a steady feature. Instead, it evolves from shallow to steep dipping as a slab matures. This conclusion is derived from our calculations which show that the magnitude of the gravitational torque of a slab increases faster than the dynamic pressure torque as the length of a slab increases. When the gravitational torque exceeds the dynamic pressure torque, a net downward pull results causing a slab to rotate towards a steeper dip angle. This result is supported by the observation that most slabs are at present under a stronger

downward gravitational pull. Consequently, their dips are changing to steeper angles (Hsui et al., 1990a). In this study, gravitational torque of a slab, especially the contribution from the olivine-spinel phase transformation, is evaluated assuming that a slab is at thermodynamic equilibrium at all times. However, chemical kinetics are often sufficiently slow that phase transformations may not be at equilibrium as pointed out by Sung and Burns (1976 a, b). If it is true, it has important implications to the gravitational torque of a subducting slab, and hence, the evolution of subduction dip angles.

### Effects of Non-equilibrium Phase Transformation on the Forces Acting on a Subducting Slab

Recently, the importance of non-equilibrium olivine-spinel phase transformation was reiterated by Kirby et al. (1991). Based on their analysis, they argued that the existence of metastable olivine may be responsible for the production of deep earthquakes beneath subduction zones. In fact, there is seismic evidence that the olivine-spinel phase boundary within a subducting slab may not warp upward as predicted by equilibrium thermodynamics (Iidaka et al., 1990). Therefore, we decided to examine analytically the effects of a non-equilibrium phase boundary (especially the olivine-spinel phase boundary) upon the dynamics of a subducting slab (Hsui, 1990, 1991a). On the basis of our analytic thermal model (Hsui et al., 1990a), temperature and pressure at any point along a subducting slab are calculated. Together with the non-equilibrium phase relationship (e.g. Sung and Burns, 1976a,b), location of phase boundaries within a slab can be calculated. If metastable olivine does exist because of slow chemical kinetics which prevent equilibrium olivine-spinel phase transformation to occur as a slab evolves, important consequences to the gravitational torque of a subducting slab can be implied. I examined the effects of metastable olivine on the dynamic evolution of a subducting slab (Hsui, 1991a). It is found that metastable olivine tends to make a subducting slab more buoyant. Magnitude of the buoyancy is directly related to the subduction velocity and the angle of subduction. It is found that for most of the subducting slabs, non-equilibrium olivine-spinel phase transformations will reduce the magnitude of the gravitational torque. However, the reduction is not sufficient to reverse the net downward pulling as discussed earlier except for fast subducting slabs. For slabs descending at about 10 cm/yr and faster, sufficient amount of metastable olivine can be produced and their penetration beneath the olivine-spinel phase boundary can generate a net upward pushing torque (Hsui, 1991b). This local buoyant force can cause upward bending within long slabs. A careful examination of subducting plate geometry indicates that the Japanese Slab shows this special characteristic, and it may be produced by metastable olivine consistent with the seismic study of the phase boundary geometry within this slab (Iidaka et al., 1991).

### A Dynamic Slab Subduction Model

Since the beginning of this project, a three-dimensional, finite element, spherical model to investigate dynamic slab subduction was planned. The model is based on a

model developed by Baumgardner (1985). We intend to improve the model such that large viscosity contrasts similar to that between a subducting plate and its surrounding mantle can be incorporated. Coding of the model and its implementation are largely complete. To ensure the proper operation of the model, we examine the generation of poloidal and toroidal energies within a spherical mantle with temperature- and pressure-dependent viscosities (Yang et al., 1992). Although constant viscosity models suggest that no significant toroidal energies can be recognized within convective systems of constant viscosity fluids, and without surface plates (Hager and O'Connell, 1978; Forte and Peltier, 1987; Olson and Bercovici, 1991), our results show that variable viscosity models are able to produce significant amount of toroidal energies in the absence of surface plates. We have also examined the effects of Rayleigh number, viscosity contrasts, and heating mechanisms on the production of toroidal energies within a convective spherical shell. In general, whether convection is driven by internal heat or heated from below seems to make little difference in the production of toroidal and poloidal energies. On the other hand, as viscosity contrasts increase, more toroidal energies are realized. This is probably due to the fact that variable viscosities are able to produce plate-like structures near the surface which, in turn, has been suggested to be the source of toroidal energies. When the Rayleigh number increases, poloidal energies are found to increase more rapidly than the toroidal energies. These results suggest that mantle dynamics remain a possible active source to drive plate tectonics. This study also indicates that our model is working probably. Computations to increase viscosity contrasts appropriate for the subducting plates continue. Results will be reported and published as they become available.

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