Reports

Role of Shallow Phase Changes in the Subduction of Oceanic Crust

Abstract. *Detailed studies of the seismicity of several subduction zones demonstrate that shallow-dipping thrust zones turn to steeper angles at depths of about 40 kilometers. An increased downward body force resulting from shallow phase changes in subducted oceanic crust may be the cause of this increased dip angle. In addition, the volume reduction associated with phase changes may produce sufficiently large stresses in neighboring rocks to cause the seismicity of the upper Benioff zone.*

Subduction of oceanic lithosphere is generally understood as the descent of cool, dense crustal and upper mantle material into the hot and less dense asthenosphere. It has been suggested that phase changes (such as those involving dehydration reactions or the phase changes from gabbro to eclogite and from olivine to spinel) occur during the subduction process and may aid its inception (*1*). In this report the distribution of earthquake hypocenters within the subduction zone is examined in order to relate dehydration reactions and the gabbro-eclogite phase change to observed features of the thrust zone and upper Benioff zone.

Although variations in subduction-zone geometries have been found in detailed seismicity studies (Fig. 1), certain features are common to all subduction zones. In general, the earthquakes within each zone can be separated into several groups (Fig. 2) based on their locations and focal mechanisms. The events of direct relevance to the role of shallow phase changes in the subduction of oceanic crust are those within the thrust zone (the plane of direct contact between the two convergent plates) and those within the Benioff zone (intraplate events within the subducting lithosphere).

The thrust zone extends from the trench axis arcward until thrust-mechanism earthquakes are no longer observed. The shallowest portions are not always apparent in seismicity studies since few earthquakes occur within the uppermost 20 km, and long periods of quiescence separate large thrust earthquakes at depths of 20 to 40 km. Within this overall depth range, the thrust plane dips at shallow angles of 5° to 15°. At depths of 40 to 60 km, frequent small thrust-type earthquakes are found (*2*) along steeper angles, reaching 30° or more. The resulting bend in the plate appears to be due to an increase in downward velocity resulting from additional downward body forces acting on the subducted oceanic lithosphere because of an increase in average density (*3*). It occurs within a depth range appropriate for dehydration and the onset of conversion of oceanic gabbro (and basalt) to more dense garnet granulite or amphibolite and, in turn, to eclogite, as determined by theoretical studies (*4*), field occurrences of eclogites (*5*), and gravity observations (*6*).

Earthquakes in the Benioff zone are located at depths greater than 40 km, exhibit maximum compressive or tensile stresses aligned within the plane of the Benioff zone, and presumably represent deformation internal to the subducted plate rather than slip between the two plates (*7*). The uppermost Benioff zone, including the upper of double Benioff zones, is nearly coincident with the upper surface of the subducted slab (*2, 8*), which suggests that these events are confined to the subducted oceanic crust (usually 5 to 8 km thick), although this cannot be proved explicitly. The onset of upper-Benioff-zone seismicity at the bend in the subducted lithosphere and its apparent confinement to the subducted crustal (gabbroic) layer suggest that the seismicity itself is directly related to the gabbro-eclogite phase change and dehydration.

The evidence for associating the bend in the subducting lithosphere and the onset of upper-Benioff-zone seismicity at depths of 40 to 60 km with phase changes in the subducted oceanic crust is circumstantial but strong. Both features occur within the depth range expected for the transitions, and simple physical arguments demonstrate that the phase changes can account for these features. The density increase from hydrated mineral assemblages to dry assemblages may be as much as 5 percent (*9*), and the density increase from dry gabbro (3.0 g/cm^3) to dry eclogite (3.5 g/cm^3) is nearly 17 percent. The total density increase of roughly 20 percent resulting from phase changes throughout 5 to 8 km of oceanic crust provides a significant downward body force due to gravity. Whether or not the oceanic lithosphere is gravita-

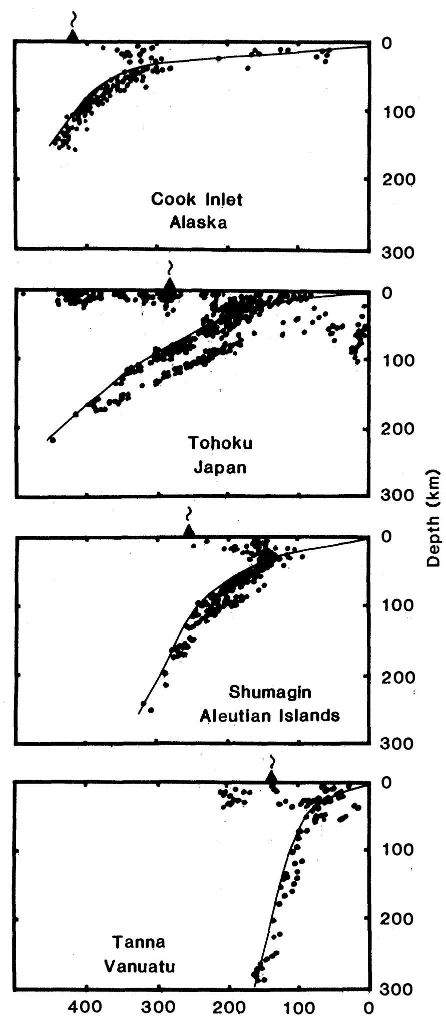

Fig. 1. Seismicity cross sections representing a variety of subduction styles; top to bottom, adapted from (*18*) to (*21*), respectively. (Vanuatu was formerly called New Hebrides.) Dots represent earthquake hypocenters; triangles represent locations of island-arc volcanoes; the right border in each part coincides with the trench axis. Lines represent the inferred upper surface of the subducting lithosphere.

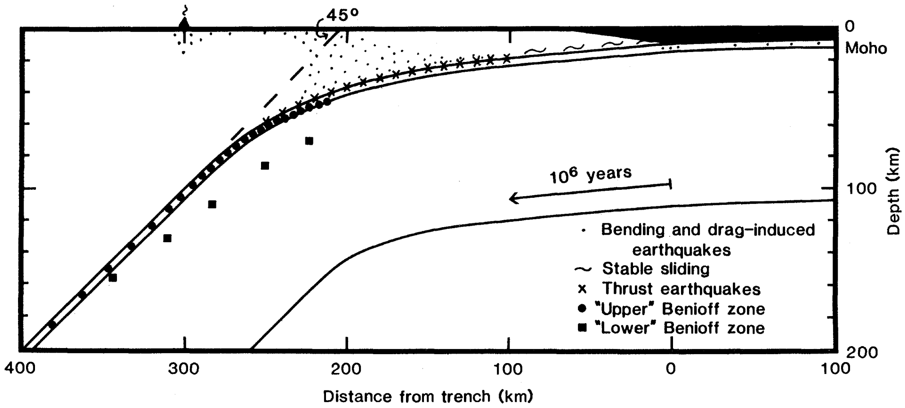

Fig. 2. Summary of groupings of earthquakes by location and focal mechanisms. The right boundary is 100 km seaward of the trench axis.

tionally unstable by the time it reaches the trench, the additional stress (σ) due to the negative buoyancy of a column containing converted crust is significant

$$\sigma = g\ \{[\rho_m\ \Delta h + \rho_l(h_0 - \Delta h)] - \rho_0 h_0\}$$

assuming that all reduction in volume associated with the density change from wet gabbro (ρ_0) to dry eclogite (ρ_l) results in a reduction (Δh) of crustal thickness (originally h_0) such that $\rho_l(h_0 - \Delta h) = \rho_0 h_0$, which is replaced by material of "normal" mantle density (ρ_m); g is the constant of gravitational acceleration at the surface of the earth. If we use $\rho_m = 3.35$ g/cm^3, $\rho_0 = 2.92$ g/cm^3, $\rho_l = 3.5$ g/cm^3, $h_0 = 5$ km, and $\Delta h = 0.17\ h_0$, we obtain $\sigma = 27$ MPa (270 bars) for the downward-directed stress experienced by a converted piece of crust in excess of that experienced by an unconverted piece of crust under similar conditions. This additional stress is likely to encourage the descent of the converted crust into the asthenosphere, and I conclude that the shallow phase changes may be expected to add significantly to the "slab pull" force of the descending lithosphere. I suggest that those phase changes occur at the onset of true subduction, where the slab descends at a relatively steep angle into the mantle.

I now investigate the relation of Benioff-zone seismicity with the shallow phase changes. The mechanism by which a volume change can produce seismicity was explained by Bridgman (*10*) and McGarr (*11*). Essentially, as a region within a rock mass undergoes conversion to a denser phase, contraction occurs in the direction of ambient maximum compressive stress. That direction may be controlled by a number of factors, including tectonic forces, overburden pressure, and local heterogeneities. Extremely large deviatoric stresses result within the neighboring rock masses, and these lead to seismic failure. Since the volume change is restricted to the oceanic crust, the resultant stresses and earthquakes themselves must be restricted to the subducted oceanic crust and nearby. The thickness of the seismic zone where it is well determined is in agreement with this constraint, being 10 km or less (Fig. 1). The largest events that occur in this depth range may be the deepest of the thrust events (*2*) or intraplate events that occur in areas of severe contortion (*12*). Dehydration reactions and gabbro-eclogite transformation each involve a variety of individual mineral reactions and occur at geologically significant rates over a range of pressure and temperature conditions (*4*) corresponding to a range in depths of subducted crust (*13*).

In Japan (Tohoku, Fig. 1), the location accuracy required to separate the events within the Benioff zone from those within the thrust zone exists, and the relation between seismicity and volume changes can be quantified for that region. I use a relation developed by McGarr (*14*) to obtain the cumulative annual seismic moment (ΣM_0) which may result from the volume change within a rock mass:

$$\Sigma M_0 = \mu LT(\Delta V/V)v_{\mathrm{sub}}$$

where μ is the rigidity of the rocks (3.5×10^{10} N/m^2), L is the length of the arc segment considered, T is the thickness of the zone in which the volume change occurs, $\Delta V/V = (\rho_l - \rho_0)/\rho_l$ is the fractional volume change, and v_{sub} is the velocity of the plate downdip. If the phase transitions are ultimately complete and occur throughout a 5-km-thick section of oceanic crust subducting at a rate of 10.5 cm/year, a cumulative seismic moment release of 31×10^{23} dyne-cm/year per 100-km width of Benioff-zone segment is possible. This is the figure that would be obtained if all the volume change resulted in seismic events, and it must be viewed as an upper limit on the moment possible. From magnitude data for Tohoku (*15*) and two different relations for deriving seismic moments from magnitudes (*16*), the cumulative seismic moment for events between the depths of 30 and 110 km (upper Benioff zone only) is found to be (1 to 7) $\times 10^{23}$ dyne-cm/year per 100-km width of segment. These are probably minima, since there are no reliable data for the Tohoku events for depths beneath 110 km and the repeat times for large events may be longer than the study period. As long as the volume changes are at least 10 to 20 percent efficient at producing seismicity, the uppermost Benioff zone may be accounted for by this mechanism.

The shallow phase changes to be expected within the subducted oceanic crust can increase the downward forces acting on the lithosphere, causing the bend in the subducted plate and initiating true subduction. I conclude that these phase changes occur within the subducted crust at depths of about 40 km, where the steepening of the slab is generally observed. The volume changes associated with the phase changes may result in the seismicity of the uppermost Benioff zone, although other contributing factors such as thermal stresses (*17*), which may also account for the lower-Benioff-zone seismicity, play significant roles as well.

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Fish Schools: An Asset to Corals

Abstract. *Schools of juvenile haemulid fish feed in sea grass beds at night. By day they rest over coral heads, where they excrete substantial quantities of ammonium and particulate nitrogen and phosphorus into the nutrient-poor waters. The percentages of these nutrients contributed by the fish were comparable to those from other sources. Coral heads with resident fish schools grew faster than those without resident schools, indicating that fish may be more beneficial to the corals than has been assumed.*

Fish schools resting over and in coral heads are a well-known feature of coral reefs throughout the world, and the benefits of such shelter to the fish have long been recognized (*1*). We found that corals may also benefit from the association. Excretory and fecal products from the fish were a substantial source of nitrogen and phosphorus in the nutrient-poor waters of a coral reef, and coral heads with fish had higher growth rates than those without fish.

It has been suggested that when fish migrate between resting and feeding areas they transfer energy and nutrients to their resting areas (*2, 3*). Although this phenomenon has been widely reported in birds (*4*), only carbon transport by fish in a temperate rocky reef community has been described (*3*). A coral reef is an ecosystem characterized by high biomass and productivity despite low nutrient content of the water. In such an ecosystem it is particularly critical to understand the pathways by which nutrients are cycled, and thereby enhance productivity. We investigated whether migrating fish could be a source of nutrient enrichment for reefs. Numerous tropical fish species migrate daily to feed (*5*); we studied heterotypic schools of juvenile French and white grunts (*Haemulon flavolineatum* and *H. plumieri*) in Teague Bay, St. Croix, U.S. Virgin Islands. These fish (30 to 120 mm total length) aggregate over coral heads during the day and migrate at sunset to surrounding sea grass beds, where they feed on benthic invertebrates; their guts are full in the morning and empty by late afternoon (*6*). The fish use the same migration routes and return to the same coral heads each morning (*6–8*). Schools have been observed on the same head for more than 3 years (*8*).

To determine whether fish excretory products were enriching the water around a coral head, we sampled water within a school resting in a large *Acropora palmata* head (*9*). When fish were present, NH_4^+ concentrations up to 0.9 μM were recorded; concentrations remained at 0.2 μM in an adjacent head without fish. No statistically significant differences in concentrations of molybdate-reactive phosphorus (MRP) were detected between the sites (*10*).

We also examined the possibility that fish feces were providing an additional nutrient source for the benthic community associated with the coral head. Sediment traps were placed in an *A. palmata* head with grunts and in a head without fish (*11*). A significantly greater quantity of nitrogen and phosphorus as well as particles with significantly higher percentages of these nutrients were collected from traps under fish schools (*12*), suggesting that the excretory products were providing a supplement to the coral head community.

To determine the amounts of nutrients contributed by fish, we monitored the biomass of grunts on six coral heads and measured nitrogen and phosphorus excretion rates of fish in the laboratory. Fish biomass was estimated on three *Porites furcata* and three *A. palmata* heads at 4-month intervals from April 1980 to December 1981. Numbers of fish and the size-frequency distribution were determined for each school from photographs (*13*). To assess the accuracy of this technique, photographs were taken just before all fish were removed from two heads. Photographic estimates of biomass were 67 and 71 percent of the biomass of captured fish. Hence, the data are probably underestimates of the nutrient contribution by fish. We present data only for grunts although the coral heads harbored squirrelfish and cardinal fish, species that also feed away from the head.

Daily generation of NH_4^+, MRP, total dissolved nitrogen and phosphorus (*14*), and particulate nitrogen and phosphorus (*15*) were measured on fish in the laboratory (*16*). Regressions of the rate of nutrient generation on body weight were developed from these data and combined with the biomass and size-frequency data from the photographs to estimate the daily production of nitrogen and phosphorus by the resident population on each coral head (Table 1).

Corals are known to use other sources of nitrogen and phosphorus, namely, dis-

Table 1. Amounts of nutrients deposited by juvenile French and white grunts resting over two species of coral heads. The nutrient contribution is also expressed as a percentage of nutrients available from other sources. Values are the means ± 95 percent confidence intervals from three heads of each species measured on three to five different dates. Fish biomass was 39 ± 13 g/m² (dry weight) on *Porites furcata* (N = 12) and 172 ± 29 g/m² on *Acropora palmata* (N = 12).

Nutrient	Contribution to *Porites furcata*: mmole/m² per day	*Porites furcata*: Percent	*Acropora palmata*: mmole/m² per day	*Acropora palmata*: Percent
Nitrogen				
NH_4^+	2.4 ± 0.7	30 ± 10	7.3 ± 2.2	48 ± 14
Dissolved	3.0 ± 0.8	0.8 ± 0.2	7.4 ± 1.2	1.1 ± 0.3
Particulate	0.9 ± 0.2	41 ± 13	2.2 ± 0.6	59 ± 17
Total	3.9 ± 0.6	1.0 ± 0.3	9.6 ± 2.8	1.4 ± 0.4
Phosphorus				
Molybdate-reactive	0.05 ± 0.02	3.0 ± 1.2	0.21 ± 0.06	6.6 ± 1.9
Dissolved	0.07 ± 0.02	1.0 ± 0.4	0.30 ± 0.09	2.2 ± 0.7
Particulate	0.12 ± 0.02	68 ± 20	0.31 ± 0.09	94 ± 29
Total	0.20 ± 0.05	2.6 ± 0.18	0.62 ± 0.8	4.4 ± 1.3