Geoscientific Investigations of the Southern Mariana Trench and the Challenger Deep

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Challenger Deep

• Deepest point on Earth’s solid surface: ~10,900 m (~35,800’)
• Captures public imagination: ~1.5 million hits on Google
• Lower scientific impact – top publication has 210 citations.
• Why the disconnect?
Challenger Expedition (1872~1875)

H.M.S. Challenger sampled the ocean across the globe heralding the beginning of oceanography as a science discipline.

Route of Challenger
On March 23, 1875, at station 225 between Guam and Palau, the crew recorded a sounding of 4,475 fathoms, (8,184 meters) deep.

Modern soundings of 10,994 meters have since been found near the site of the Challenger’s original sounding.

Challenger’s discovery of the deepest spot on Earth was a key finding of the expedition and now bears the vessel's name, the Challenger Deep.
Mean depth of global ocean is 3,682 m
Talk outline

1. Subduction zone animation
2. Mariana arc system
3. A few words about Trenches
4. Methods of study
5. What we are doing and what we have found?
6. The future
The Mariana Arc is in the Western Pacific, halfway between Japan and Australia.

The Mariana Trench marks where the Pacific Plate subducts beneath the Philippine Sea Plate.
Mariana islands are part of USA.
Guam = US Territory, rest of Marianas is US Commonwealth

 Territory of Guam population = 162,000
Northern Mariana Commonwealth population = 53,000
January 6, 2009, President George W. Bush created the *Mariana Trench Marine National Monument*

3 components:

1. (Yellow box): The waters and submerged lands encompassing the coral reef ecosystem of the three northernmost Mariana Islands.

2. (Red outline): The Mariana Trench, approximately 940 nautical miles long and 38 nautical miles wide.

3. (stars) Active undersea volcanoes and thermal vents in the Mariana volcanic arc and backarc.
4 components of a convergent plate boundary:

1. Back-arc basin
   Spreading axis
2. Magmatic arc
   Magmatic front
3. Forearc basin
   Accretionary prism
4. Trench
   Outer trench high

Note relationship between trench and underlying subduction zone.
Florida and Marianas at same scale
Principal Crustal features of the Mariana Convergent Margin

The Mariana Convergent Margin
Well-behaved except in the south

Thanks to Dan Scheirer
Let’s look at the interesting tectonics of the S Mariana Trough – Challenger Deep region

Note: Mariana Trench and Mariana Trough are different!
Mariana Trough is an active backarc basin that formed by rifting the arc followed by seafloor spreading.

Martinez et al. 1995
Southern Marianas formed by seafloor spreading to open the Mariana Trough over the past 5 million years.

Note complex tectonics in far south.
Crustal (<30 Km deep) Earthquakes

Note concentration of seismicity in the south. This region is deforming rapidly!

Thanks to Dan Scheirer
Let’s talk about trenches....
Trenches define convergent plate boundaries, where one plate subducts beneath another.

VE $\sim 4x$
Trenches near continents can be filled with sediments (like Cascadia).
Western Pacific trenches subduct older and deeper seafloor than Eastern Pacific trenches.
Two major controls on trench depth:
1) Age of subducted lithosphere (older = deeper)
2) Sediment flux (sediments fill trench)

Mariana Trench and Challenger Deep have very small sediment flux.

Great depth of Challenger Deep suggests very old seafloor is subducted.
We do not know age of seafloor subducted beneath southernmost Marianas!
The Key to Understanding the Challenger Deep and Tectonics of the Southernmost Marianas: 
*The subducting slab is narrow, shallow and able to rollback rapidly...*

...this results in strong extension on the overriding plate.
A short slab (~200 km deep) west of a N-S slab tear allows rapid rollback.

Fryer et al. 2001
WEAK COUPLING BETWEEN SUBDUCTING AND OVERRIDING PLATES
Normally, the overriding plate is coupled to the downgoing slab across a broad zone....
...as is the case in most of the Central Marianas...
...but the coupling zone in the Challenger Deep segment is unusually narrow.

Weak coupling between narrow, short slab and overriding plate is reflected in remarkable depth of trench and forearc ridge uplift.

Gvirtzman & Stern 2004
Let’s go Deep

On 23 January 1960, Trieste reached the ocean floor in the Challenger Deep (the deepest southern part of the Mariana Trench), carrying Jacques Piccard and Don Walsh.

The descent to the ocean floor took 4 hours 47 minutes. After passing 9,000 m (30,000 ft) one of the outer Plexiglas window panes cracked, shaking the entire vessel. The two men spent twenty minutes on the ocean floor.
Jan. 23, 1960: the Trieste reached the bottom of the Challenger Deep after a 5-h descent. The bathyscaphe remained on the bottom for 20 min before ascending back to the surface. Don Walsh recounted: “As we landed, a cloud of sediment was stirred. This happened with all of our dives and usually after a few minutes it would drift away. Not this time. The cloud remained for the entire time on the bottom and showed no signs of moving away. It was like looking in a bowl of milk”.

What is this white sediment??
March 26 2012: manned solo descent was made by James Cameron using the deep-submergence vehicle Deepsea Challenger.

Unfortunately, no samples returned.
Dawn of the 21st Century witnessed a “Technologic Trifecta” in Mapping the Seafloor

Result: Modern marine geoscientists now have tools that let them do field geology on the seafloor. *We are in the throes of a modern revolution in seafloor geosciences, and it is the new generation of marine geoscientists that stand to benefit most.*
What is a “Trifecta”?

In horse racing, picking the horses that come in first, second and third. Pays off very well.
The 21st Century Technological Trifecta
Opens the Door for Marine Field Geology

ROVs and manned submersibles!
Recent scientific work concentrates on geology of upper trench slope above the Challenger Deep.

Working at water depths = 3.5 – 6.5 km is expensive and difficult. Working in deeper water is almost impossible!
R/V Yokosuka
~100m long
Shinkai 6500

Japanese manned submersible can reach 6500m = 3.6 miles
Pressure is problem. Each 10m = 1 atm. 11,000 m = 1100 atmospheres

Fun with Styrofoam cups

6” tall going down 2” tall coming back up
On June 27, 2012, the *Jiaolong* with two oceanauts reached a depth of 7,062 metres (23,169 feet) in the Mariana Trench. What did they find?
The *Nereus* hybrid remotely operated vehicle (HROV) is designed to operate down to depths of 11,000m.

The Nereus HROV operates while tethered to the ship or swimming freely. It can carry a 25 kg payload for collecting core, rock, biological and water samples, measure temperature and take still and video images.
On May 10, 2014, *Nereus* was lost at 9,990 meters (6.2 miles) deep in the Kermadec Trench northeast of New Zealand. Surface debris was found, suggesting the vessel suffered a catastrophic implosion as a result of the immense pressures where it was working.

RIP Nereus
JAMSTEC Kaiko ROV

Able to dive to 11 km
Operational soon!
R/V KAIMEI.

Crustal seismic imaging system, core sampling using drilling equipment installed on the seabed, simultaneous use of multiple autonomous underwater vehicles, and detailed survey using acoustic devices.

Length overall Approx. 100 meters
Beam 19.0 meters
Gross tonnage Approx. 5,800 tons
Sea speed 12.0 knots
Cruising distance 9,000 nautical miles
Accommodation 65 (27 crew members, 38 researchers)
US-Japan studies of Challenger Deep segment of Mariana Trench

2006 - 2015

2 Camera Deep Tows

2015: 3 Shinkai dives

2015

1 Shinkai Dive

Parece Vela Basin

Mariana Trough

Guam

CD = Challenger Deep

SS = Shinkai Seep

Dallas - Houston 385 kilometers

900 kilometers

2006 - 2015
Note: Everything in dark blue is deeper than 4500m. Mean depth of ocean is 3700 m

Q: What geology is it useful to study at these depths?
A: The crust and upper mantle are exposed and can be studied in place!
We have \(~5\text{km}\) section of upper mantle exposed in the Mariana Trench available for study. We can use Shinkai to study the upper 1 km. How to study the rest?
Mariana Trench peridotites (photomicrographs)

Thanks to Yas Ohara
Electron backscatter image of chromite

Formula: \((\text{Mg,Fe})(\text{Al,Cr})_2\text{O}_4\). With progressive melting, residual spinel becomes increasingly Cr-rich. Cr/Al ratio of spinels increase with melting.
Challenger Deep Segment Peridotite Spinels

Peridotite spinel compositions range from very fertile to depleted (Cr# ~0.2 to ~0.8).
Strong extension inhibits formation of magmatic arc

Strong extension captures and disrupts arc magma budget, prohibits localization of magma flux and growth of large arc volcanoes.

BABB-like REE patterns replace LREE-enriched patterns of mature arc (Tracey Smt.)
Volcanic arc disrupted by strong extension south of 14°N

Stern et al. 2013
Fina Nagu Volcanic Chain and Malano-Gadao Spreading Ridge

Fina Nagu reflects “smearing out” of magmatic arc axis by S Mariana trough extension.
SE Mariana Forearc rift: more evidence of strong extension

MORB-like basalts 2.7-3.7 Ma

Contain ~2% magmatic water (Ribeiro et al., 2014)
Young Forearc basalt volcaniclastics

MORB-like basalts with ~2% water

Is there volcanism in the trench?
Discovery of Shinkai Seep Field

6K-1234 dive
Sep. 23, 2010
2010 surprise! Life on inner trench wall (5600m)

clams  Calyptogena
Brucite and Carbonate Chimneys

Shinkai Seep
Sunlight penetrates only a few hundred meters deep into the ocean.

No photosynthesis possible below a few hundred meters water depth.

Concentrated life requires a reliable energy source like sunlight

How is life possible at 5600m deep in the ocean?

Deep sea communities are based on chemosynthesis.

Energy for life comes from oxidation-reduction reactions of compounds released by deep sea vents.
Interaction of fluids with mantle minerals forms serpentine (serpen tinization).

Formation of serpentineite happens beneath slow-spreading mid-ocean ridges and at convergent plate boundaries. Serpentinization causes ~30% volume increase and releases heat. It also oxidizes Fe+2 to Fe+3, which generates free Hydrogen.
Serpentinized mantle peridotite with white veins in Mariana Trench. White veins are fossil fluid channels

Dive 1366
Polished veined serpentinite slabs

Fluids flow through fractures; fracture surfaces are where chemical reactions occur.
Biology of the Shinkai Seep Field

- Shinkai 6500 dive 1234

Discovered biological community ~6 km deep, on the inner trench wall in 2010

Ohara et al. (2012)
Vesicomyid clam: typical chemosynthetic animal

- Symbiotic sulfide-oxidizing bacteria
- H$_2$S as the food source, mainly via Anaerobic methanotrophy (AOM) by bacteria of methane seep

First report from the Marianas & low-T serpentinite-hosted system
- A new species akin to that from the Logatchev Field on Mid-Atlantic Ridge

SSF: Calyptogena mariana

Krylova and Sahling (2010)

Thanks to Yas Ohara
Calyptogena Dive 1365
Dive 1362: Dead *Calyptogena*, gastropods, anemone
All life requires an energy source on which to build a food chain. What is the energy source for the Shinkai Seep community?
Hydrocarbons from the Mantle

1. Fe olivine + water = magnetite + quartz + Hydrogen
   \[3Fe_2SiO_4 + 2H_2O = 2Fe_3O_4 + 3SiO_2 + 2H_2\]

 then

2. Hydrogen + carbon dioxide = oxygen + methane
   \[4H_2 + CO_2 = 2O_2 + 2CH_4\]

Fischer-Tropsch reaction; Methane generated supports life around Shinkai Seep
Anaerobic methanotrophy (AOM) occurs where upflowing methane and seawater sulfate mix. In this mixing zone, Anaerobic methanotrophic Euryarchaeota (ANME) and sulfate-reducing bacteria (SRB) are the dominant microorganisms. At the surface above the AOM zone, chemosynthetic bacteria in *Calyptogena* depend on hydrogen sulfide produced by AOM. There are also aerobic methanotrophs independent of AOM and mussels harboring aerobic methanotrophs in their gill cells (Miyazaki 2009).
Dive 1365

White chimneys mark vent sites
Dive 1366
4-5 m tall
‘Weird Animal’
extinct chimney

Broken surface exposes massive brucite
Dive 1365 sections through barite chimney
Brucite (Mg(OH)₂)

Formation of brucite requires highly alkaline fluids containing abundant Mg²⁺ but little SiO₂ or CO₂. Most brucite forms in association with serpentinization of magnesium-rich rocks, such as mantle peridotite.
Brucite Chimney slice

Minor Aragonite, Barite
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Publication Opportunity

Subduction Top to Bottom 2

– A thorough look at the subduction process, including related hazards and resources
– Arranged by depth, not methods or approach
– Goal of providing state of knowledge, encouraging papers with a multidisciplinary spin
– All-electronic (in Geosphere), underway in late 2015, accepting manuscripts during 2016

Editors: Gray Bebout, Dave Scholl, Bob Stern, Laura Wallace, and Philippe Agard
Stay tuned for new discoveries!
Thanks for your attention! Stay tuned for new discoveries!
Southern Mariana Arc
Dashed box = Area surveyed with sonar backscatter
HMR1 Sonar backscatter
SW Rift Zone: 150 km-long zone of strong extension

T53A-4651 Ohara et al. The first Shinkai dive study of the southwestern Mariana arc system
How to study the trench wall deeper than 6500m?