

# Tonga slab deformation: The influence of a lower mantle upwelling on a slab in a young subduction zone

Michael Gurnis, Jeroen Ritsema and Hendrik-Jan van Heijst<sup>1</sup>

Seismological Laboratory, California Institute of Technology, Pasadena

Shijie Zhong

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge

**Abstract.** There are fundamental geographic variations in the deformation of slabs in the transition zone. The seismic energy release and morphology of the Tonga slab show that it is deforming faster and has accumulated more deformation than any other slab. We show that Tonga overlies the edge of the large-scale Pacific superplume. There is no substantial aseismic penetration into the lower mantle beneath Tonga, consistent with initiation of subduction during the Eocene. Other major subduction systems overlay seismically fast structures. For long-lived subduction systems, the lower mantle tends to pull down on slabs while in Tonga the lower mantle pushes upward, partially accounting for the intense deformation. The perturbation to the state of slab stress due to large-scale mantle flow is 10 to 40 MPa – nearly as large as that expected from slab pull.

## Introduction

Seismic energy release, on average, has a pronounced peak within the transition zone (410 to 660 km depth) [Abe and Kanamori, 1979]. Transition zone seismicity shows strong geographic variability (Fig. 1A). A few subduction zones, particularly the Tonga-Kermadec, have intense seismicity within the transition zone while most subduction zones have little or none [Isacks and Molnar, 1971; Vassiliou, 1983]. The number of transition zone earthquakes associated with the Tonga slab is an order of magnitude larger than that within any other subduction zone (Fig. 1B). Especially within the transition zone, the three-dimensional morphology of Tonga-Kermadec is more complex than all other slabs [Chiu *et al.*, 1991; Giardini and Woodhouse, 1984]. Since the length scale of the deformed portion of slab is  $> 100$  km and if the slab is descending at  $< 10$  cm/yr, then the total time required to accumulate the deformation must have lasted for  $> 1$  Myr. Consequently, the present day deformation rate (seismic activity) is not an ephemeral, short time-scale process.

The causes of such fundamental geographical variations in transition zone deformation have received little attention. The increase in seismicity with depth and stress orientation from focal mechanisms [Isacks and Molnar, 1971],

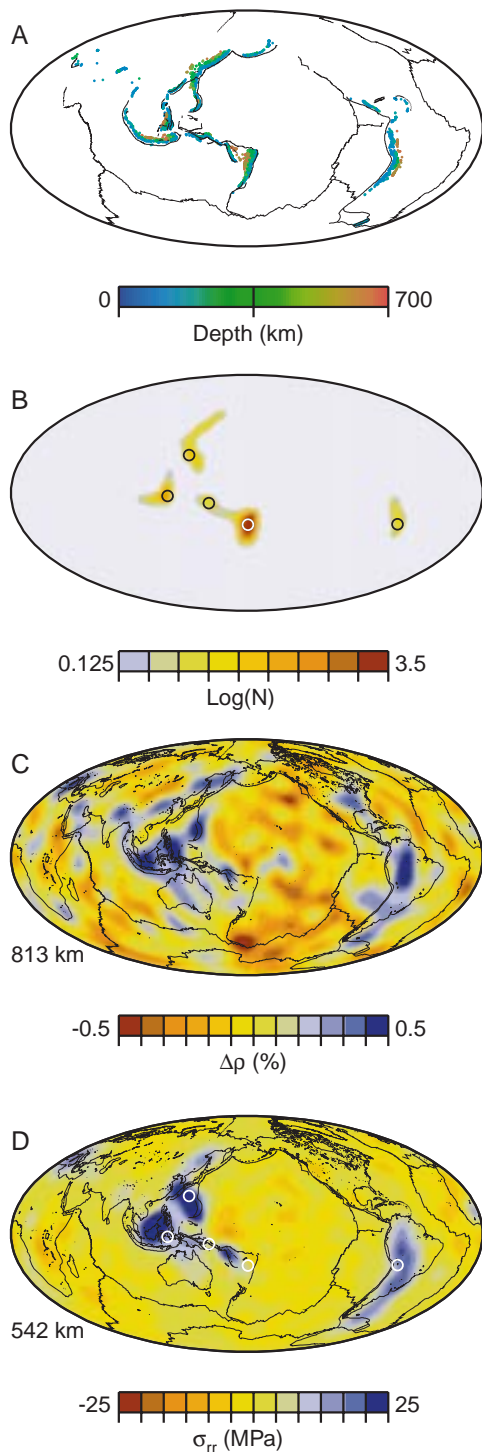
have been interpreted in terms of slabs encountering: An impenetrable chemical boundary [Richter, 1979], a jump in effective viscosity [Vassiliou *et al.*, 1984], or a force associated with the spinel to perovskite phase transition [e.g. Christensen and Yuen, 1984]. While there are few doubts that a combination of these effects could be important, it is reasonable to suppose that large-scale mantle density structure has an important influence on the state of stress within slabs and that it plays a role in modulating the geographic variability in transition zone seismicity and slab deformation. Now that seismic constraints on mantle structure have improved, it is time to reevaluate the controls on slab deformation.

**Large-scale mantle structure** There are large-scale variations in seismic velocity and density in the mantle. Recent tomographic inversions show high seismic velocity structures at the core mantle boundary (CMB) attached to present day subduction beneath Central America and Japan [Grand, 1997; van der Hilst *et al.*, 1997; van Heijst *et al.*, 1999]. This is particularly obvious in a cross section through central Honshu (Fig. 2A) showing the subducting Pacific oceanic plate as a high velocity upper mantle slab which in turn is connected with fast structures down to the CMB.

Not all Benioff zones are attached to high shear-velocity structures in the lower mantle. Two cross sections through Tonga-Kermadec (Fig. 2A, B) show that high shear velocities do not extend into the lower mantle below the transition zone. Resolution kernels for seismic model S20RTS show that the difference between the transition zone and the top 500 km of the lower mantle, and hence the absence of slab penetration through the 660 km discontinuity, is resolved (Fig. 3). The high seismic velocities just below 660 km discontinuity (Fig. 2) are likely an artifact of the inversion procedure and are probably not indicative of penetration into the lower mantle (Fig. 3). The contrast between Tonga-Kermadec and both Japan (Fig. 2A) and South America (Fig. 2B) is striking. Tonga-Kermadec has a transition zone structure dominated by high shear velocities immediately atop a large-scale, low velocity anomaly in the lower mantle. Within both the Japan and South America subduction zones, high shear velocity structures in the transition zone continue into the deep mantle.

**Geologic history of the Tonga system** The morphology of the Tonga-Kermadec subduction zone and associated lower mantle (Fig. 2) suggests that subduction has not been operating for extended periods of geological time. Subduction within the Tonga-Kermadec system initiated only during Eocene times [Gaina, 1998; Gaina *et al.*,

<sup>1</sup>Now at Shell International Exploration and Production

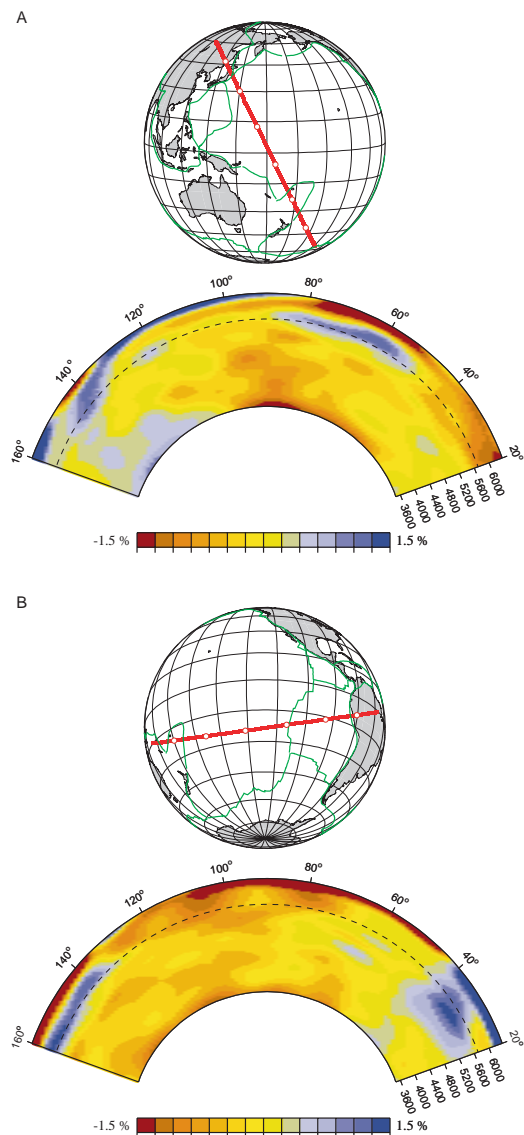


**Figure 1.** A. Earthquake locations with magnitude  $> 5$  and deeper than 100 km, color coded according to depth using the relocated hypocenters of *Engdahl et al.* [1998]. B. Only those events between 400 and 700 km depth color coded according of number of events per  $10^\circ \times 10^\circ$  region. C. Density at 813 km by scaling S20RTS by  $\partial\rho/\partial v_s = 200 \text{ kg m}^{-3}/\text{km s}^{-1}$ . D.  $\sigma_{rr}$  (positive values tensional) in the middle of the transition zone derived from a global flow model with density is given in C. Viscosity increases by  $50\times$  from surface to lower mantle and is temperature-dependent (see *Gurnis et al.* [1999]).

2000] in contrast to the much longer periods of subduction ( $\sim 200 \text{ Myr}$ ) beneath Japan and the Americas [*Engbretson et al.*, 1992].

Although the Pacific margin of Gondwanaland in the vicinity of the restored position of the southwest Pacific was the site of long-term subduction, the margin only remained convergent until Late Jurassic/Early Cretaceous. Recent interpretations of the Cretaceous geology of eastern Australia suggest that there was no Andean-type magmatic arc there [*Bryan et al.*, 1997]. From the Cretaceous to the Eocene, tectonics in the region east of Australia, which includes the opening of the Tasman Sea and Coral Sea, was dominated by rifting [*Gaina*, 1998].

Subduction reinitiated during the Eocene along the Norfolk ridge, including the area around New Caledonia. Prior to  $\sim 43 \text{ Ma}$ , Pacific motion was parallel to the Norfolk ridge while after  $\sim 43 \text{ Ma}$  it was perpendicular [*Gaina*, 1998]. New Caledonia is dominated by an ophiolite that was em-



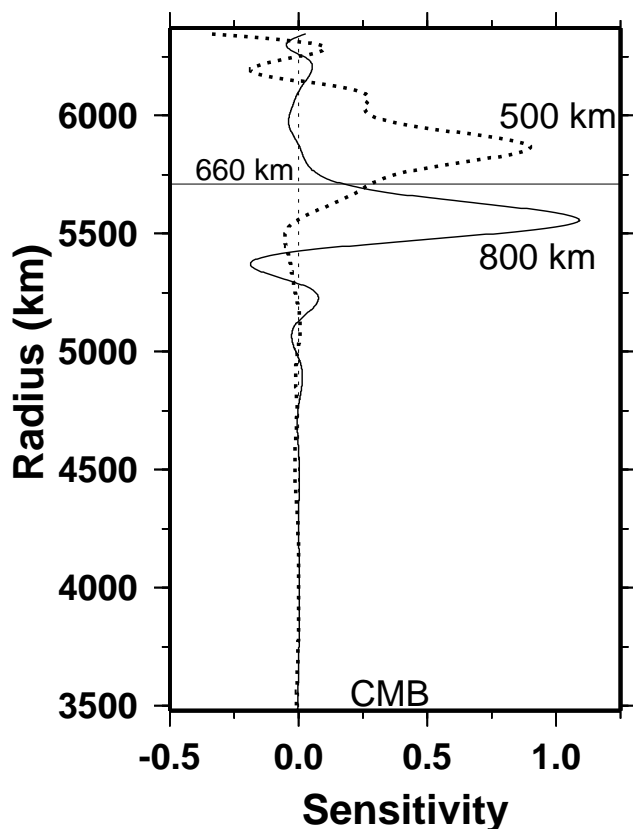
**Figure 2.** Cross sections through the global shear wave velocity model S20RTS. A. For Tonga-Kermadec to Japan. B. From Tonga to Peru.

placed over Mesozoic basement during the Eocene [Aitchison *et al.*, 1995]. Although the Eocene position of the island arc is uncertain, the thrusting event is thought to mark the resumption of convergence in the southwest Pacific [Aitchison *et al.*, 1995]. A short-lived, northeast verging subduction zone may have occurred from  $\sim 50$  to  $\sim 45$  Ma before an opposite polarity WSW verging proto-Tonga system initiated at  $\sim 43$  Ma [Eissen *et al.*, 1998].

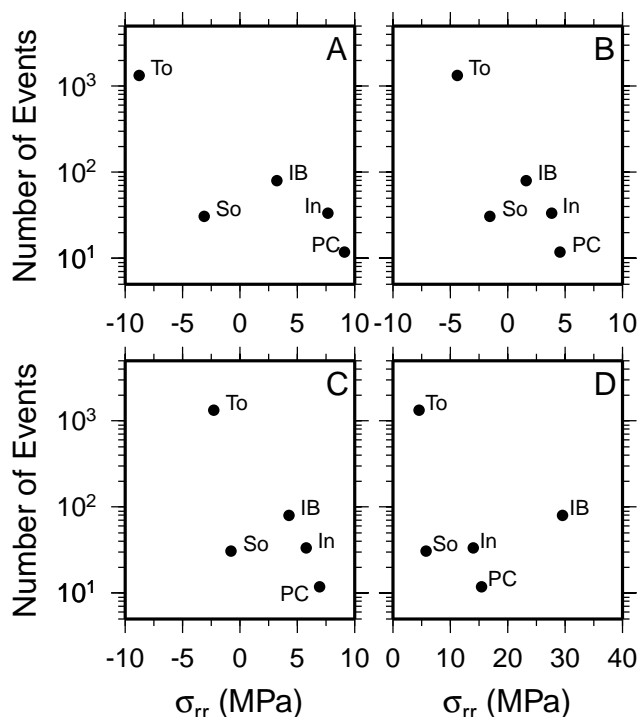
## Dynamic Models

We now determine how large-scale mantle density variations could perturb the regional stress field within subduction zones using a tomographic inversion of mantle seismic structure, S20RTS [van Heijst *et al.*, 1999]. The setup of these models is only slightly different from those described in Gurnis *et al.* [1999]. Using a full spherical finite element model [Zhong *et al.*, 1999], we solve for the instantaneous state of stress in a mantle with lateral and radial variations in viscosity. Above a depth of 200 km the density variations are set to zero. Elsewhere, a simple linear scaling is used to obtain density from shear wave perturbations. The free parameters are  $\partial\rho/\partial v_s$ , the radial variation in viscosity, and the temperature-dependence of viscosity.

Independent of these free parameters, the radial deviatoric stress,  $\sigma_{rr}$ , in the middle of the transition zone is tensional in nearly all major subduction systems around the



**Figure 3.** Backus-Gilbert resolution kernels of the S20RTS tomography model (see Ritsema *et al.* [1999]) beneath Tonga ( $179^\circ\text{E}$ ,  $22^\circ\text{S}$ ) for point anomalies at 500 km (dotted line) and 800 km (solid line) depths.



**Figure 4.** Number of earthquakes with magnitude  $> 5$  against  $\sigma_{rr}$  from four different dynamic models. Individual regions shown in Fig. 1B and labeled as: To (Tonga), So (Solomon), In (Indonesia), IB (Izu-Bonin), and PC (Peru-Chile). A.  $\partial\rho/\partial v_s = 400 \text{ kg m}^{-3}/\text{km s}^{-1}$  with a  $50\times$  increase in viscosity; B. 200,  $50\times$ ; C. 200,  $10\times$ ; D. 200,  $50\times$  and with temperature-dependent viscosity (see Fig. 1C,D).

world except Tonga (Fig. 1D). This quantifies what we have seen in the subduction zone cross sections: Most systems have extensive high seismic velocity (dense) anomalies beneath, except Tonga which has an extensive low shear velocity anomaly beneath it. In map view, there is a correlation between the predicted state of stress within the transition zone (Fig. 1D) and density anomaly within the top of the lower mantle (Fig. 1C). In long-lived subduction systems the lower mantle tends to pull slabs down while in Tonga the lower mantle pushes upward.

We have selected five regions (circles, Fig. 1B) with transition zone seismicity to show how model parameters influence the state of stress. The geographic variability in the rate of seismicity between these regions was estimated by considering all earthquakes with magnitude  $> 5$  between 400 and 700 km (Fig. 1B). We use  $\partial\rho/\partial v_s = 400 \text{ kg m}^{-3}/\text{km s}^{-1}$  and a jump in viscosity of 50 from the surface to the lower mantle (Fig. 4A), parameters typically used to explain the geoid [Hager *et al.*, 1985]. A negative correlation is found between the number of earthquakes and the deviatoric stress,  $\sigma_{rr}$ , with a range of  $\sim 20$  MPa. If  $\partial\rho/\partial v_s$  is reduced by a factor of two then the stress range is reduced to  $\sim 10$  MPa (Fig. 4B). A smaller increase in viscosity from the surface to the lower mantle of a factor of 10 has only a minor influence on  $\sigma_{rr}$  (Fig. 4C). When temperature-dependent viscosity is introduced, the entire range in stress between subduction zones is  $\sim 30$  MPa (Fig. 4D).

## Discussion

We have shown that the geographic variations in the deformation of slabs in the transition zone may be partly controlled by large-scale mantle flow. Compared to any other slab, we argue that the strong deformation of the Tonga-Kermadec slab in the transition zone is caused by the short period over which subduction has persisted ( $\sim 40$  Myr) and by the upward flow in the lower mantle. The slab in this subduction zone is now descending into the top of a large mantle upwelling. Global variations in stress driven by large-scale structure is 10 to 40 MPa and is of the same magnitude as the resisting stress from chemical layering or jumps in viscosity [Vassiliou *et al.*, 1984]. The correlations shown in Figure 4 between seismicity and model predictions are not perfect. Perfect correlations are not expected since there are good reasons to think that other features (the age of the slab, rate of local convergence, etc.) are also important.

One of the controls on this variability is the recent, regional plate motions. An important control on the morphology of the Tonga-Kermadec slab has been the recent geological history, especially the rapid trench rollback associated with the opening of the Lau Basin [Bevis *et al.*, 1995; Taylor *et al.*, 1996]. We have no reason to think that  $\sim 1$  to 10 Myr history is unimportant. Indeed, the detailed morphology of the slab can be partly accounted for by rapid trench rollback [Han and Gurnis, 2000]. However, we have now shown that subduction into the lower mantle occurring over the longer term history ( $>10$  Myr) is also likely to be an important control on the state of slab stress. Slabs underlain by aseismic slabs in the lower mantle have an additional down-dip tensional force, while slabs descending into hot upwellings will have an additional down-dip compressional force.

**Acknowledgments.** This work has been supported by NSF grants EAR-9809771 and EAR-9814908. We thank C. Conrad and D. Müller for helpful comments on the manuscript. This represents Contribution Number 8695, Division of Geological and Planetary Sciences, California Institute of Technology.

## References

- Abe, K., and Kanamori, H., Temporal variation of the activity of intermediate and deep focus earthquakes, *J. Geophys. Res.*, **84**, 3589-3595, 1979.
- Aitchison, J. C. and Clake, G. L. and Meffre, S. and Cluzel, D., Eocene arc-continent collision in New Caledonia and implications for regional southwest Pacific tectonic evolution, *Geology*, **23**, 161-164, 1995.
- Bevis, M., *et al.*, Geodetic observations of very rapid convergence and back-arc extension at the Tonga trench, *Nature*, **374**, 249-251, 1995.
- Bryan, S. E., Constantine, A., Stephens, C., Ewart, T., Schön, R., and Parianos, J., Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: Implications for the break-up of eastern Gondwana, *Earth Planet. Sci. Lett.*, **153**, 85-102, 1997.
- Chiu, J.-M., Isacks, B. L., Cardwell, R. K., 3-D configuration of subducted lithosphere in the western Pacific, *Geophys. J. Int.*, **106**, 99-111, 1991.
- Christensen, U. R., and Yuen, D. A., The interaction of a subduction lithosphere slab with a chemical or phase boundary, *J. Geophys. Res.*, **89**, 4389-4402, 1984.
- Eissen, J.-P., Crawford, A. J., Cotten, J., Meffre, S., and Bellon, H. and Delaune, M., Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia, *Tectonophysics*, **284**, 203-219, 1998.
- Engdahl, E. R., van der Hilst, R., and Buland, R., Global teleseismic earthquake relocation with improved travel times and procedures for depth-determination, *Bull. Seism. Soc. Am.*, **88**, 722-743, 1998.
- Engebretson, D. C., Kelley, K. P., Cashman, H. J., and Richards, M. A., 180 million years of subduction, *GSA Today*, **2**, no. 5, 93-100, 1992.
- Gaina, C., Tectonic history of microplates east of Australia, Ph.D. Thesis, 211 pp., The University of Sydney, 1998.
- Gaina, C. and Müller, R. D. and Cande, S. C., Absolute plate motion, mantle flow and volcanism at the boundary between the Pacific and Indian Ocean mantle domains since 90 Ma, in *The History and Dynamics of Global Plate Motions*, edited by Richards, M. A., *et al.*, Am. Geophys. Un., Washington, D.C., in press, 2000.
- Giardini, D., and Woodhouse, J. H., Deep seismicity and modes of deformation in Tonga subduction zone, *Nature*, **307**, 505-509, 1984.
- Grand, S. P., van der Hilst, R. D., Widiyantoro, S., Global seismic tomography: A snapshot of convection in the Earth, *GSA Today*, **7**, no. 4, 1-7, 1997.
- Gurnis, M., Mitrovica, J. X., Ritsema, J., and van Heijst, H.-J., Constraining mantle density structure using geological evidence of surface uplift rates: The case of the African superplume, *Geochem., Geophys., Geosys.*, submitted, 1999.
- Hager, B. H., Clayton, R. W., Richards, M. A., Comer, R. P., and Dziewonski, A. M., Lower mantle heterogeneity, dynamic topography and the geo, *Nature*, **313**, 541-545, 1985.
- Han, L., and Gurnis, M., Subduction in semi-dynamic models and application to the Tonga-Kermadec system, *J. Geophys. Res.*, submitted, 2000.
- Isacks, B., and Molnar, P., Distribution of stresses in the descending lithosphere from a global survey of focal-mechanism solutions of mantle earthquakes, *Rev. Geophys. Space Phys.*, **9**, 103-174, 1971.
- Richter, F. M., Focal mechanisms and seismic energy release of deep and intermediate earthquakes in the Tonga-Kermadec region and their bearing on the depth extent of mantle flow, *J. Geophys. Res.*, **84**, 6783-6795, 1979.
- Ritsema, J., van Heijst, H. J., and Woodhouse, J. H., Complex shear wave velocity structure related to mantle upwellings beneath Africa and Iceland, *Science*, **286**, 1925-1928, 1999.
- Taylor, B., Zellmer, K., Martinez, F., and Goodliffe, A., Sea-floor spreading in the Lau back-arc basin, *Earth Planet. Sci. Lett.*, **144**, 35-40, 1996.
- van der Hilst, R. D., Widiyantoro, S., Engdahl, E. R., Evidence for deep mantle circulation from global tomography, *Nature*, **386**, 578-584, 1997.
- van Heijst, H. J., Ritsema, J., Woodhouse, J. H., Global P and S velocity structure derived from normal mode splitting, surface wave dispersion and body wave travel time data (abstract), *Eos Trans. AGU*, Spring Meet. Suppl., S221, 1999.
- Vassiliou, M. S., Part I: The energy release in earthquakes; Part II: Subduction zone seismicity and stress in slabs, PhD Thesis, 258 pp., California Institute of Technology, Pasadena, 1983.
- Vassiliou, M. S., Hager, B. H., and Raefsky, A., The distribution of earthquakes with depth and stress in subducting slabs, *J. Geodyn.*, **1**, 11-28, 1984.
- Zhong, S., Zuber, M. T., Moresi, L. N., and Gurnis, M., The role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection, *J. Geophys. Res.*, in press, 1999.

M. Gurnis and J. Ritsema, Seismological Laboratory, Caltech, Pasadena, CA 91125. (e-mail: gurnis@caltech.edu; jeroen@gps.caltech.edu)

H.-J. van Heijst, Shell International Exploration and Production. (e-mail: hendrik@gps.caltech.edu)

S. Zhong, Dept. of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA 02139. (e-mail: szhong@rayleigh.mit.edu)

(Received January 22, 2000; revised April 26, 2000; accepted May 30, 2000.)