Appendix E

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Driving Forces: Slab Subduction and Mantle Convection

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Introduction

Mantle convection is the mechanism ultimately responsible for most geological activity at Earth's surface. To zeroth order, the lithosphere is the cold outer thermal boundary layer of the convecting mantle. Subduction of cold dense, lithosphere provides the major source of negative buoyancy driving mantle convection and, hence, surface tectonics (e.g., Forsyth and Uyeda, 1975; Richter and McKenzie, 1978; Hager and O'Connell, 1986).

There are, however, important differences between plate tectonics and the more familiar convecting systems observed in the laboratory. Most important, the temperature dependence of the effective viscosity of mantle rocks makes the thermal boundary layer mechanically strong, leading to nearly rigid plates. This strength stabilizes the cold boundary layer against small amplitude perturbations and allows it to store substantial gravitational potential energy. Paradoxically, through going faults at subduction zones make the lithosphere there locally weak, allowing rapid convergence, unlike what is observed in laboratory experiments using fluids with temperature dependent viscosities. This bimodal strength distribution of the lithosphere distinguishes plate tectonics from simple convection experiments. In addition, Earth has a buoyant, relatively weak layer (the crust) occupying the upper part of the thermal boundary layer. Phase changes lead to extra sources of heat and buoyancy (e.g., Schubert et al, 1975; Anderson, 1987). These phenomena lead to the observed richness of behavior of the plate tectonic style of mantle convection.

In this note, I summarize the current paradigms, then state my view of the key questions that need to be addressed, as well as techniques for addressing them. This review is inevitably biased towards the research in which I have been most heavily involved.

State of Current Knowledge

Empirical

Much of the current state of understanding of the subduction process is based on empirical associations. For example, plates with subducting slabs attached move faster than plates without subducting slabs, consistent with the negative buoyancy associated with slabs being a dominant driving force (Forsyth and Uyeda, 1975). The maximum size of earthquakes at subduction zones is directly proportional to convergence velocity and inversely proportional to the age, and hence negative buoyancy, of the subducting plate (Ruff and Kanamori, 1980). The presence of back-arc spreading is associated with steep subduction of old lithosphere, while back-arc spreading is absent where the dip of the subducting slab is shallow and where rapid convergence is occurring (e.g., Uyeda and

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Kanamori, 1979). While at short wavelengths, deep sea trenches have geoid lows over them, at wavelengths of 4,000-10,000 km, there is a spectacular association of geoid highs with subduction zones (Chase, 1979; Hager, 1984) as can be seen in Figure 1.

Long-wavelength geoid highs are also associated with hotspot provinces (e.g., Africa and the central Pacific; Crough and Jurdy, 1980; Richards and Hager, 1988). Inversions of lower mantle structure using seismic tomography have revealed that these hotspot provinces at the surface are associated with anomalously slow, presumably hot, regions in the lower mantle, suggesting a thermal link between the surface and the deepest mantle (Hager et al, 1985; Hager and Clayton, 1988).

Seismicity traces the location of and state of stress within subducted slabs down to the base of the upper mantle at the 670 km discontinuity. Slabs are generally in extension above 300 km depth (e.g., Isacks and Molnar, 1971) and in down-dip compression below 300 km depth. Seismic activity is high at the surface, decreases exponentially with depth to about 350 km depth, then increases exponentially with depth to 670 km, where is abruptly ceases (e.g., Vassiliou et al, 1984).

Observations

Several more specific observations seem important in understanding the dynamics of mantle convection and subduction. The fate of subducted slabs when they reach the 670 km discontinuity is a first order question, related to the geochemical evolution of Earth. Important observations relevant to this question include the topography and sharpness of this discontinuity (Hager and Clayton, 1988; Hager and Richards, 1988). At present, there is no observational evidence for any substantial topography (i.e., greater than 20 km) on this discontinuity. Reflection and conversion of seismic phases suggests that this boundary is, at least locally, very sharp (e.g., Bock and Ha, 1984).

Analysis of travel time residuals from deep seismic events indicates that subducted material extends over significantly greater volumes than have seismic activity. Long-wavelength variations of travel time anomalies projected onto the focal spheres of deep earthquakes have been interpreted as showing slabs extending deep into the lower mantle, often with a kink at the 670 km discontinuity (e.g., Creager and Jordan, 1984, 1986). Local tomographic analyses of these travel time anomalies reveal significant thickening of subducted slabs in the transition zone, consistent with the state of stress inferred from focal mechanisms (Zhou et al, 1987). Regional tomographic studies of the lower mantle beneath North America reveal high velocity anomalies that have been interpreted as the fossil remains of the Farallon Plate (Grand, 1987).

While subducted slabs are thought to have high density and provide a major source of the body forces driving global plate motions, in two locations in South America, the subducted slab seems to be moving subhorizontally, rather than sinking into the mantle (e.g., Isacks and Barazangi, 1977). This subhorizontal subduction has been proposed for North America during the Laramide orogeny (e.g., Bird, 1988)

The state of stress in subduction zones is intimately related to the dynamic processes occurring. Recent observations of changes in stress state associated with major earthquakes at converging plate boundaries seem potentially important in illuminating the absolute level of stress in these regions. Before these major events focal mechanisms show compression updip of the events and tension downdip, while this situation seems to be reversed afterward (Astiz and Kanamori, 1983; Dmowska and Rice, 1988; Christensen and Ruff, 1983). Since stress drops associated with these events are 100 bars or less, this change in sign of the apparent stress state is suggestive of a low overall stress level.

Local tomographic studies of the upper mantle beneath southern California have revealed a curtain of high velocity material extending to a depth of 250 km beneath the Transverse Ranges in the Big Bend region of the San Andreas fault (Figure 2, after Humphreys et al, 1984). While there are no deep earthquakes associated with this feature, and hence it is not typical subduction, it has been interpreted as the convective downwelling of the cold, dense base of the thermal lithosphere. The basal tractions from this convection cell have been proposed as the dynamic explanation for the maintenance of the Big Bend (Humphreys, 1985), although kinematic models have also been proposed to explain the Big Bend as the result of the effects of relative motion between plates (Bird and Rosenstock, 1984).

Models

Many of these observations have been interpreted quantitatively in terms of numerical models. The geoid observations have been interpreted in terms of fluid mechanical models that include the effects on the geoid of the mass anomalies introduced by dynamically maintained topography (Richards and Hager, 1984). The geoid can be explained by two families of models (Hager and Clayton, 1988; Hager and Richards, 1988). The first allows mantle-wide flow and requires a substantial increase in viscosity across the 670 km discontinuity. The second class of models has a mantle which is chemically stratified; it requires that subducted slabs have very high density and predicts many hundreds of km of dynamically maintained topography on the 670 km discontinuity.

Fluid mechanical models of subduction zones based on the first model of mantle structure show a variety of features, including kinking at the 670 km discontinuity (Gurnis and Hager, 1988). Such a model is also consistent with the state of stress in subducted slabs and the inferred advective thickening of slabs at the base of the upper mantle.

Simple viscoelastic models of subduction zones have been proposed to address the observed change in stress state associated with great subduction zone earthquakes (Dmowska and Rice, 1988).

Key Questions

There are a number of important questions suggested by these and other observations. One of the most general is the relationship between the observed kinematics of subduction and the dynamics of the process. What driving forces are transmitted over great distances through the strong plates and what are generated by local sources of buoyancy? Related issues are the stress level and amount of dissipation occurring locally in subduction zones -- since the driving forces from density contrasts are eventually balanced by dissipative resisting forces, the distribution of this dissipation is a crucial question (e.g. Christensen, 1985).

A related question is the amount of negative buoyancy associated with subducting slabs. Is this mainly the result of simple thermal expansion, or are the effects of phase changes dominant (Anderson, 1987)? Knowing the phase diagram of subducting slabs is important for understanding the driving forces, as well as determining whether the slab penetrates the 670 km discontinuity.

Determining the fate of subducting material at 670 km is an important issue for much of Earth Science. What happens to the crust? Is it stirred back into the depleted lithosphere or does it separate? Does subducted material mix into the lower mantle? Does it penetrate briefly only to be regurgitated when reheated? Is it stopped at 670 km depth? How are subducted slabs distorted in this region (see, e.g., Silver et al, 1988)?

On a more regional scale, important questions include the mechanics of flat subduction and the dynamics of back arc basins. What forces are responsible for sliding a subducting plate for ~1,000 km beneath an overriding plate? Once back arc spreading is initiated, how is the back arc spreading center shut off?

The variation of the dip of subducted slabs from place to place has not yet been explained in a comprehensive model. What are the competing effects of slab buoyancy, mantle viscosity, and global flow (e.g., Hager et al, 1983)? How are the dynamics of slab dip and back arc spreading related?

While the empirical association of maximum earthquake size with convergence velocity and plate age has intuitive appeal, it is generally recognized that earthquake size is controlled by the distribution of asperities on the fault plane (e.g., Kanamori, 1986). How do the empirical variables relate to the physical state of the fault plane?

On a local scale, the process of small scale convection such as is seen tomographically beneath southern California raises a number of questions. How are these mantle motions linked to deformation in the upper crust? How is the convective timescale linked to the timescale associated with earthquakes? What is the distribution of crustal rheologies? Why does the lithosphere go unstable in some places, but not elsewhere? The latter question is closely related to the process of creating stable cratonic nuclei.

The premier question associated with subduction zones is what causes the initiation of a new subduction zone? How is the strong, cold lithosphere initially fractured to form a weak plate boundary? The subduction process is extremely important in regulating the thermal balance of Earth; understanding the initiation of subduction is crucial in understanding the dynamic evolution of our planet.

New Observations, Experiments, and Models

Understanding the process of subduction will require activities in a number of areas spanning a range of geosciences. Given the limited resolution of most techniques, these activities will be most productive if they are carried out in such a way as to answer specific questions and test specific, relevant hypotheses. Suggested activities are grouped by discipline, roughly in order of priority within each group.

Seismology

The fate of subducted slabs when they reach the 670 km discontinuity is a first order question that can be addressed by seismologists. The topography and sharpness of the 670 km discontinuity are two features that can discriminate between mantle-wide and chemically stratified convection scenarios. Imaging of the 670 km discontinuity in the vicinity of subducted slabs is of highest priority.

Determination of the seismic velocity structure in the vicinity of slabs by tomographic means is also a high priority. Determining the shape of subducting slabs places strong constraints on dynamic models. Investigation of locations in the deep mantle beneath fossil subduction zones are important to increase the temporal coverage of the subduction process.

Regional tomographic studies of the upper mantle in both tectonically active areas and cratons would help to understand the distribution of "lithospheric drips" such as have been observed beneath southern California, as well as the processes of cratonization.

Further investigation of temporal and spatial variations in focal mechanisms associated with large earthquakes will help to constrain the absolute level of stress in subduction zones, as well as the mechanical properties of the lithosphere-asthenosphere system.

Given the importance of the concept of asperities, direct imaging of fault asperities by reflection seismology would be an important accomplishment.
Reflection seismology and other seismological techniques should also be used to image the deep crust to constrain the structures and material properties involved in the coupling between mantle convection and crustal deformation.

Determination of whether other phase boundaries within the slabs are elevated or depressed is of high importance, bearing on questions of the mineralogy of the mantle, the thermal state of the slab, and the magnitude of body force driving subduction.

A regional tomographic study of the upper mantle in the vicinity of the flat lying subducted slabs beneath South America would place important constraints on the dynamics of flat subduction. Such a study would address whether mantle heterogeneity outside the slab is important in driving the system.

Geodesy

The newly developed, highly accurate space based geodetic techniques (e.g., GPS) make it possible to obtain crucial observations at relatively little cost. Surveys should be carried out in regions such as southern California where good tomographic images of mantle structure exist in order to better constrain the coupling of mantle convection to surface tectonics. These measurements should be made frequently enough that the coupling of forces from convective timescales to the timescales of the seismic cycle can be addressed. Since the basic temporal spectrum of regional crustal deformation is as yet unconstrained by observations, permanent, continuously monitored regional strain networks should be installed in a few active regions.

Transfer of stress and strain after large subduction zone events should be monitored to address the questions of stress level and coupling of subduction zones. This requires initial epoch surveys. Development of high precision underwater geodetic controls is also very important.

Observations of spatial variations in gravity have proven useful in discriminating among geodynamic models. Gathering of data sets spanning the continent-ocean transitions in active margin areas would be very valuable to increasing our understanding of dynamic processes associated with subduction.

Mineral physics

Determination of the state and physical properties of materials under ambient conditions is crucial for making further progress in understanding Earth dynamics. Determining phase diagrams for subducted slabs is important for constraining the body forces associated with subducted slabs. The predictions of these phase diagrams must be tested using seismological observations to discriminate among different models of mantle structure, temperature, and composition.

Better constraints on crustal and mantle rheology are also important. Rheological descriptions are needed on all timescales, from brittle failure to viscoelastic deformation to slow, creeping convection.

Numerical Modeling

Progress in geodynamics requires quantitative testing of hypotheses against observations. Numerical modeling helps to provide the intuition needed to formulate hypotheses to be tested, as well as providing quantitative predictions to be tested. With increasing computational power available, numerical models will continue to become more realistic. An important improvement will be the ability to address the effects of three dimensions and time dependence. Advances in computational geophysics will be most rapid if trained numerical analysts work closely with geophysicists.

For convection modeling, important problems to address include the effects of phase changes and variations in composition and rheology on flow. Specifically, the interaction of subducted slabs with the 670 km discontinuity must be addressed for a wide range of models of upper and lower mantle composition. In these models, it will be important to consider realistic geometries for subduction (i.e., asymmetrical convergence and three dimensions), as well as the effects of global flow. The models must be sufficiently well resolved to address the amount of entrainment of layers with differing compositions. The process of stabilization of subcratonic lithosphere is another problem involving variations in composition and phase.

The problem of the mechanics of subhorizontal subduction is another important problem that requires a fully dynamic treatment. It is important that these models be guided by observations of mantle structure and rheology discussed above.

Transmission of stress and strain through viscoelastic effects should be addressed. These models should include three dimensional effects, as well as realistic parameterizations of the rheological variations within the crust and mantle.

Dynamical models of flow in the back arc region, including dynamically determined slab dips, should be posed to address the questions of initiation and cessation of back arc spreading.

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Figure Captions

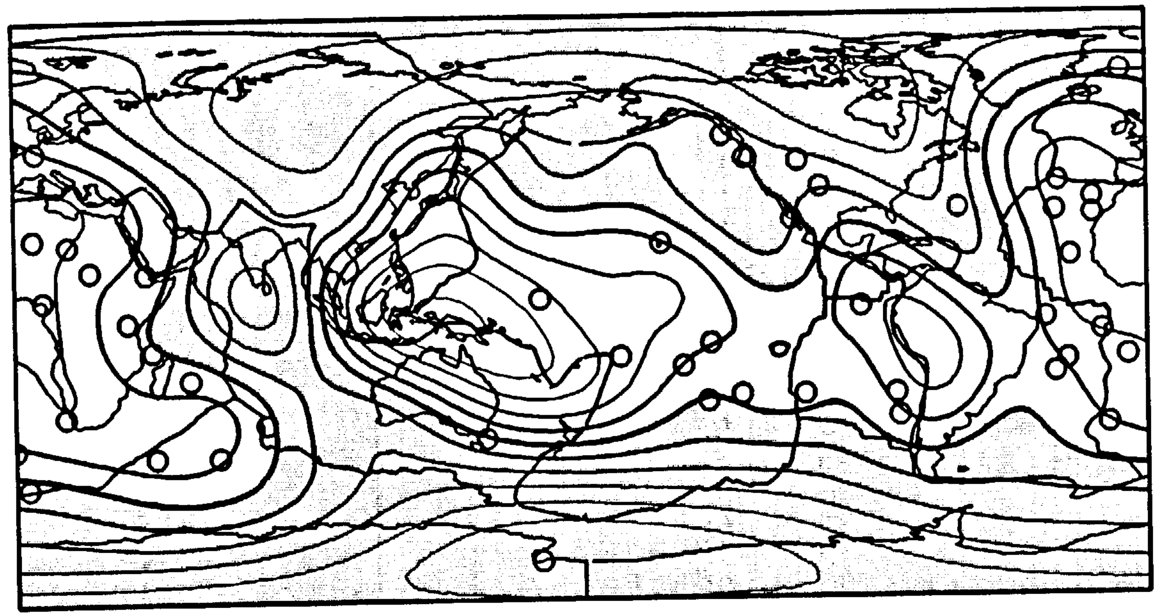
Figure 1a) The observed long-wavelength geoid (Lerch et al, 1983) referred to the hydrostatic figure of the earth (f = 1/299.63), with plate boundaries and hotspots indicated. The contour interval is 20m and geoid lows are shaded. Cylindrical equidistant projection.

Figure 1b) The observed geoid, filtered to include spherical harmonic degrees 4-9 to emphasize the association with subduction zones.

Figure 1c) A model geoid calculated from a fluid dynamical model of mantle flow driven by density contrasts inferred for subducted slabs (Hager, 1984).

Figure 2) Tomographic reconstruction of the mantle structure beneath southern California. In the upper-left panel a map view of the velocity structure at a depth of 100 km is superimposed on a location map. Also shown are the locations of the cross sections shown in the other three panels. These sections extend from the surface to 500 km depth, with no vertical exaggeration. The contour interval is 1.5% relative velocity variations, with regions faster than 1.5% dotted and regions slower than -1.5% hatched. The major feature is a slab-like high velocity anomaly penetrating the uppermost mantle beneath the Transverse Ranges (After Humphreys et al.).

Observed Geoid: degree 2-9



contour interval: 20 m

Fig 1a

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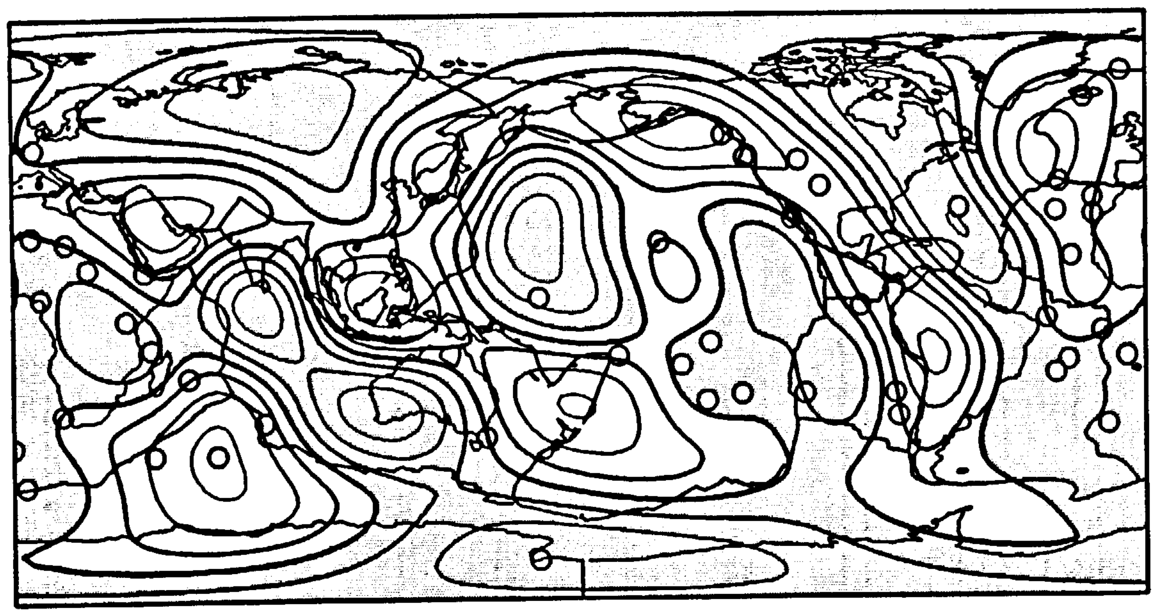
Observed Geoid: degree 4-9



contour interval: 10 m

Fig 1b

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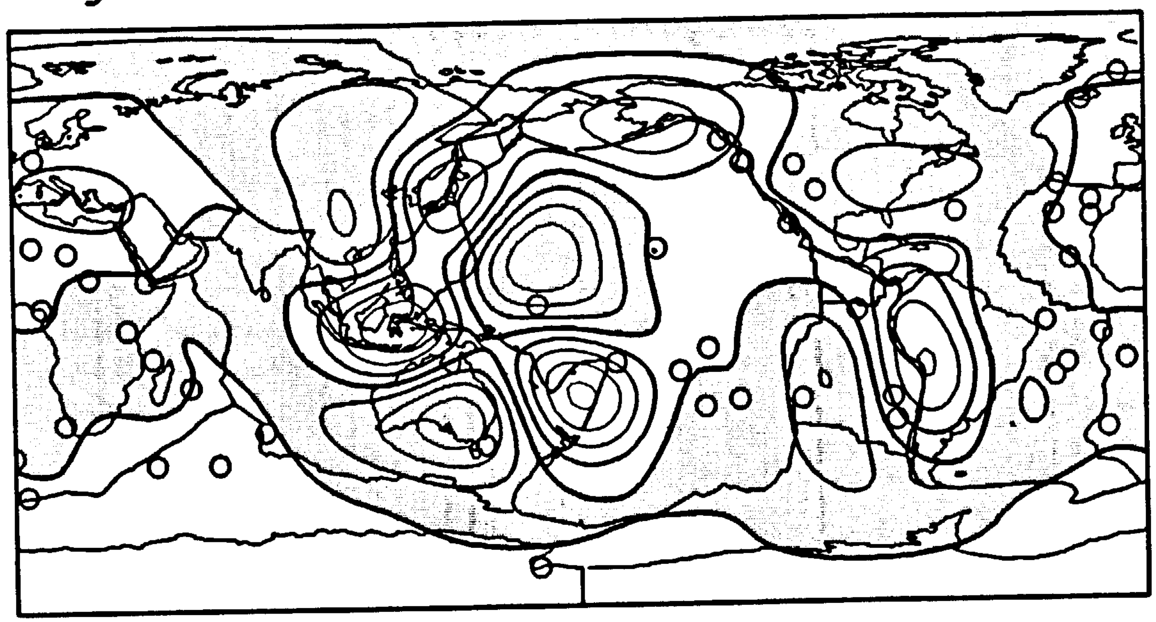
Dynamic Slab Geoid: degree 4-9



contour interval: 10 m

Figure 1c)

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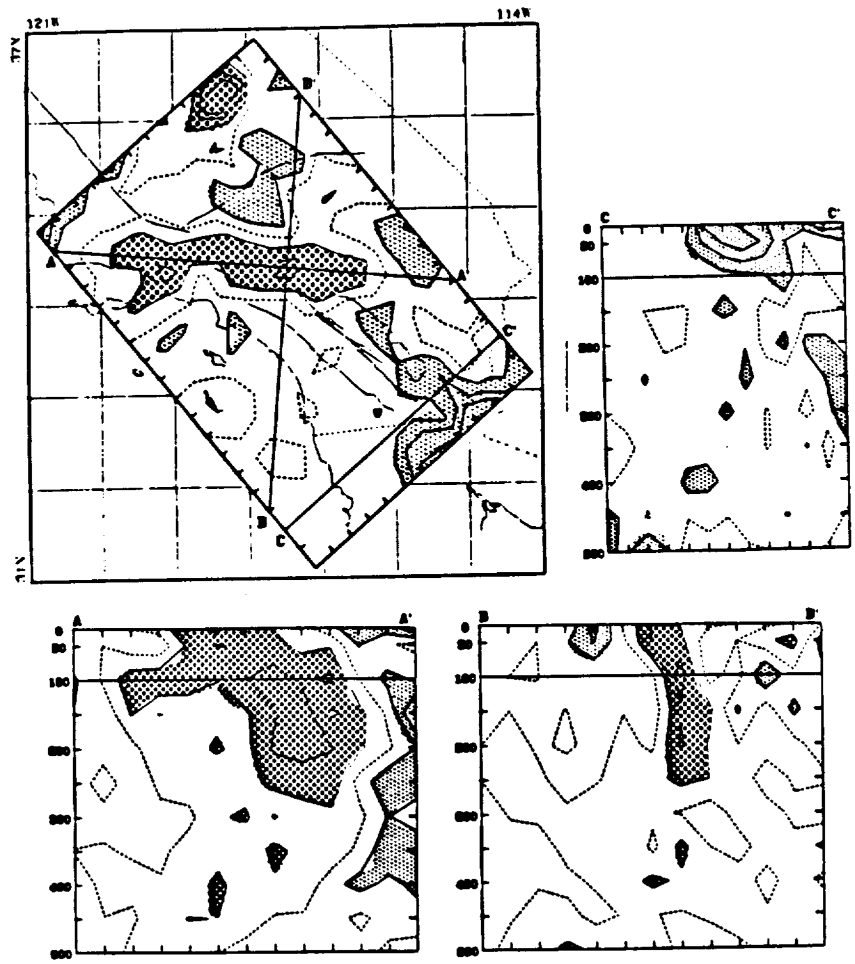

Figure 2