# Introduction

Deformation within the earth, driven by mantle convection due primarily to cooling and subduction of oceanic lithosphere, is expressed at every length scale in various geophysical observations. At short length scales, brittle deformation of the crust is recorded in the fabric of the seafloor at spreading centers and extensive faulting of subducting oceanic lithosphere observed within trenches. At intermediate length scales, both the elastic and viscous response to local and regional stresses are observed in the bathymetry and gravity of oceanic lithosphere, across mid-ocean ridges, seamounts and trenches and in the inferred state of stress within subducting lithosphere from deep seismicity. At long wavelengths, viscous deformation, driven by density anomalies within the upper mantle, is observed in the geoid and motions of plates at the Earth's surface. These observations reflect the complexities of a dynamic system, controlled by coupling between rheology and buoyancy structures with variations at short and long length scales. This thesis aims to demonstrate that integration of detailed observations of deformation at short to long length scales with carefully formulated numerical modeling is an effective method for simulating the complex multiscale nature of mantle-lithosphere dynamics. The thesis is composed of two parts. In Part I, I discuss the use of short length scale observations of seafloor bathymetry, gravity and magnetics to constrain past plate motions and current deformation of a subducting plate, while in Part II, I present numerical modeling of instantaneous viscous flow within a subduction zone constrained by geophysical, geochemical and rheological observations over a broad range of length scales.

Part I focuses on the use of marine geophysical observations (gravity, magnetics and swath bathymetry). Data collected in 1998 on the vessel *R/VIB Nathaniel B. Palmer* over the Osbourn Trough seaward of the Tonga-Kermadec Trench are used as constraints on the history of plate motions in the southwest Pacific. Data collected on the same cruise on the subducting Pacific Plate within the Kermadec Trench are used to study the current deformation of subducting lithosphere. The history of plate motions provide a crucial data set for understanding the evolution of the earth and exploring possible variations in the nature of convection in the past. Deformation of the lithosphere within subduction zones provides important constraints on the relative importance of elastic and viscous strength of the plates and the length scale over which plates are weakened at convergent margins.

The survey of the Osbourn Trough (Chapter 1) had two primary motivations. The first was to discover the origin of the trough. Small and Abbott [1998] suggested that this trough, visible in the gravity field, could be a recent crack in the Pacific Plate caused by subduction of the Osbourn Seamount at the intersection of the Tonga and Kermadec Trenches, rather than an extinct spreading center as suggested by Lonsdale [1997]. The second motivation was to constrain the age of this trough, if it was a spreading center, thus contributing to the data available for tectonic studies in this region. A short three-line survey perpendicular to the trough collected swath bathymetry, gravity, magnetic and echo sounder data. Morphologic studies of the bathymetry image revealed that this trough is an extinct spreading center and together with modeling of the gravity data constrained the shape and depth extent of the trough and the spreading rate. Modeling of the magnetic data provided the first constraint on the age of the oceanic crust in this region, which may be only 72 Ma at the ridge.

The survey of the Kermadec Trench (Chapter 2) was motivated by the need for a better understanding of the evolution of the strength of oceanic plates as they bend into the mantle. We used bathymetric data from swath mapping together with gravity measurements to estimate the flexural rigidity of the plate using spectral isostatic flexural response models. The response function technique is normally limited by the difficulty in obtaining sufficient signal-to-noise ratio at short to intermediate wavelengths (10–500 km) in order to constrain the flexural rigidity and elastic plate thickness. This normally requires long ship tracks (several thousand kilometers) or multiple ship tracks across the same feature. The short length of the Kermadec trench data is overcome by averaging the spectra of several adjacent tracks within the swath bathymetry data. Using this technique we find that the flexural rigidity of the plate and elastic plate thickness within the subduction zone are $10^{19}$–$10^{20}$ Nm and 1–2 km, respectively. These values are much smaller than the expected flexural rigidity ($10^{23}$–$10^{24}$ Nm) and elastic plate thickness (30–45 km) normally measured for old oceanic lithosphere. We are not able to constrain the distance from the trench over which the strength of the elastic plate decreases. However, estimates from a single ship track (MW9003, University of Hawaii) parallel to the Kermadec Trench but, 100 km seaward of the survey in the trench, suggests that the lithosphere in this region is already significantly weaker ($D = 10^{20}$–$10^{21}$ Nm) than normal oceanic lithosphere of the same age. More complete 3-D mapping of both the inner trench wall and forebulge region of the subducting plate is needed to better constrain the lengthscale over which the elastic strength of the plate decreases..

Part II focuses on integrating several geophysical, geochemical and rheological observations to simultaneously constrain subduction zone dynamics. Finite element models of instantaneous, viscous flow are developed to include realistic 3-D geometry of the subduction zone interface and slab in spherical coordinates, faults between major plate boundaries, radial- and temperature-dependent viscosity and strong lateral viscosity variations due to composition. Together, observations of the geoid, gravity, dynamic topography, stress field and strain rates reduce the number of plausible models and begin to allow interpretation of surface observables, on short to long wavelengths, in terms of specific features of the models: radial variations in viscosity versus lateral heterogeneities, response to crustal fault geometry versus viscously controlled deformation and the depth and location of driving forces.

This approach is first applied to 2-D and 3-D models of the Tonga-Kermadec subduction zone (Chapter 3) to investigate the influence of a low viscosity wedge on the surface deformation of the overriding and subducting plate. It is found that a localized region of low viscosity decouples the slab-induced flow within the wedge from the overriding plate, greatly reducing the size of a topographic depression on the overriding plate which occurs in models that include only radial- and temperature-dependent viscosity. The presence of a low viscosity region in the wedge is consistent with various seismological, petrologic and geochemical observations which are also discussed.

The influence of short wavelength variations in viscosity on subduction dynamics is explored in detail in Chapter 4. A large suite of 2-D models is used to investigate which observations are sensitive to various aspects of the viscosity structure. We find that in 2-D models without a low viscosity wedge, the topographic depression on the overriding plate is sensitive to the viscosity of the slab and not sensitive to the viscosity of the lithosphere; topography on the subducting plate (forebulge height and trench depth) is sensitive to both the viscosity of the slab and radial viscosity structure; strain-rate within the slab is sensitive to the absolute viscosity of the slab; and orientation of stress within the slab is sensitive to the relative viscosity of the slab and the lower mantle. In models with a low viscosity wedge, topography on the overriding plate is sensitive to the depth to the top of the low viscosity zone, but is only sensitive to the horizontal extent of the low viscosity region if the upper plate has uniform thickness and density. In addition, the orientation of stress within the overriding and subducting plate are modified by the presence of a low viscosity region: the stress in the overriding plate changes from horizontal compression to horizontal extension and stress within the slab at depths of 100–300 km changes from down-dip tension to down-dip compression. We then use observations of strain-rate, stress orientation, dynamic topography and the geoid for the Tonga-Kermadec subduction zone as simultaneous constraints on the viscosity and buoyancy in a 3-D regional dynamic model. Together these observations are used to develop a self-consistent model of the viscosity and buoyancy by taking advantage of the sensitivity of each observation to the different aspects of the dynamics over a broad range of length-scales explored in the 2-D models. For a model with a low viscosity and low density region, providing a good fit to the observed topography, we find that a reduction of the slab density by a factor of two is required to match the observed geoid. It is unclear what process could lead to such a large decrease in the slab density and further modeling is needed to confirm this result. However, the result suggests that compensation of the slab by dynamic topography may be a much smaller effect at short to intermediate wavelengths than predicted by long wavelength modeling of the geoid, and that inferences of the density and viscosity structure within the upper mantle are strongly dependent on short wavelength lateral variations in viscosity.

Finally, in Chapter 5, the results of similar dynamic modeling for the Central Aleutian subduction zone are compared to the results for the Tonga-Kermadec subduction zone. Three-dimensional models presented for the Central Aleutian subduction zone demonstrate that a low viscosity and low density region in the wedge above the slab is also necessary to match observations of topography, geoid and stress within the slab and overriding plate in the Central Aleutians. The lack of observed extension beyond the island arc region in the central Aleutians constrains the width of the low viscosity wedge perpendicular to the slab to the width of the island arc. Crustal density anomalies are needed to match the observed short wavelength ($<$ 100–200 km) topography coincident with the island arc and are probably associated with long-term emplacement of magma in the lower crust and beneath active volcanoes in the upper crust. Agreement between the observed and predicted topography and geoid at intermediate wavelengths (500–1000 km) is improved by also including a region of lower density coincident with the LVW, consistent with the hypothesis that the viscosity and density within the wedge are altered by water derived from the slab and subsequent depletion of the wedge material due to high degrees of melting. The differing stress states observed in the Aleutians (weak down-dip compression and down-dip tension in the slab with no back arc extension) and Tonga-Kermadec (strong down-dip compression in the slab with back arc extension) illustrate the range of stress states observed in all subduction zones. The presence or lack of a low viscosity region may contribute to the observed variability in the combination of stress states within the slab and the overriding plate: down-dip compression or tension together with either extension or compression of the overriding plate. The difference in the viscosity structure and state of stress in the two regions presented here may reflect differences in the history of subduction including subduction rates, lithosphere age, influences of back arc spreading, dehydration of the slab and melting within the wedge.