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Commentary on JGR-Sold Earth Paper "Deep Seismic Structure Across the Southernmost Mariana Trench: Implications for Arc Rifting and Plate Hydration" by Wan et al.

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Among Earth's physical features, the Challenger Deep is especially aptly named. As the deepest place on Earth's solid surface, it continues to challenge our understanding as it challenges us to descend and touch the bottom. The latter was the challenge that the U.S. Navy team of Auguste Picard and Don Walsh responded to on 23 January 1960 when they descended in the bathyscaphe TRIESTE to the bottom of the Challenger Deep 10,916 m below sea level, the one that Canadian film director James Cameron responded to in March 2012, and the one that Dallas businessman Victor Vescovo responded to in April 2019 when they also went down to the bottom of this trench. Their efforts are testaments to human determination, ingenuity, will, and resources. But "touching bottom" is not the only challenge that the Challenger Deep presents us: It also challenges us to understand it—what caused it, what the rocks on either flank are made of, what, if anything, is different about the seawater that fills it, what kinds of sediments rest on the seafloor, and what kind of life is found there. Solving the "Challenger Deep Puzzle" requires exploring not only the deepest points but also the hyper-deep-sea environment for hundreds of kilometers around it.

Exploring oceanic trenches like the Challenger Deep is an endeavor fit for the 21st century. In fact, there are two challenges involved. First, there is the technological challenge due to the extreme pressures that machines and sensors must survive. Every 10 m of seawater adds about 1 atmosphere of pressure, so the pressure at the bottom of the 11-km-deep Challenger Deep is more than a thousand atmospheres. Picard and Walsh in 1960 learned firsthand about the pressure challenge when one of the TRIESTE's plexiglass windows cracked as they descended below 9,000 m. Manned submersibles cannot operate deeper than 6.5 km (the U.S. ALVIN and Japan's SHINKAI) although China's JIALONG can go down to 7.5 km (although the submersibles built by Cameron and Vescovo call this conclusion into question). A few remotely operated vehicles can operate still deeper, down to the bottom of the Challenger Deep. In 1995, Japan's KAIKO became the first Remotely Operated Vehicle (ROV) to reach the bottom of the Challenger Deep, followed in 2008 by the Japanese autonomous undersea vehicle (AUV) ABISMO, and in 2009 by U.S. AUV NEREUS. The difficulty and risk involved in working at these depths and pressures was demonstrated by the loss of the NEREUS in 2014 working 9,900 m deep in the Kermadec Trench. Such deep diving by manned submersible, ROV, or AUV is not yet routine, as it must become if we are to use such tools to systematically study deep-sea trenches.

The second challenge is scientific, focused on what causes this great gash and what do the rocks, fluids, and life in it tell us about our planet? We geoscientists want to examine the crust and upper mantle exposed on the overriding plate as well as the crust of the downgoing plate. Our exploration of this region has only begun, but already we have been surprised, for example, by discovering evidence of young basaltic volcanism in the inner trench wall (Ribeiro et al., 2013), that the overriding plate is tearing itself apart by extension (Martinez et al., 2018), and by stumbling on a unique system of seafloor vents and associated ecosystem 5,800 m deep on the overriding plate (Okumura et al., 2016). We have not even started to study the downgoing plate!

Regardless of the costs and risks involved, it is clear that the international scientific community wants to keep working on the Challenger Deep puzzle. The new paper by Wan et al. (2019) adds some important new puzzle pieces. In 2016, an international scientific team (from South China Sea Institute of Oceanology, Woods Hole Oceanographic Institution, and the Chinese University of Hong Kong) conducted the first wide-angle reflection/refraction study of the crust and upper mantle beneath the Challenger Deep and the flanking overriding Philippine Sea and subducting Pacific plates. They deployed 18 ocean-bottom

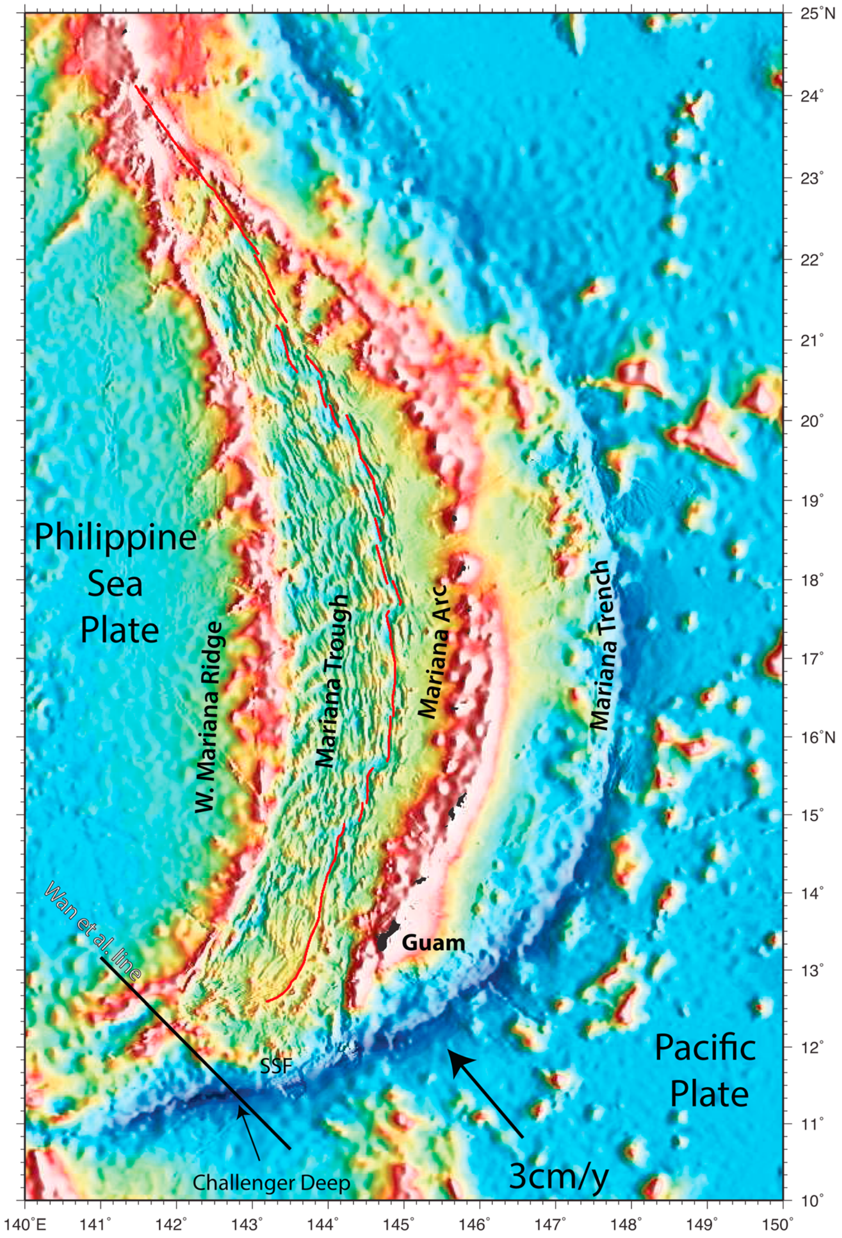

Figure 1. Bathymetric map of the Mariana arc system showing its principal features and location of the seismic profile of Wan et al. (2019). Location of Challenger Deep and Shinkai Seep Field are also shown.

seismometers (OBSs) to the seafloor every 15 km along a 349-km line, specially building some of the OBSs to operate as deep as 9 km (Figure 1). The team used air guns towed by the R/V Shiyan 3 as a seismic source, and the OBS's recorded the *P* waves that arrived. The team discovered that the subducting Pacific plate has a normal oceanic crustal thickness of about 6 km and that the crust beneath the upper inner trench slope was thicker, about 12 km thick, thickening to about 18 km beneath the forearc. Wan et al. found thinner crust beneath a poorly known feature called the SW Mariana Forearc Rift, 12–14 km thick, suggesting that this is a zone of strong extension (Figure 2a). They also found that the crust beneath the West Mariana Ridge was 9–12 km thick, significantly thinner than previously measured for this feature farther north.

These measurements of crustal structure by Wan et al. provided valuable new information, but even more tantalizing was their discovery of two regions of unusually slow seismic velocity: a large region centered on the Challenger Deep and a smaller region beneath the SW Mariana Rift (Figure 2b). These two slow zones have different causes: the one beneath the rift is probably due to the presence of rift-related partial melt, but

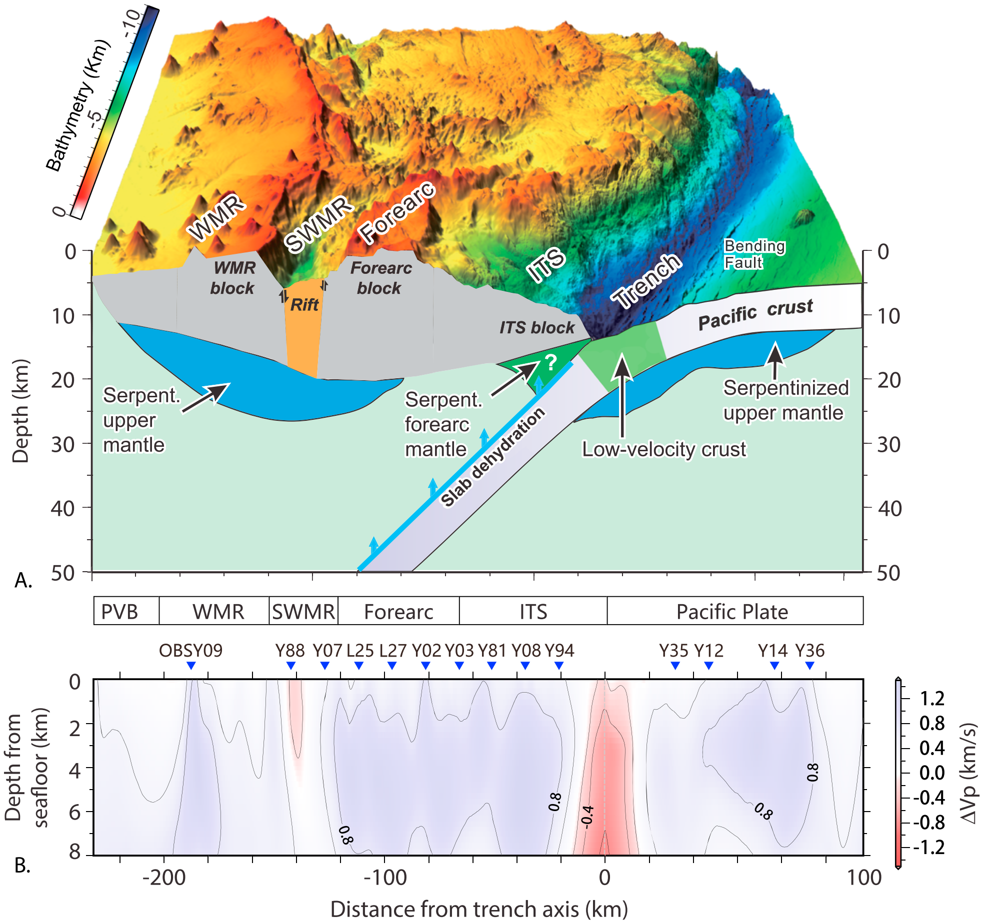

Figure 2. Results of study by Wan et al. (2019). (a) Cut-away perspective along seismic profile of Wan et al. (2019). WMR = West Mariana Ridge (remnant arc); SWMR = Southwest Mariana Forearc Rift; ITS = Inner Trench Slope; Serpent. = serpentinized. Note that locations of earthquakes shown in original figure have been removed because these were from the global catalog, with relatively poor locations (J. Lin, personal communication, April 12, 2019). Position of slab is approximate/uncertain. (b) Cross section showing velocity perturbation in the top 10 km of the velocity model after subtracting the average 1-D velocity at each depth.

the one centered on the Challenger Deep has much larger reduction in velocity and probably reflects the weakening effects of water. Massive amounts of seawater seep into the subducting Pacific plate where it must break as it bends to start descending into the subduction zone (Bending Fault; Figure 2a). There are swarms of these faults where the seafloor stair steps down the outer trench slope. These faults allow seawater to infiltrate to unknown depths, but almost certainly into the upper mantle. Wan et al. show that beneath the Challenger Deep slow zone, seismic velocities get relatively slower down to 10 km beneath the seafloor, presumably reflecting the presence of hydrated or serpentinized mantle. Similar slow zones have been documented at other convergent plate margins (e.g., Grevemeyer et al., 2018).

The presence of all this fluid moving into the subducting plate has great implications for our understanding of subduction zones, for example, how much water is carried deep into the mantle in subduction zones. A recent study (Cai et al., 2018) concluded that existing estimates of the global water flux deeper than 100 km should be increased threefold; this much extra water must be delivered by a much larger volume of subducted serpentinized mantle (such as that beneath the Challenger Deep) than heretofore appreciated. The tremendous amounts of water moving along faults of the outer trench slope has another important implication: Because fluids circulate up as well as down along faults, there is likely to be a new kind of seafloor hydrothermal vents built on some of these faults. These vents have not yet been discovered, but perhaps sometime in the 21st century they will be?

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