common in light-exposed anaerobic habitats such as shallow-water sediments and stratified lakes (*9*, *10*).

About 20 years ago, a new group of photosynthetic bacteria—the aerobic anoxygenic photoheterotrophs (belonging to the α-group of proteobacteria)—was discovered. In contrast to other known anoxygenic phototrophs, these microbes are obligatory aerobes: They metabolize carbon and other organic substrates and use O_2-dependent respiration, but they also contain bacteriochlorophyll a, carotenoids, as well as photosynthetic reaction centers and light-harvesting complexes. Although the amount of bacteriochlorophyll in these photoheterotrophs is lower than in other photosynthetic bacteria, they are capable of fixing CO_2 during photosynthesis, and light enhances their growth. Their ancestors appear to be purple nonsulfur bacteria, and they have arisen independently several times during evolution. So far, they have not attracted much attention, although they are abundant in organic-rich sediments (on the surface of seaweeds) (*11*) and in seawater (*12*, *13*).

Kolber *et al.* (*8*) are the first to calculate the abundance of these microbes in the upper open ocean. They extracted and quantified bacteriochlorophyll a from seawater, and directly counted infrared fluorescent microorganisms. They identified strains of these aerobic anoxygenic photoheterotrophs from the Atlantic and Pacific oceans and found that they all belonged to the genus *Erythrobacter.* In the northeastern Pacific Ocean, these anoxygenic photoheterotrophs constitute about 11% of the total bacterial population in the upper 150 m of the water column (although this figure may be an underestimate, as nonliving bacterial "ghosts" may have been included in the total count of bacteria) (*14*). In this region of the Pacific, the ratio of bacteriochlorophyll a to chlorophyll a (the principal photosynthetic pigment of cyanobacteria and algae) is about 1%, but in more oligotrophic (nutrient-poor) areas this ratio increases to as much as 10% (the authors suggest a global mean ratio of 5 to 10%). The amount of CO_2 assimilated by these anoxygenic photoheterotrophs is likely to be far less than that assimilated by oxygenic photosynthetic bacteria, but their ability to produce energy from light provides them with a significant survival advantage. As long as they have light, these microbes do not have to depend on the metabolism of carbon or other organic substrates to generate energy.

The Kolber *et al.* work adds a new dimension to our current picture of the flow of carbon in the ocean. Our ability to predict the production of organic matter and to quantify the extent to which oceans act as sinks for atmospheric CO_2 depends crucially on our understanding of the marine microorganisms through which carbon flows. The new findings provide additional challenges for those attempting to model the flow of organic matter and energy through ocean water columns. Although Kolber *et al.* suggest that aerobic anoxygenic photoheterotrophs are especially important in oligotrophic regions of oceans, I would not be surprised if they prove to be key players in coastal waters as well.

Conventional wisdom dictates that the organisms in the ocean's water column consist principally of bacterial species that have not been described or cultured. With their new work, Kolber *et al.* flout convention by culturing and identifying a major constituent of the ocean's bacterial biota.

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PERSPECTIVES: PLATE TECTONICS

A Graveyard for Buoyant Slabs?

Harry W. Green II

For 20 years, there has been a lively debate over whether large-scale convection deep within Earth involves the whole mantle or is divided into two layers separated at the prominent seismic discontinuity at 660-km depth. Protagonists of layered convection—generally geochemists—base their arguments on differences in trace element, isotopic, and rare gas abundances between ocean-island and mid-ocean ridge volcanic rocks (*1*, *2*). Those favoring whole-mantle convection—generally geophysicists—cite success in modeling geophysical observables and seismic tomographic imaging (*3*).

Attempts to reconcile the two views have led to compromise models in which chemical inhomogeneities are maintained through incomplete stirring, either on a local scale (*4*, *5*) or because of temporary ponding of subducted material at the base of the upper mantle followed by avalanches of material into the lower mantle (*6*). Delayed penetration of the discontinuity in the latter class of models has been attributed primarily to differences in viscosity and to kinetic hindrance induced by the phase change believed to be responsible for the 660-km discontinuity. On page 2475 of this issue, Chen and Brudzinski (*7*) propose a different model in which large volumes of subducted material may be retained in the mantle transition zone, at depths of 400 to 700 km, because of buoyancy.

Previous workers have interpreted seismic evidence for cool, slablike bodies in the lower mantle as evidence that subducted lithosphere had penetrated the discontinuity. Chen and Brudzinski turn the argument around and ask why there is no seismic sign of a large and very strong temperature anomaly in the lower mantle beneath Tonga, the fastest and coldest subduction zone in the world. Subduction in the northern part of Tonga occurs at a rate of ~250 mm/year, sufficient to produce a slab extending to the base of the seismogenic zone (700 km) in just 3 million years—much too fast for thermal assimilation. Why, then, is there no evidence for a cool slab extending deep into the mantle?

The authors reason that the visibility of a slab can be reduced substantially if its mineralogy counteracts the tendency for colder slabs to have faster seismic velocities, thereby diminishing its contrast in seismic tomography. They then show that a very large slab remnant appears to be "floating" beneath Fiji (see the figure). They also provide an explanation of the "outboard" earthquakes that occur west of and above the lithospheric slab currently subducting beneath the Tonga arc.

The authors begin with the simple premise that the presence of earthquakes indicates cold temperatures (*8*) and hence would be expected to yield fast seismic velocities. They then show that in the region of "outboard" earthquakes, the seismic ve-

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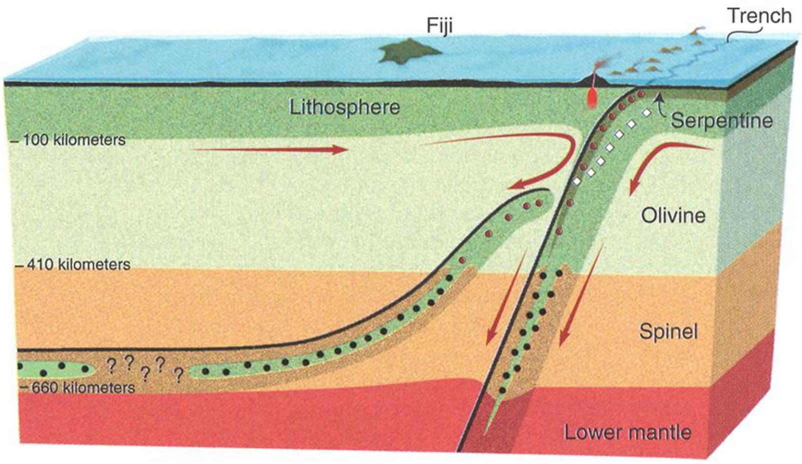
locities in the mantle transition zone (but not at shallower depths) are much slower than in immediately adjacent areas without earthquake activity. They argue that the much slower than expected seismic velocities observed within this body can have only two reasonable explanations: retention of substantial amounts of metastable olivine due to cold temperatures in the interior of the body or enhanced fluid content in the form of hydrous minerals or a free fluid phase.

Both of these possibilities suggest that the slab is neutrally buoyant (it has the same density as its surroundings) because of mineralogical differences between its interior and its surroundings. The authors propose that similar retention of subducted material in the transition zone over geological time could have reduced the mass flux between the upper and lower mantle substantially. This increases the probability that heterogeneities in the lower mantle have been maintained since early in Earth's history, thereby enabling the preservation of very old reservoirs as required by the geochemistry of volcanic rocks.



Schematic cross section below Fiji. The fossil subducted slab (subhorizontal feature on left) exhibits earthquake distributions similar to those in the currently active slab. Within the fossil slab, red dots represent intermediate-depth earthquakes in a region with normal slab seismic velocities; black dots represent transition-zone earthquakes in an interior zone of slow seismic velocities. White diamonds represent a lower zone of intermediate-depth earthquakes present in some subduction zones and attributed to dehydration in (*13*).

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Chen and Brudzinski conclude that the fossil slab originated in the fossil Vitiaz trench, which runs west-northwest from the current northern extreme of the Tonga subduction zone. Okal and Kirby (*9*) reached the same conclusion for a much smaller patch of very deep earthquakes centered near 14°S, 170°E (see the figure). Chen and Brudzinski think that this slab was formerly a part of the slab they have identified. Okal and Kirby had no seismic velocity data; they based their interpretation on the lack of evidence for a source of tectonic stresses that could be responsible for the earthquakes. They argued that the earthquakes are a result of faulting induced by the progressive transformation of olivine to ringwoodite in a tabular subduction remnant (*10–12*). This interpretation also fits the observations of Chen and Brudzinski, who have in addition found evidence of low seismic velocities, which are required for the presence of metastable olivine.

The second explanation for the slow seismic speeds, the presence of hydrous phases, fares less well. The crust and uppermost mantle are altered at oceanic spreading centers during formation of the lithosphere. Deeper hydration of lithosphere at oceanic trenches may occur along bending-induced great normal faults (*13*, *14*). It has been proposed that dehydration of such phases is the cause of deep earthquakes (*13*, *15*). However, for the slow velocities observed by Chen and Brudzinski to be attributed to hydrous phases in the transition zone, such phases would have to be incorporated earlier into the slab and carried down to great depth. One would therefore expect a similar reduction of seismic wave speeds at all levels in the fossil slab. This is not observed. The presence of a pervasive fluid phase is highly unlikely; the densities of hydrous fluids are much lower than those of transition-zone minerals, and any fluid phase generated would be expected to escape upward, just as it does from dehydration of slabs at shallower depths (*16*, *17*).

These arguments indicate that Chen and Brudzinski have produced the strongest evidence to date for the presence of metastable olivine in subducted lithosphere. Additional careful seismic studies of this and other regions should be conducted to verify whether cold slabs exhibit slow internal velocities in the transition zone but not at shallower depth.

Previous interpretations of this region will have to be revisited in the light of these results. One particularly relevant paper (*18*) investigates the depth and continuity of the 410- and 660-km seismic discontinuities along a cross section where Chen and Brudzinski now argue for two different slabs. The complexities implicit in the fossil slab model have implications for the interpretations of the seismic discontinuities and vice versa. It will be interesting to see if the new model simplifies or makes more complex this and other previous interpretations of this most seismically active region of Earth's mantle.

The present work suggests a new method for sequestering subducted material in the transition zone, but it is not clear to this reader how much it resolves the original question: Where is the material that has been subducted down the Tonga subduction zone? The seismogenic zone in the currently active slab ends at the base of the transition zone (the maximum limit of earthquake activity worldwide). Tomographic images (*19*) do not record a clear signal for direct penetration into the lower mantle, and residual sphere analysis (*20*) indicates continuation only to a maximum of 900 km. If the fossil slab represents the Vitiaz trench, where is the material from the Tonga trench?

Is it possible that the fossil slab is instead a severed remnant of the Tonga slab that has buoyantly risen in the transition zone and is now slowly settling again as it warms up and continues to transform to the stable mineral assemblage? The severing process remains enigmatic but this interpretation offers a simpler explanation for the fact that in its shallowest regions the fossil slab appears to be draped over the Tonga slab.

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