Shearing instabilities accompanying high-pressure phase transformations and the mechanics of deep earthquakes

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Deep earthquakes have been a paradox since their discovery in the 1920s. The combined increase of pressure and temperature with depth precludes brittle failure or frictional sliding beyond a few tens of kilometers, yet earthquakes occur continually in subduction zones to ≈700 km. The expected healing effects of pressure and temperature and growing amounts of seismic and experimental data suggest that earthquakes at depth probably represent self-organized failure analogous to, but different from, brittle failure. The only high-pressure shearing instabilities identified by experiment require generation *in situ* of a small fraction of very weak material differing significantly in density from the parent material. This "fluid" spontaneously forms mode I microcracks or microanticracks that self-organize via the elastic strain fields at their tips, leading to shear failure. Growing evidence suggests that the great majority of subduction zone earthquakes shallower than 400 km are initiated by breakdown of hydrous phases and that deeper ones probably initiate as a shearing instability associated with breakdown of metastable olivine to its higher-pressure polymorphs. In either case, fault propagation could be enhanced by shear heating, just as is sometimes the case with frictional sliding in the crust. Extensive seismological interrogation of the region of the Tonga subduction zone in the southwest Pacific Ocean provides evidence suggesting significant metastable olivine, with implication for its presence in other regions of deep seismicity. If metastable olivine is confirmed, either current thermal models of subducting slabs are too warm or published kinetics of olivine breakdown reactions are too fast.

anticrack | dehydration | subduction zone | serpentine | metastable olivine

Crustal earthquakes are the result of brittle fracture of virgin rock or frictional sliding on preexisting faults, with the latter greatly predominating. Such failure, however, is strongly resisted by the normal stress across the fault and therefore severely inhibited by pressure. In contrast, ductile flow is essentially impossible in most rocks at near-surface conditions but the flow stress decreases exponentially with temperature. Because both pressure and temperature increase with depth in Earth, within a few tens of kilometers of the surface rocks will flow at lower stresses than they can break. Nevertheless, in subduction zones (regions where portions of the lithosphere, the outermost 50–100 km of Earth, plunge deep into the mantle as the return flow of plate tectonics) earthquakes occur continuously from the surface to depths approaching 700 km (Fig. 1). Seismic focal mechanisms show that these deep earthquakes represent slip across a fault, just like shallow earthquakes.

A variety of seismic observations strongly suggests that subduction zone earthquakes below ≈70 km involve failure of intact rock (1, 2). Therefore, as is the case for brittle shear fracture, self-organizing failure mechanisms are probably necessary.

At high pressure, microcracks cannot open in response to application of a deviatoric stress because they are held closed by the normal stress across any potential crack plane. The only way that such cracks can open is if a low-viscosity pore fluid is available to flow into such a crack as it opens. In confirmation, laboratory experiments show that shear failure of virgin rock at high pressure is only possible in the presence of a small amount of low-viscosity "fluid;" the fluid can be either a true fluid (3–5) or a polycrystalline solid that is extremely weak at seismic strain rates (6–9). At shallow depth, introduction of fluid could be by infiltration of fluid into porous or cracked rock. At greater depth, elevated temperature, very high pressure, and the buoyancy contrast between fluid and solid drive pore fluid out of the rock and toward the surface, leaving rock generally fluid-free and with very low permeability. Therefore, failure-enabling fluids must be generated *in situ* by: (*i*) devolatilization of hydrous phases or carbonates, or (*ii*) induction of a solid-solid phase transformation under conditions resulting in generation of a nanocrystalline product (9–11). Thus, pressure- and temperature-induced mineral phase transformations are central to enabling earthquakes at depth.

In brittle material under a small confining pressure, self-organization of faulting occurs in the following manner: (*i*) As stress rises, tensile microcracks initiate at stress concentrations and propagate a short distance, stopping when the deviatoric stress at the crack tip falls below the tensile fracture strength; (*ii*) with rising stress, the process repeats itself as microcracks initiate at progressively less severe stress concentrations; (*iii*) when the density of microcracks reaches a critical density at some location, further microcrack generation concentrates there; and (*iv*) when the local microcrack density is sufficiently high, they self-organize in response to the interacting stress fields at their tips; a microfault is born and propagates by repetition of the "microcracks-first" process. In fracture mechanics, tensile cracks are referred to as mode I, to emphasize that the displacements associated with the crack are normal to the plane of the crack. I will use this terminology here for two reasons: (*i*) At depth in the earth, stresses are all compressive, hence "tensile crack" becomes a misnomer because it is tensile only in the sense of the deviatoric stress; (*ii*) I will introduce the concept of an "anticrack" that is a compressional feature having the geometry of a tensile crack but the displacements are directed inward toward the plane of the feature rather than outward as in tensile cracks. The term mode I applies in all of these situations and formally draws attention to the analogy between cracks and anticracks.

Experimental High-Pressure Faulting Mechanisms

Faulting Caused by Devolatilization of Hydrous Phases. Serpentinite deformed under confining pressure of a few hundred MPa and elevated temperature breaks down to olivine + talc + H_2O and

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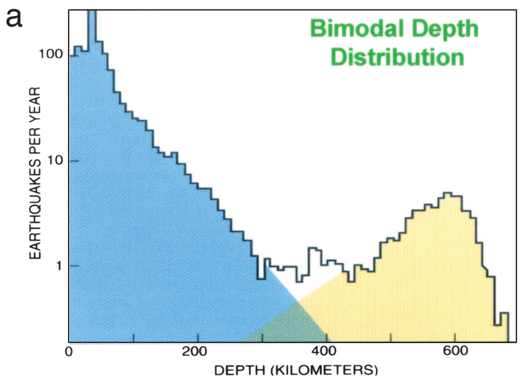

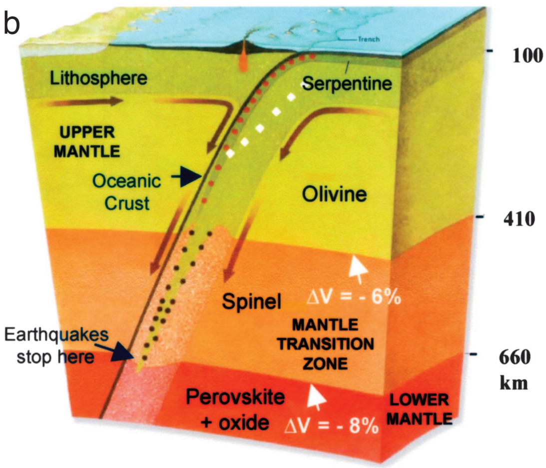

Fig. 1. Earthquake depth distribution. (*a*) Semilog plot of global earthquake frequency per 10-km-thick depth interval, showing a bimodal distribution. All earthquakes below ≈50 km are in subduction zones, the coldest parts of the mantle. The boundary between the mantle transition zone and lower mantle in subduction zones is at ≈700 km. No earthquake has ever been detected in the lower mantle. Modified from ref. 35. (*b*) Cartoon of subduction zone and earthquake distribution. Lithosphere (speckled) at right, with uppermost layers altered to antigorite (serpentine), is subducting beneath lithosphere at left. Earthquakes in olivine-dominated upper mantle are shown as red dots in serpentine and white diamonds. In the mantle transition zone, olivine is hypothesized to remain present despite being no longer thermodynamically stable and to slowly react away to spinel (wadsleyite or ringwoodite) during descent, occasionally generating earthquakes (black dots) by the process discussed in the text. Note volume reductions accompanying phase transformations at 410 and 660 km. Modified from ref. 36.

fails catastrophically by faulting (3). Such failure can be described by reduction of the effective normal stress across the fault by the following relationship:

$$\tau = \tau_o + \mu(\sigma_n - p_f), \quad [1]$$

where τ is the shear stress, τ_o is a constant, μ is the coefficient of friction, σ_n is the normal stress on the fault, and p_f is the pressure of the pore fluid. Eq. **1** describes both brittle failure of intact rock and frictional sliding under conditions where p_f is less than the least principal compressive stress, σ_3 (11, 12). However, the qualitative description of the fluid as partially supporting the normal stress is unsatisfactory in a mechanistic sense because if $p_f < \sigma_3$, then the fluid can only exist in pores sheltered by the strength of the solid matrix. If such is the case, how does the fluid reduce the normal stress on a fault? Worse, in unbroken material, how does it reduce the normal stress on a fault that has not yet been created?

Understanding comes from modern knowledge that brittle shear failure is fundamentally tensile failure (11, 13). Experimentally, it has been known for 40 years that a small shear crack cannot be made to propagate in its own plane. Application of a shear stress to material containing such a crack causes new tensile cracks ("wings") to appear at the tips of the shear crack and propagate a short distance along the trajectory of the greatest principal stress, σ_1, as explained above.

This mechanistic understanding of the process provides explanation of how a pore fluid facilitates faulting. It does so by enhancing the local tensile stress concentrations that lead to formation of the tiny tensile microcracks and by holding them open after they form. Thus, the greater the pore pressure, the lower the applied stress necessary to bring local stress concentrations to the failure stress, and the lower the overall stress required to generate proliferation of microcracks to the point of self-organization into an incipient fault zone. If the pore pressure reaches σ_3, the failure mode is runaway propagation of a tensile crack, leading to sample splitting in the laboratory or a fluid-filled vein (or melt-filled dike) in Earth. In a natural situation with a slowly evolving pore pressure, the more usual case should be generation of shear failure while $p_f < \sigma_3$.

There is abundant laboratory evidence that this mechanism can induce brittle shear failure at greatly reduced stresses compared with those required in the absence of a pore fluid. Importantly, development of a pore pressure can lead to brittle failure under conditions where rock behavior would otherwise be ductile (3, 5). As a consequence, dehydration embrittlement is an attractive hypothesis to explain earthquakes under conditions where unassisted brittle failure is inhibited.

There is a problem, however. Fluids are very much more compressible than solids, hence dehydration reactions, which all produce a positive ΔV of reaction at low pressures (because of the low density of hydrous fluids), will have a progressively reduced ΔV as pressure rises. Ultimately, ΔV becomes negative at pressures where the more dense solid product phases come to dominate. For antigorite, the serpentine mineral stable at the highest temperatures and pressures, the point of $\Delta V = 0$ is at ≈750°C, 2.2 GPa (14), representing a depth of only ≈70 km in Earth (Fig. 2*a*). For other hydrous minerals likely to be reasonably abundant in mantle lithologies (e.g., chlorite), the conditions are comparable. Under conditions where $\Delta V < 0$, the pore-pressure effect is expected to disappear because generation of a droplet of fluid should result in a low-pressure pore surrounded by compressive hoop stresses. As a consequence, a stress concentration that encourages formation of mode I microcracks is pushed away from local failure rather than toward it. The greater the negative ΔV, the lower is the pore pressure produced and the greater the compressive "capsule" in which it is confined. Both effects push the material away from local tensile failure, hence this has been interpreted as inhibiting bulk shear failure (15). If that were the case, then dehydration embrittlement would be limited to depths of a few tens of kilometers as a mechanism for triggering earthquakes.

Jung *et al.* (4) tested this hypothesis in the laboratory, finding that dehydration of antigorite under stress leads to faulting at confining pressures of 1–6 GPa, demonstrating that bulk shear failure can still occur with $\Delta V_{reaction} < 0$. Remarkably, the microstructures accompanying faulting were the same under all conditions; all fault zones were decorated with extremely fine-grained solid reaction products (olivine + talc or olivine + enstatite) (Fig. 2 *b* and *c*). Mode I microcracks were not visible in serpentine, but regions of residual olivine showed them in abundance; many of them had already healed (forming surfaces decorated with fluid inclusions) before the end of the experiment (Fig. 2*d*). These observations contain the answer to why shear failure is not inhibited when the total volume change upon dehydration becomes negative; the solid and fluid reaction

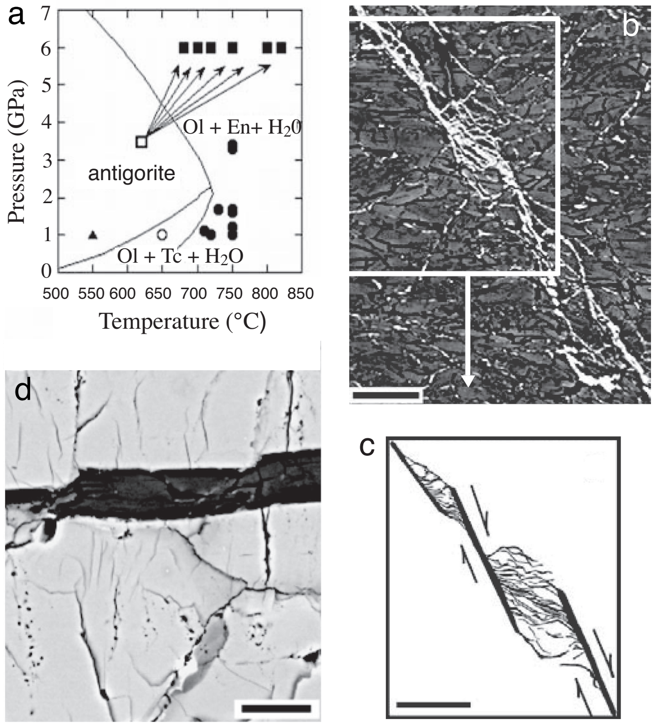

Fig. 2. Serpentine faulting experiments. (*a*) Phase diagram showing stability field of antigorite serpentine and its break-down products. Circles, squares, and triangle show experimental conditions of ref. 4. (*b*) En echelon faults and anticracks decorated by solid reaction products (bright) in dark antigorite matrix. (*c*) Sketch illustrating fault segments (heavy lines) and anticracks (light, wavy lines). (*d*) Region of relict olivine with antigorite inclusion showing mode I cracks produced during dehydration of antigorite; several early formed cracks are marked only by arrays of water bubbles after crack healing. Modified after ref. 4. (Scale bars: 20 μm.)

products separate immediately after their generation; each component contributes to failure independently, the true fluid with $\Delta V > 0$ and the nanocrystalline solid as a pseudofluid with $\Delta V < 0$ (see ref. 4 for extended discussion).

Much remains to be learned about the fundamental physics of failure under these conditions. Nevertheless, it is now clear that, regardless of the sign of the ΔV of reaction, breakdown of hydrous minerals is a viable trigger mechanism for earthquakes to depths of 250 km (approximate limit of antigorite stability in a cold subduction zone) and potentially much more if other hydrous phases are present.

A new variant of dehydration embrittlement has been discovered recently during a study of the rheology of eclogite (the high-pressure equivalent of common basalt, the rock type making up the oceanic crust) at $P = 3$ GPa (5). During experiments on a natural eclogite with no hydrous phases, but with small amounts of H_2O dissolved in both pyroxene and garnet, faulting occurred when specimens were deformed at temperatures above the water-saturated solidus. H_2O exsolved from the silicates and triggered small amounts of melting at grain boundaries, leading to myriad melt-filled mode I microcracks and shear failure; the broken material within the fault zone (gouge) consisted of angular fragments except for the presence of small amounts of glass. These microstructures were exactly as expected for $\Delta V > 0$. Remarkably, the amount of fluid required for faulting was <1 vol% (5). This mechanism of dehydration of nominally anhydrous minerals provides a mechanism for explaining earthquakes in hot subducting oceanic crust.

Faulting Associated with Solid–Solid Phase Transformations. The other experimentally established, self-organizing, high-pressure faulting instability requires an exothermic polymorphic phase transformation accompanied by significant volume change (Table 1) and is known to operate under certain restrictive conditions during the olivine $\rightarrow$ wadsleyite and olivine $\rightarrow$ ringwoodite transformations. Olivine is the most abundant mineral in the upper mantle, and it undergoes densification phase transformation to wadsleyite (with a spineloid structure) and ringwoodite (with a true spinel structure) with increasing pressure. The transformation to wadsleyite creates the prominent discontinuity in seismic velocities at $\approx$410 km in Earth and the breakdown of ringwoodite to still more dense phases (perovskite + magnesiowüstite) creates the even stronger seismic discontinuity at $\approx$660 km. The instability associated with olivine breakdown leads to production of mode I microanticracks (Fig. 3 *a* and *b*) that interact via the compressive stress concentrations at their tips in an analogous way to the interactions between tensile stress concentrations at the tips of open or fluid-filled mode I microcracks. Rather than containing a true fluid, these microanticracks are filled with a nanocrystalline aggregate of the new, denser phase (see ref. 8 for extended discussion). Like normal brittle failure and dehydration embrittlement, anticrack failure in the laboratory generates acoustic emissions (16) and therefore is potentially an earthquake mechanism.

The reason an exothermic polymorphic transformation is required to support this instability is shown in Fig. 3*c* (10). Along the near-vertical left-hand branch of the nucleation-rate curve in Fig. 3*c*, formation of a nucleus of the stable phase releases a small amount of heat that produces a small increase in local temperature, leading to significant increase in the local nucleation rate, which releases more heat, etc. At the same time, the negative ΔV of the reaction causes the nucleus to be immediately surrounded by compressive hoop stresses that increase the driving force for nucleation of additional crystals adjacent to the original nucleus. Therefore, unless the metastable host is a good thermal conductor, the combination of these two effects under nonhydrostatic stress

Table 1. Systems tested for transformation-induced faulting

Chemical system		Fault?	P, GPa	Micro-structure	Reaction type		
$\alpha \rightarrow \gamma$	Mg_2GeO_4	Yes	1–2	Anticracks	Exothermic	Polymorphic	Transformation
$\alpha \rightarrow \beta$	$(Mg,Fe)_2SiO_4$	Yes	14–15	Anticracks	Exothermic	Polymorphic	Transformation
$\alpha \rightarrow \beta$	Mn_2GeO_4	Yes	4–4.5	Anticracks	Exothermic	Polymorphic	Transformation
pv $\rightarrow$ il	$CdTiO_3$	Yes	0.2	Cracks	Exothermic	Polymorphic	Transformation
Ice1 h $\rightarrow$ II	H_2O	Yes	0.2–0.5	Anticracks	Exothermic	Polymorphic	Transformation
il $\rightarrow$ pv	$CdTiO_3$	No	0.2	Blocky xls	Endothermic	Polymorphic	Transformation
ab $\rightarrow$ jd + coes		No	3–3.5	Symplectite	Exothermic	Disproportionate	Disproportionate
Predictions for the top of the lower mantle							
$\gamma \rightarrow$ pv + mw		No	25	Symplectite	Endothermic	Disproportionate	Disproportionate
$\alpha \rightarrow$ pv + mw		No	25	Symplectite	Exothermic	Disproportionate	Disproportionate

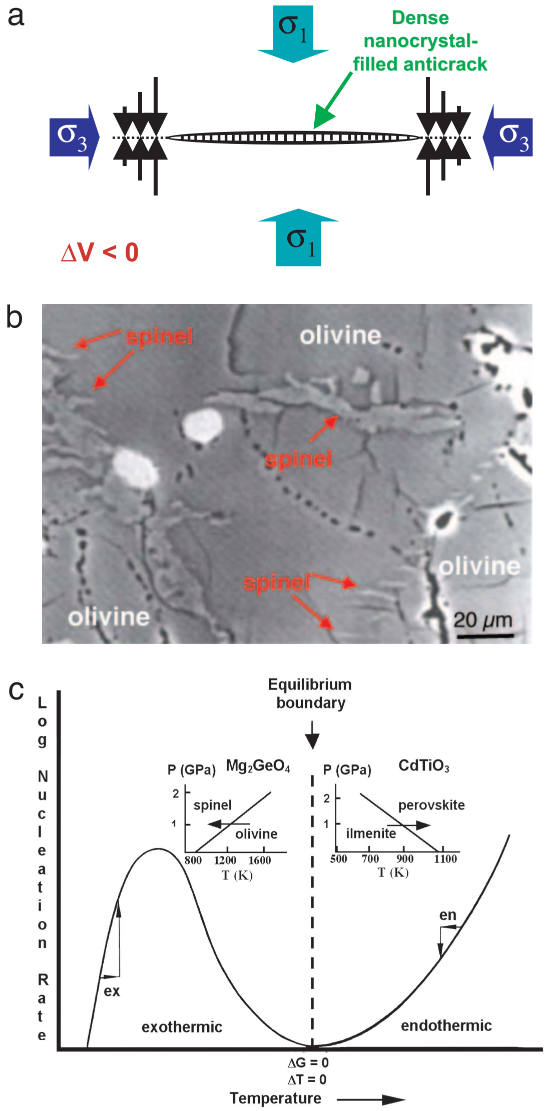

Fig. 3. Anticracks: their nature, appearance, and explanation. (*a*) Cartoon showing idealized shape and orientation of anticracks in the stress field that caused them. Extremely rapid nucleation of a more dense phase in a less dense one leads to nanocrystalline lenses of the daughter phase that orient themselves normal to maximum compressive stress and develop very large compressive stresses at their tips. See text for discussion of analogy to fluid-filled cracks. (*b*) Anticracks filled with nanocrystalline spinel produced in olivine. (*c*) Thermodynamic explanation for anticrack formation (see text), modified from ref. 10.

can lead to runaway nucleation in the plane normal to σ_1, yielding mode I microanticracks filled with a nanocrystalline solid with properties of a low-viscosity fluid (Fig. 3*b*). As in the case with mode I cracks, the greater the aspect ratio of the anticrack, the greater the stress concentration at the tip. Therefore, under stress, microanticracks interact with each other through the elastic strain fields at their tips in a way analogous to microcracks, culminating in initiation of a fault and catastrophic shear failure. In contrast, both the driving force and the kinetics for endothermic transformations increase monotonically with temperature, hence positive feedback for runaway nucleation is absent; no anticracks form and no instability is generated (see refs. 10 and 11 for additional data and discussion).

Clearly, then, a critical requirement for failure is an exothermic reaction. The breakdown of ringwoodite to form two new, more dense minerals at the base of the upper mantle is endothermic, hence passage of ringwoodite from the upper mantle to the lower mantle cannot trigger this instability. However, if olivine were carried metastably through the transition zone and into the lower mantle, the breakdown reaction would be exothermic. Could such a disproportionation reaction support the instability if the reaction is exothermic and ΔV is large? Or is the diffusive step necessary to partition the chemical components into two phases sufficiently slow that it abrogates the localized runaway nucleation of the daughter assemblage to form anticracks and hence quenches the instability? This hypothesis was tested by using a proxy breakdown reaction that is more exothermic and has a larger volume decrease than any of the systems exhibiting transformation-induced faulting (Table 1). The hypothesis was confirmed; at high pressure, decomposition under stress of albite ($NaAlSi_3O_8$, a feldspar common in granitic rocks) yielded blocky crystals of jadeite ($Na_2Al_2SiO_6$), a pyroxene, filled with "wormy" intergrowths of coesite, a high-pressure polymorph of quartz (SiO_2); no anticracks were observed and faulting did not occur (unpublished results).

Application to Subduction Zones

We see from the above that the hydrous phase expected to be most abundant in the uppermost mantle (antigorite) supports the dehydration embrittlement instability and the most abundant mineral of any kind in the upper mantle, olivine, supports the anticrack instability if it is carried metastably into the transition zone. Any olivine entering the transition zone during subduction will follow a particle trajectory that unavoidably must encounter the conditions that favor anticrack development (8) if stresses are sufficient. Therefore, as shown in Fig. 1, this instability potentially could trigger earthquakes at all depths between the two seismic discontinuities that define the transition zone but would not trigger earthquakes in the lower mantle. Ulmer and Trommsdorff (14) showed how the antigorite dehydration boundary "paints" onto the temperature distribution in a subduction zone, yielding a pattern closely similar to the shallow double seismic zones observed in most subduction zones, as shown schematically in Fig. 1*b*; dehydration of antigorite could potentially trigger earthquakes to depths approaching 250 km. Thus, most earthquakes observed in subduction zones could potentially be triggered by breakdown of antigorite or olivine. Of the remainder, the shallowest can be accounted for by dehydration of hydrous minerals in altered oceanic crust (e.g., refs. 17 and 18), and the relatively rare earthquakes between 250 and 350 km could potentially be triggered by dehydration of such minor minerals as titanian clinohumite (19, 20).

Nevertheless, there are three major questions that would have to be answered to reach the conclusion that these two mineral reactions trigger the great majority of subduction zone earthquakes:

(*i*) There is no direct evidence for antigorite to a depth of $\approx$40 km directly beneath oceanic trenches and no generally accepted mechanism for achieving hydration of deep lithosphere. Therefore, whether antigorite dehydration can explain the lower zone of uppermost mantle earthquakes (white diamonds in Fig. 2) is not clear.

(*ii*) For the anticrack mechanism to trigger earthquakes, olivine must be carried across the olivine $\rightarrow$ wadsleyite phase boundary without reacting. However, until very recently, evidence for metastable olivine in any subduction zone has been equivocal.

(*iii*) It has been argued that very large, very deep earthquakes are difficult to explain by the metastable olivine hypothesis because it has been thought that very little metastable olivine is likely to be present at depths in subduction zones exceeding $\approx$550 km (21, 22). This concern could be alleviated if earthquakes triggered by the anticrack mechanism can propagate into peridotite in which the olivine has been completely transformed.

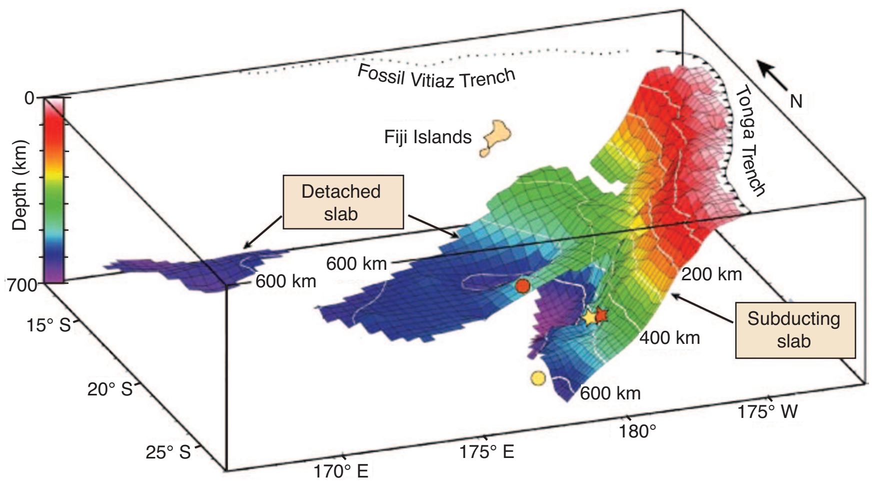

Fig. 4. Cartoon showing active Tonga subduction zone and fossil slab floating above it. Original figure is modified after ref. 26. Yellow and orange stars and circles were added in ref. 28.

Preliminary observations from my laboratory (unpublished results) demonstrated this in principle, yielding microstructures suggesting glass in the fault zone, implying shear heating during propagation through the fully transformed material, similar to a model of the great Bolivia earthquake of 1994 (23). More work is needed.

Evidence is now very strong for the presence of extensive metastable olivine in the Tonga subduction zone of the Southwest Pacific Ocean (beneath the Fiji islands). This region is the location of almost half of all earthquakes deeper than 300 km. Moreover, many of these earthquakes do not occur within the steeply dipping subduction zone *sensu strictu*; they occur west of the subduction zone as "outboard" earthquakes that have been a paradox for many years. Over the last 6 years, the seismic properties of the region of the transition zone in which these earthquakes occur, as well as earthquake-free regions to the south, have been interrogated in great detail (2, 24–27). Those authors have identified a "petrologic anomaly" that contains the outboard earthquakes and defines a shallowly dipping slab-like feature in the transition zone (Fig. 4 and ref. 26). This anomaly has markedly reduced seismic velocities compared with cold transition zone and shows strongly anisotropic seismic wave speeds (Fig. 5 and ref. 28), and the earthquakes within it have chaotic focal mechanisms on scales of a few kilometers to hundreds of kilometers (2, 26). Importantly, at the southern margin of the region of outboard earthquakes (Fig. 5), there is a very narrow region (≈30 km wide) in which the seismic velocities in the transition zone abruptly increase to be significantly faster than normal transition zone, lose seismic anisotropy, and are progressively slower further to the south until velocities characteristic of normal transition zone are reached. After considering various possibilities for the source of this petrologic anomaly over the course of their work, those authors conclude that it is a "fossil" subducted slab with ≈60% of its olivine remaining metastable. The seismically very fast zone adjacent to the south is then interpreted as cold ringwoodite that has replaced metastable olivine; progressive falloff of seismic velocities further south is attributed to warming up to the temperature of ambient mantle (25, 26, 28).

Another set of seismic data relevant to this problem is the report of remote triggering of deep earthquakes, again in the Tonga subduction zone (29). These workers demonstrated that

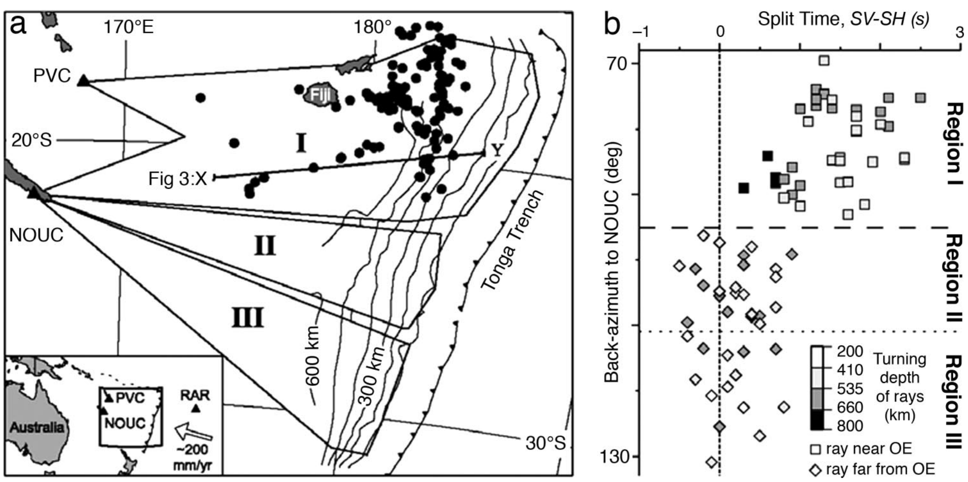

Fig. 5. Mapped areas of petrologic anomaly in mantle transition zone beneath Fiji showing anisotropy only where earthquakes are occurring (*a*). Black dots in sector I show hypocenters of outboard earthquakes; sector II has markedly higher seismic velocities in transition zone that slow to the south; sector III is normal mantle transition zone. (*b*) Shear-wave splitting measurements. Note that anisotropy ends abruptly at the boundary between sectors I and II, coincident with jump in seismic velocities and cessation of earthquakes. [Reproduced with permission from ref. 27 (Copyright 2003, American Geophysical Union).]

in 2002 a magnitude 7.6 earthquake at ≈590 km depth in the steeply dipping active slab of Tonga (yellow star in Fig. 4) triggered two other earthquakes, 300 km away and 70 km deeper, within 7 min of the triggering shock. The remotely triggered shocks, of magnitude $M = 5.9$ and 7.7, occurred in a location in which there had been no previously recorded earthquakes (yellow circle of Fig. 4). The same authors (29) identified another sequence of remotely triggered deep events in which the triggering earthquake ($M = 6.8$) was in the currently active Tonga slab and the triggered earthquakes (M up to 7.1) in the fossil slab discussed above (orange star and circle in Fig. 4). The timing of both sequences of triggered events is consistent with earthquakes initiated by transformation-induced faulting of metastable olivine but inconsistent with runaway shear heating (30).

A third set of seismic observations (2) shows that, worldwide, there are five regions of approximately horizontal subducting slab, three in the shallow upper mantle beneath South America and two in the transition zone west of Tonga, one of which is the fossil slab of outboard earthquakes discussed above. The focal mechanisms of the earthquakes in all of these shallowly dipping (<20°) slab segments are chaotic, as previously shown for the outboard earthquakes west of Tonga. The chaotic nature of focal mechanisms on all scales in these subhorizontal regions, including separations of only a few kilometers in the case of the triggered earthquakes located by the orange circle of Fig. 4 (see details in refs. 2 and 29), requires a local origin of the stresses. The most likely source of local stresses in these regions is a highly irregular boundary between transformed and untransformed slab material, antigorite-bearing material adjacent to antigorite-absent material in shallow subhorizontal slab elements and metastable olivine-bearing material adjacent to olivine-absent material in deep subhorizontal slab elements (see also ref. 31). In both cases, a large volume reduction is associated with the indicated mineral reactions, yielding large stresses in the immediate vicinity of the interface between reacted and nonreacted volumes (32).

The majority of this discussion of deep earthquakes has focused on Tonga because there are vastly more data on Tonga and its environs than elsewhere. A particularly confusing subduction zone is South America, in which there is a very large gap in seismicity (between 325 and 520 km depth) along much of the length of the continent. A possible explanation of this gap was offered by Kirby *et al.* (33), who suggested from plate reconstructions that the deeper parts of the subducting slab may be much older and colder than the shallower portions. The implication is that the aseismic region is too warm to generate earthquakes, having lost the critical minerals that could trigger a shearing instability, whereas the deeper portions of the slab are colder and still may contain metastable olivine (33).

There are several observations that, when compared with the data on Tonga, support the Kirby *et al.* hypothesis and suggest that the deep South America subduction zone may be similar to, although less active than, Tonga. The first of these is that the great Bolivia deep earthquake of 1994 remotely triggered a significant earthquake ($M = 6$) a few hundred kilometers away and in a region of essentially no previously recorded seismicity (34). Second, there are a few outboard earthquakes as many as 150 km east of the slab at the bottom of the seismic zone, under Argentina (see figure 3 of ref. 33). Neither of these observations proves the presence of metastable olivine but, given the recent Tonga results, both are consistent with the possibility. The presence of these outboard earthquakes invites a seismic investigation analogous to that of the Tonga investigations to test the possibility.

Conclusions

The potential implications of metastable olivine in subducting slabs go considerably beyond an explanation of deep earthquakes. Currently accepted thermal models of subduction zones, combined with laboratory measurement of rates of olivine breakdown reactions, suggest that metastable olivine should be possible only in the Tonga subduction zone (the coldest) and, even there, it should disappear before reaching the bottom of the seismogenic zone (22). Therefore, if metastable olivine is present in the fossil slab west of Tonga, then either current thermal models of deep slabs must be too warm or the kinetics of olivine breakdown must be slower than current experiments imply. The latter could be the result, for example, of small amounts of H_2O in the experiments leading to increased kinetics that may not be applicable in Earth.

Here, I have argued that intermediate-depth earthquakes require dehydration of hydrous phases, hence confirmation of metastable olivine in deep slabs would also require that slabs are wrung essentially dry before reaching 400 km, which would provide an explanation for the exponential decrease of earthquake frequency to extremely low levels between 300 and 400 km. Lastly, the presence of metastable olivine may be at least partially responsible for containment of subducted slabs of the western Pacific in the upper mantle (26).

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