Relation Between Volcanism, Tectonism, and Hydrothermal Activity Along the Mid-Ocean Ridges*

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Abstract

Just over 30 years ago, scientists exploring the global mid-ocean ridge system made the spectacular discovery of black smokers—hydrothermal chimneys made of metal sulfide minerals that vigorously discharge hot, particulate-laden fluids into the ocean. These chimneys are the surface manifestation of convection of seawater through the oceanic crust and water-rock reactions that produce hot, hydrothermal fluids that discharge at the seafloor. This hydrothermal circulation process plays an important role in regulating the chemistry of seawater, building mineral deposits, and supporting chemosynthetically based ecosystems.

Early studies focused on hydrothermal systems on the fast-spreading East Pacific Rise, where shallow magma lenses beneath the ridge crest provide heat to drive convection of seawater through the oceanic crust. Ten years later, studies of the slow-spreading Mid-Atlantic Ridge revealed much larger mineral deposits – a surprising result given the lower magma delivery rate and heat availability.

Through the use of different deep-submergence technologies, this presentation explores the characteristics of vents and their associated communities along the mid-ocean ridge, and the varying relations between volcanic and tectonic processes at sites on ridges of different spreading rates. It will focus in particular on how one active hydrothermal system has constructed a large mineral deposit on the Mid-Atlantic Ridge and how recent experiments at that site have shed light on the role tectonics and faulting play in the evolution of long-lived hydrothermal systems.

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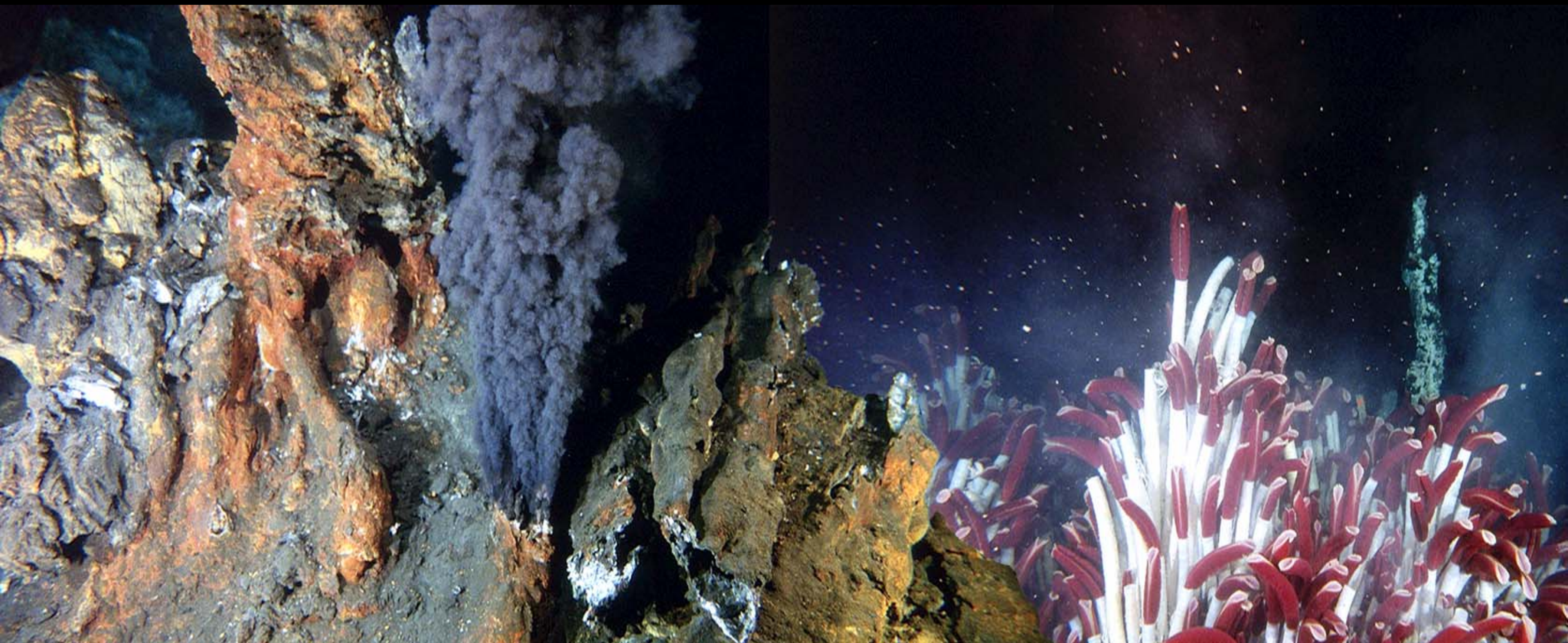
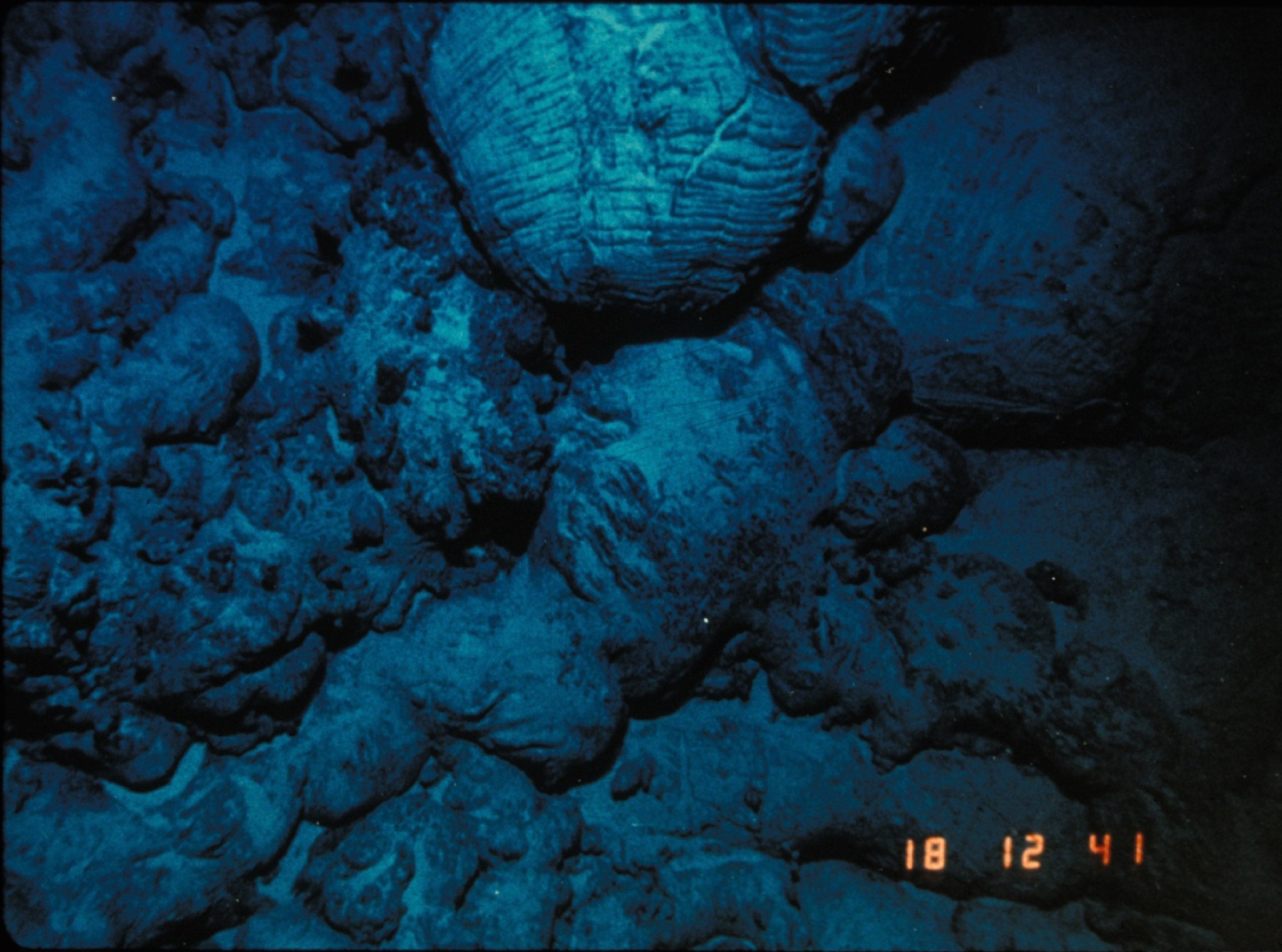
Relation Between Volcanism, Tectonism, & Hydrothermal Activity Along Mid-Ocean Ridges



Susan E. Humphris
Woods Hole Oceanographic Institution

AAPG Distinguished Lecture Series 2008-2009


WORLD OCEAN FLOOR
BY BRUCE C. HEEZEN AND MARIE THARP
Based on Research and Exploration Initiated and Supported by the
UNITED STATES NAVY OFFICE OF NAVAL RESEARCH
1977
GREENLAND
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
AUSTRALIA
ANTARCTICA
ANTARCTICA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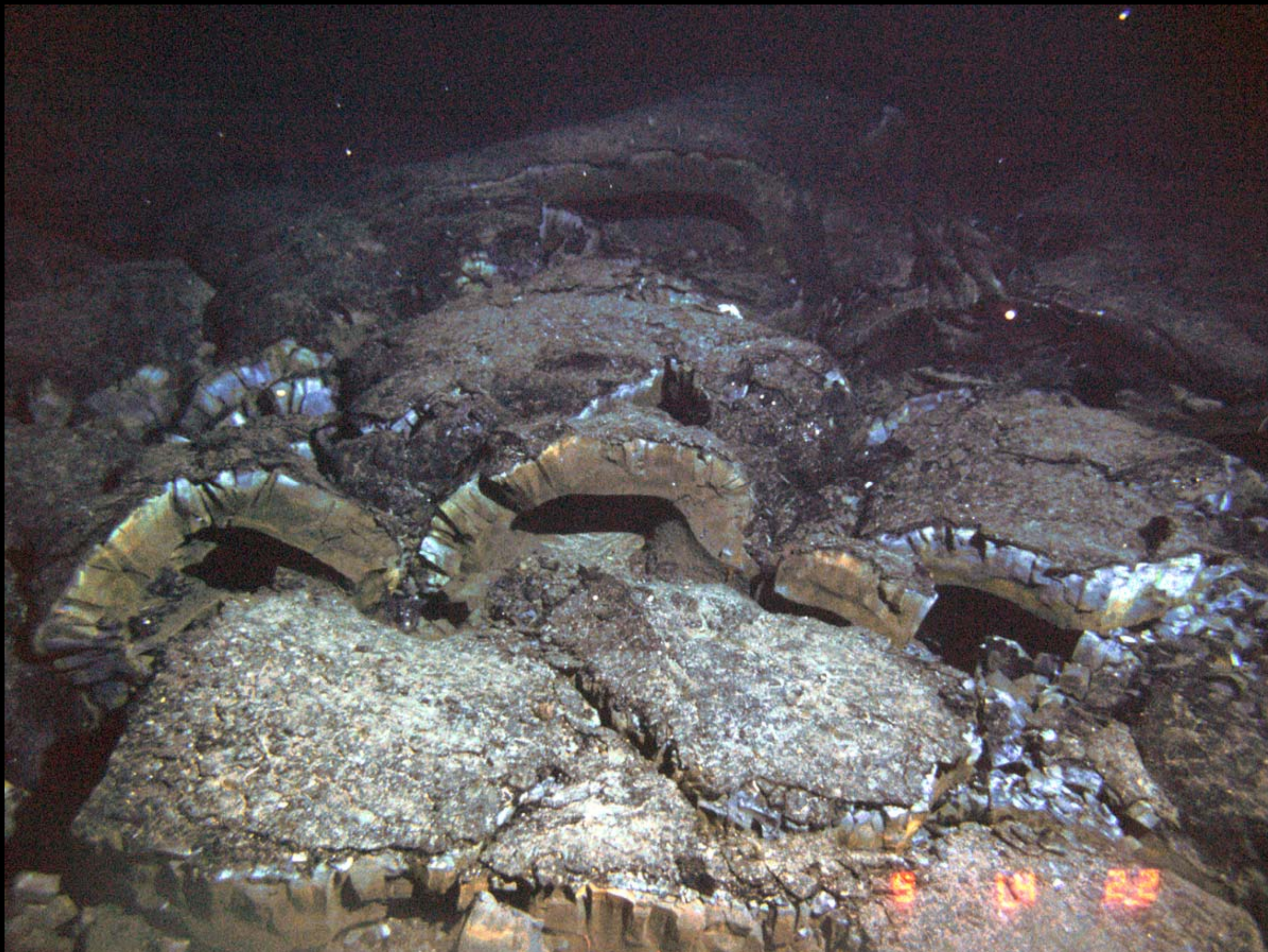
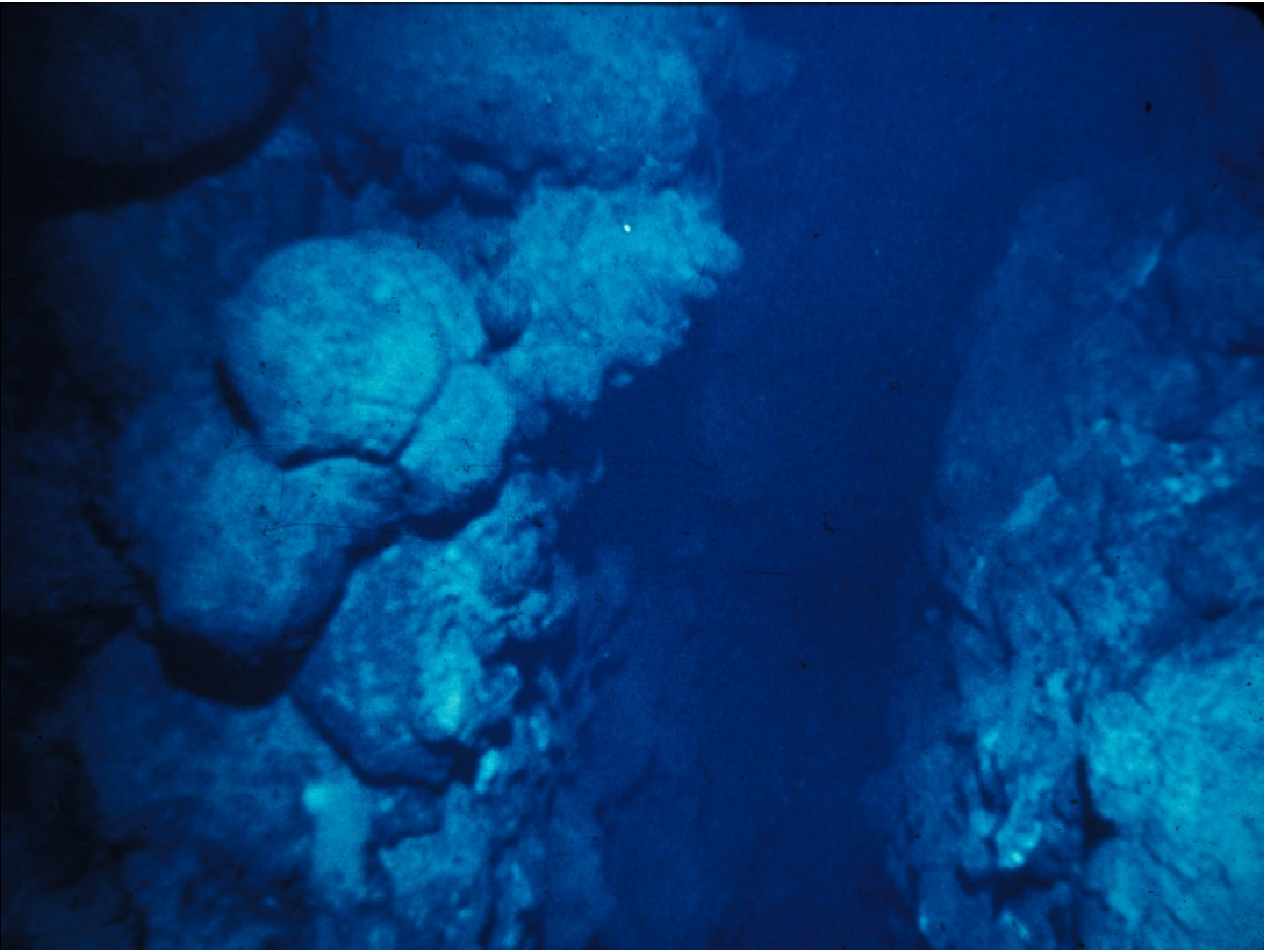
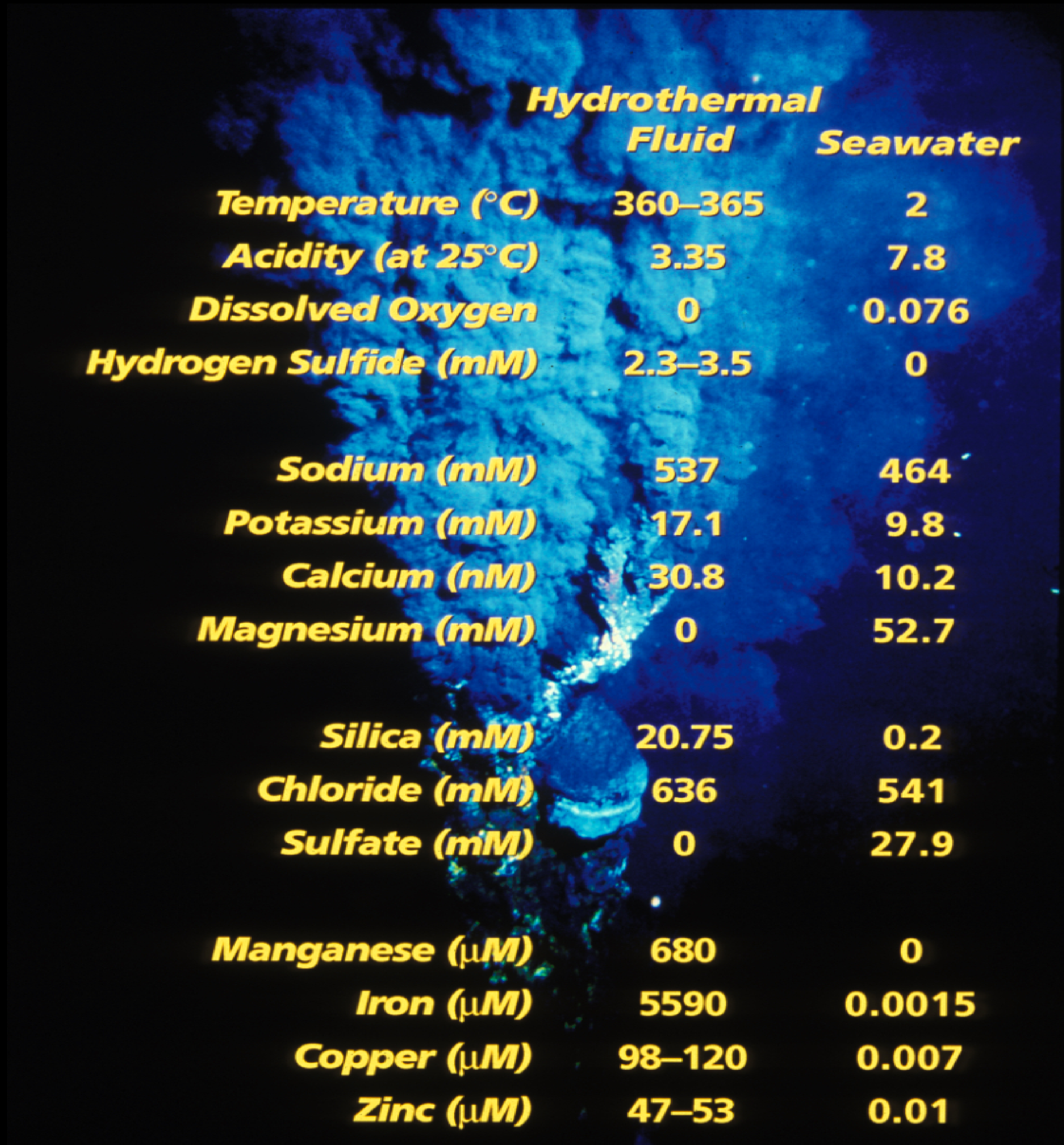
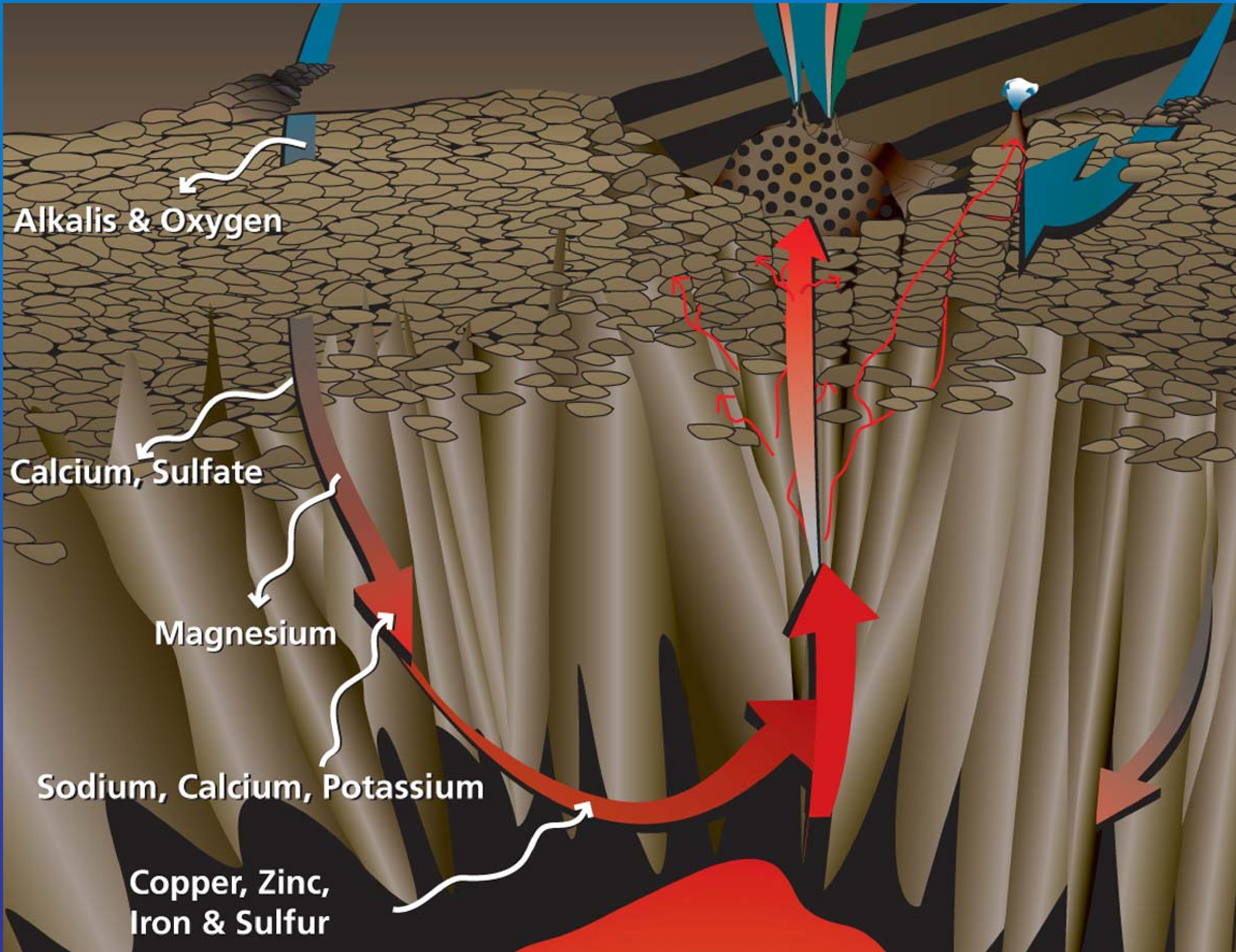




What is a Hydrothermal Vent?



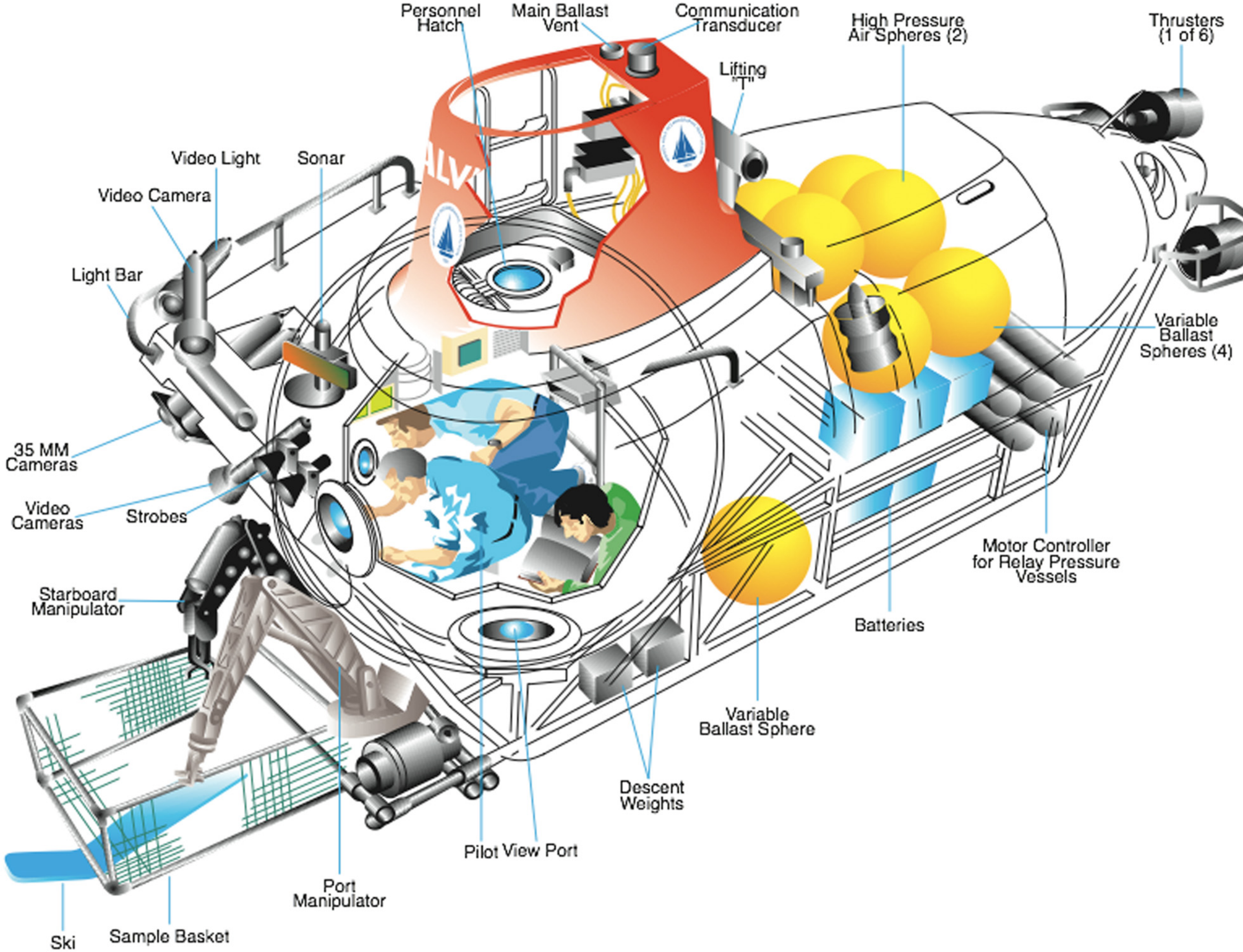
	Hydrothermal Fluid	Seawater
Temperature (°C)	360–365	2
Acidity (at 25°C)	3.35	7.8
Dissolved Oxygen	0	0.076
Hydrogen Sulfide (mM)	2.3–3.5	0
Sodium (mM)	537	464
Potassium (mM)	17.1	9.8
Calcium (nM)	30.8	10.2
Magnesium (mM)	0	52.7
Silica (mM)	20.75	0.2
Chloride (mM)	636	541
Sulfate (mM)	0	27.9
Manganese (μM)	680	0
Iron (μM)	5590	0.0015
Copper (μM)	98–120	0.007
Zinc (μM)	47–53	0.01


Alkalis & Oxygen
Calcium, Sulfate
Magnesium
Sodium, Calcium, Potassium
Copper, Zinc,
Iron & Sulfur

What is the Relation between Hydrothermal Activity and Volcanic-Tectonic Relations on MOR?

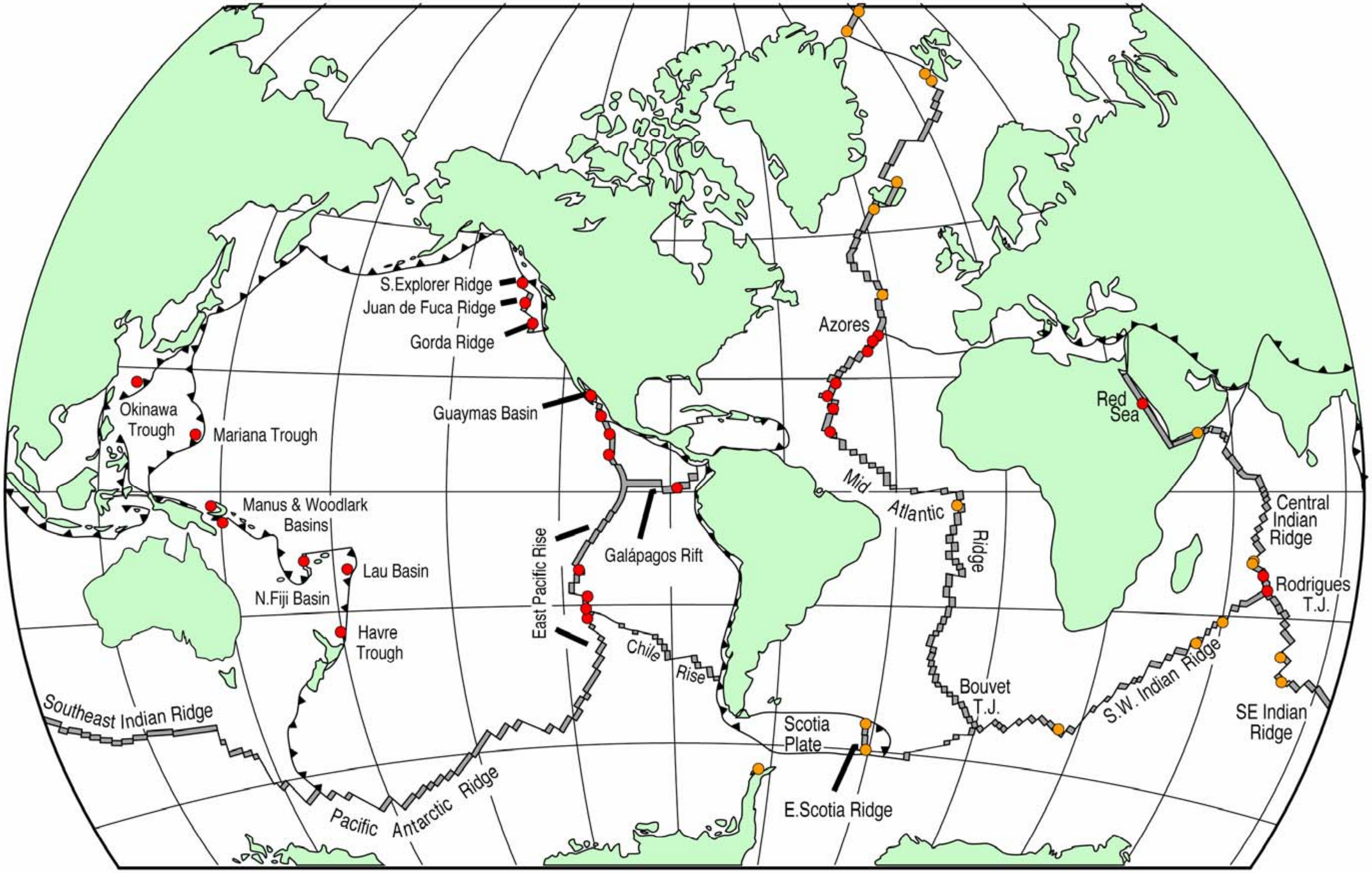
- Volcanism and tectonism on the fast-spreading EPR
- The TAG active mound on the slow-spreading MAR
- Seismicity and fluid flow at TAG (STAG) experiment
- Implications for volcanic-tectonic relations and hydrothermal flow on slow spreading ridges


ATLANTIS



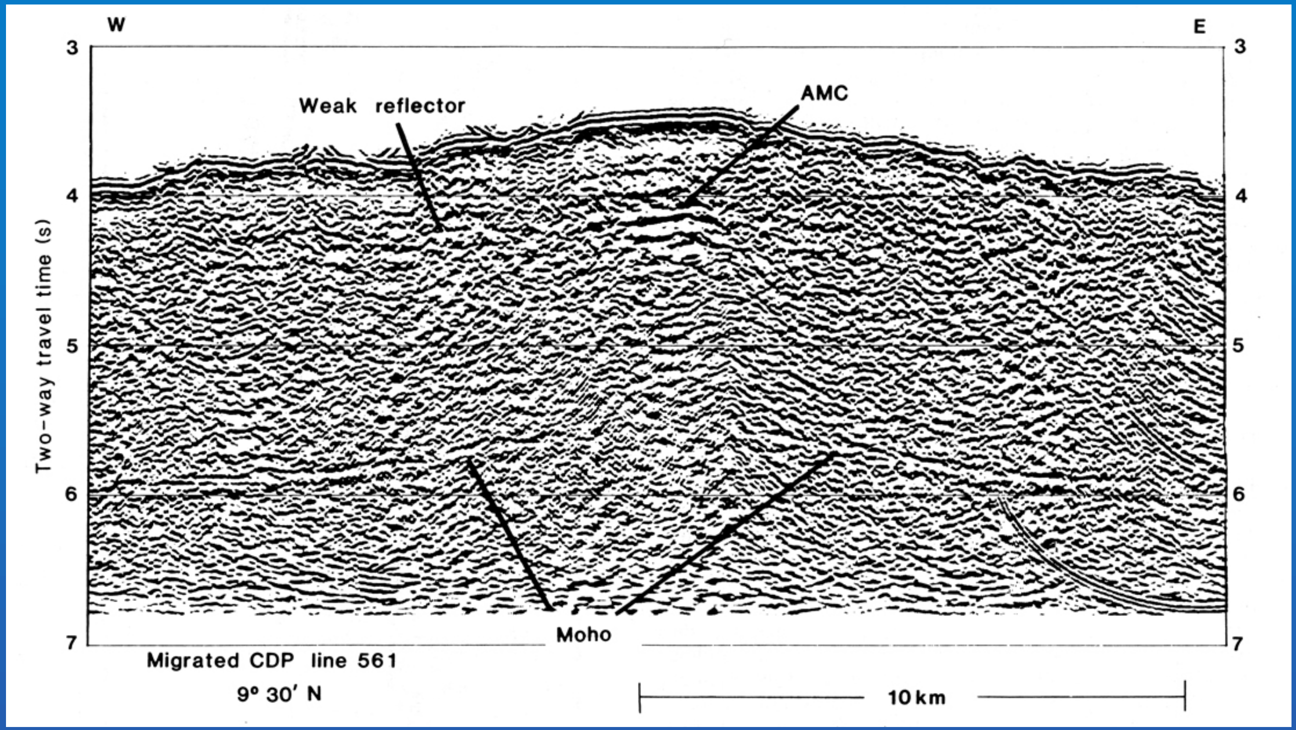
Personnel Hatch
Main Ballast Vent
Communication Transducer
High Pressure Air Spheres (2)
Thrusters (1 of 6)
Lifting "T"
Video Light
Sonar
Video Camera
Light Bar
Variable Ballast Spheres (4)
35 MM Cameras
Video Cameras
Strobes
Motor Controller for Relay Pressure Vessels
Starboard Manipulator
Batteries
Variable Ballast Sphere
Descent Weights
Pilot View Port
Port Manipulator
Ski
Sample Basket

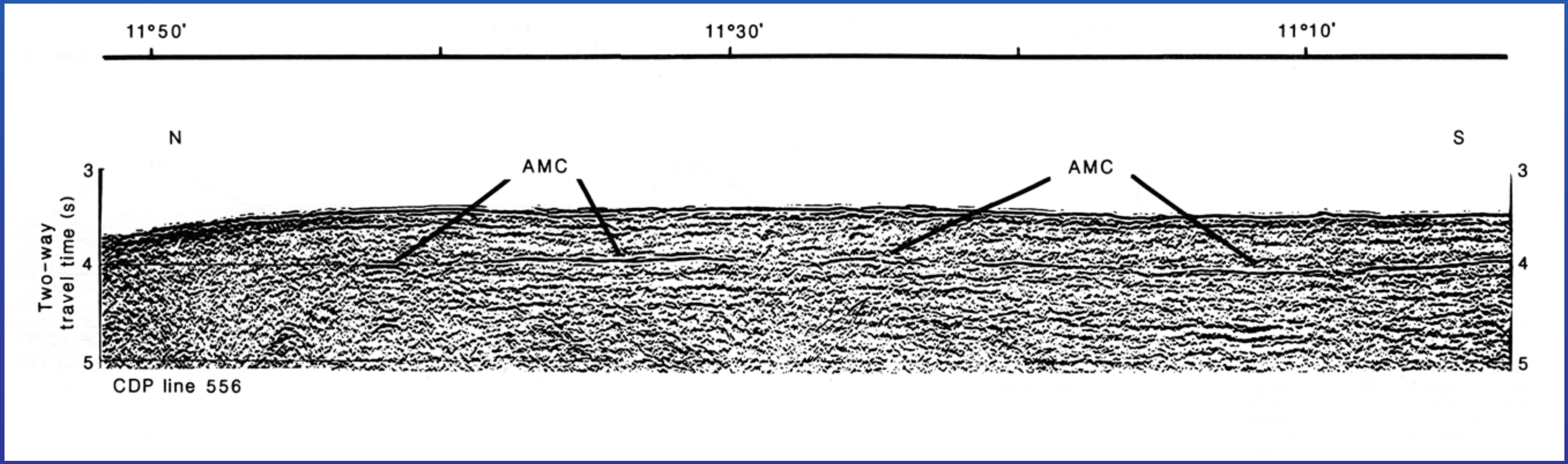
Autonomous Underwater Vehicle



Locations of known hydrothermal activity along the global mid-ocean ridge system

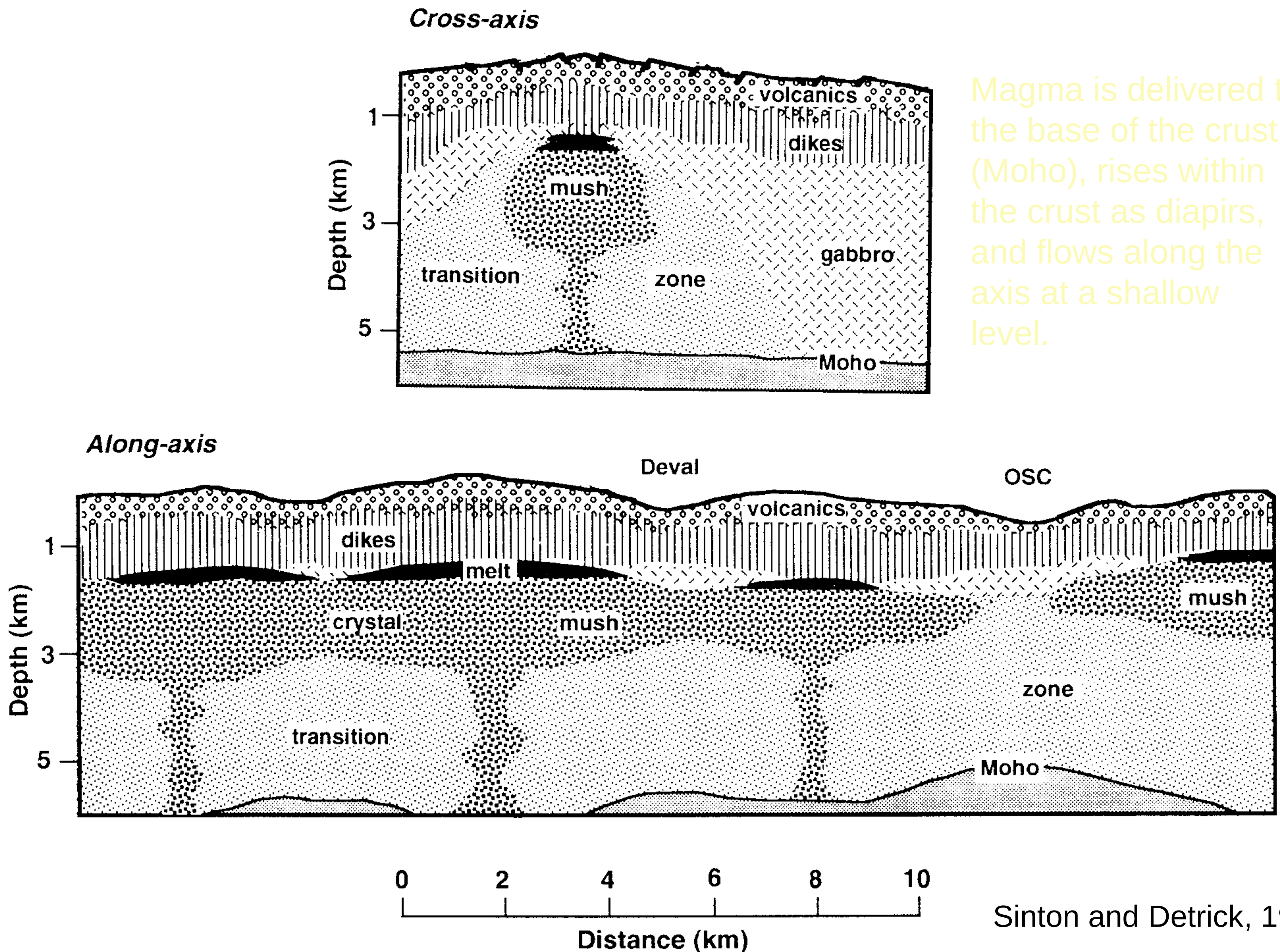
● = Known active sites ● = Active sites indicated by midwater chemical anomalies





Detrick et al. (1987)

Model for Building the Crust at a Fast-Spreading Ridge

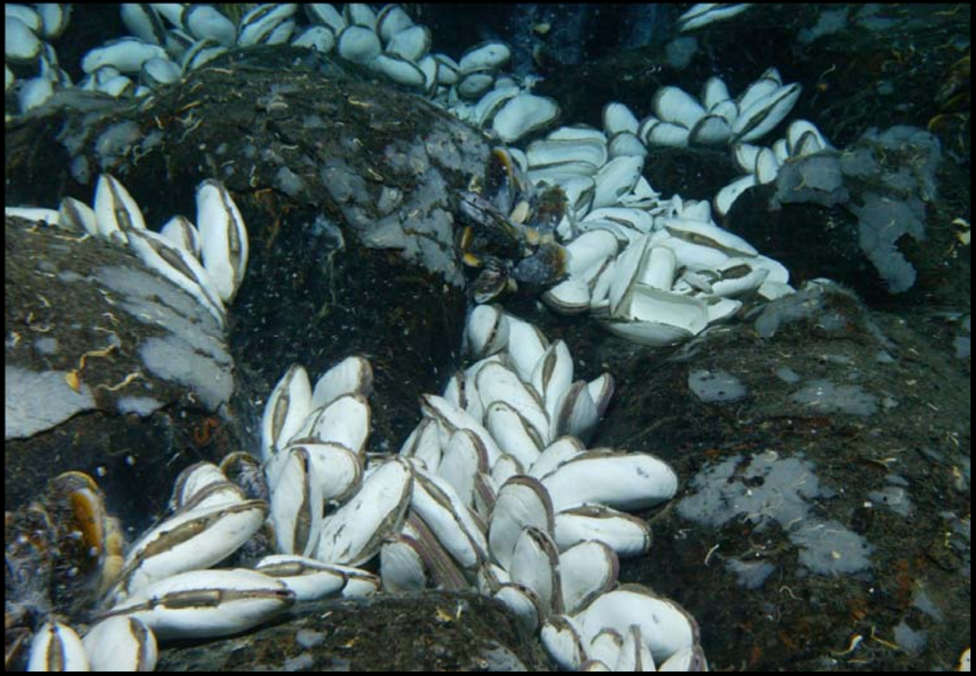


Magma is delivered to the base of the crust (Moho), rises within the crust as diapirs, and flows along the axis at a shallow level.

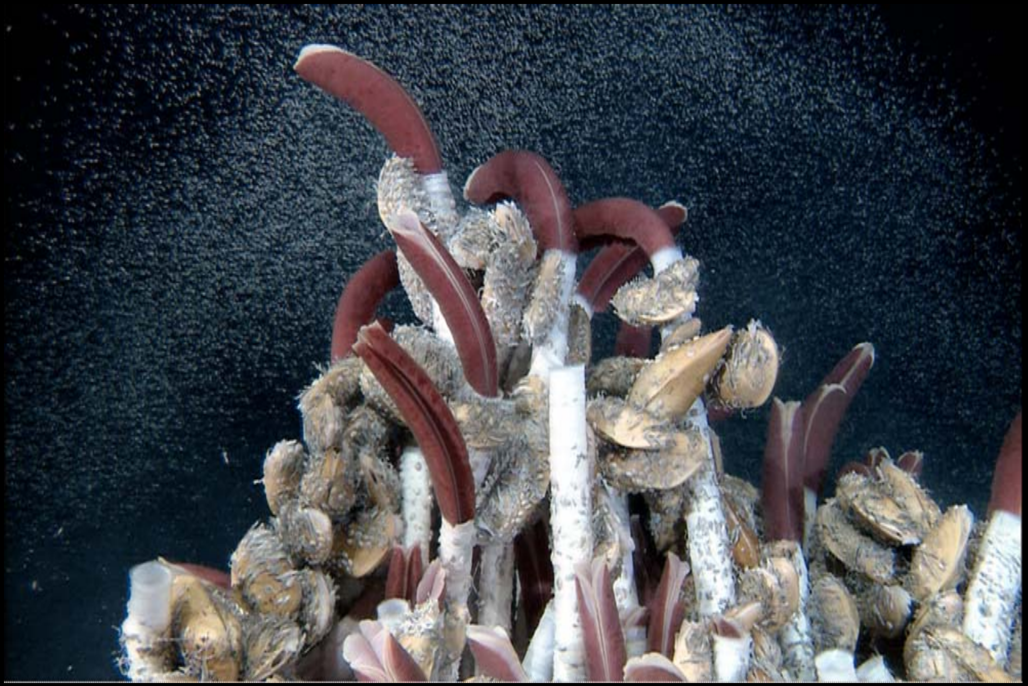
Sinton and Detrick, 1992

Tubeworms

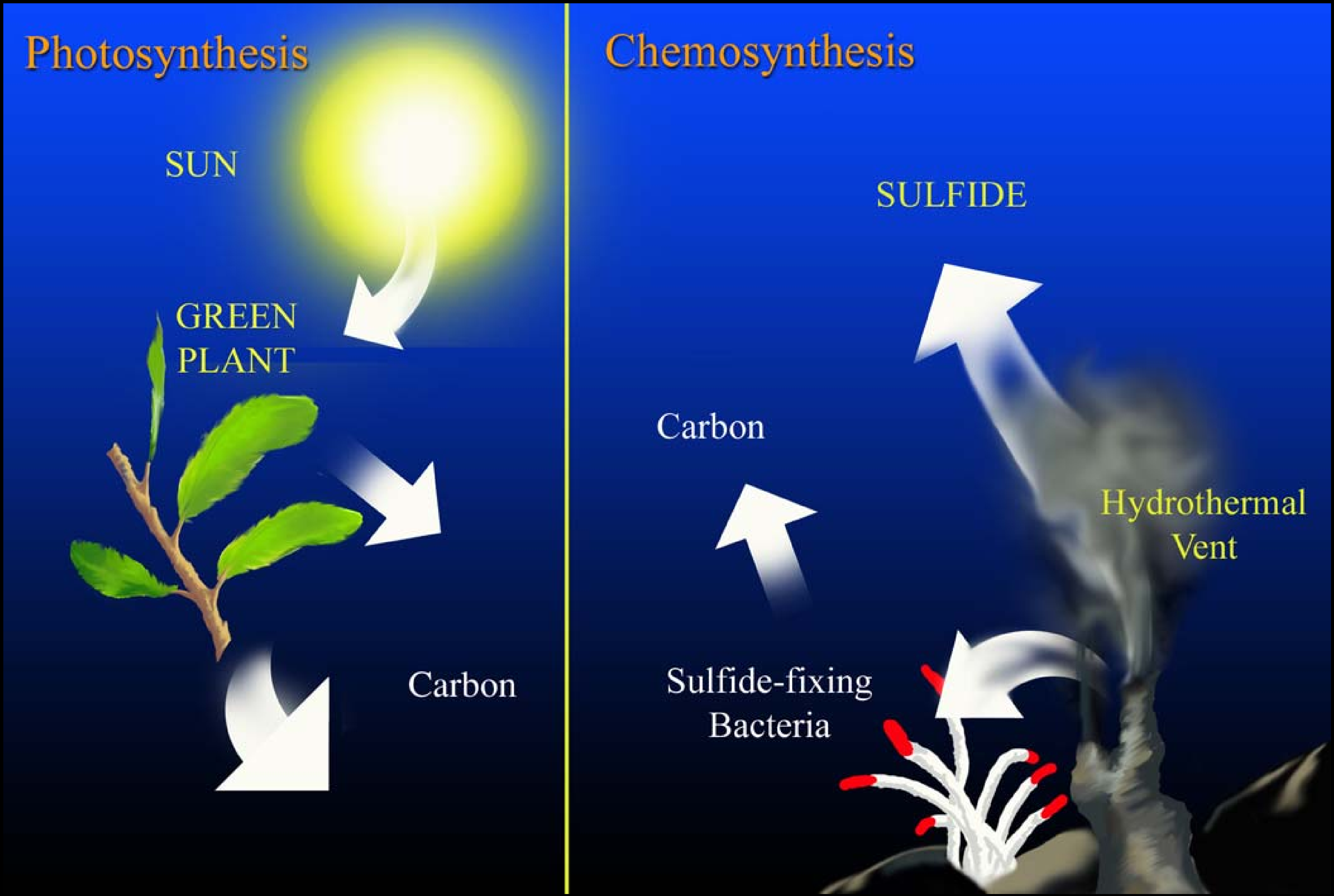
Mussels



Clams



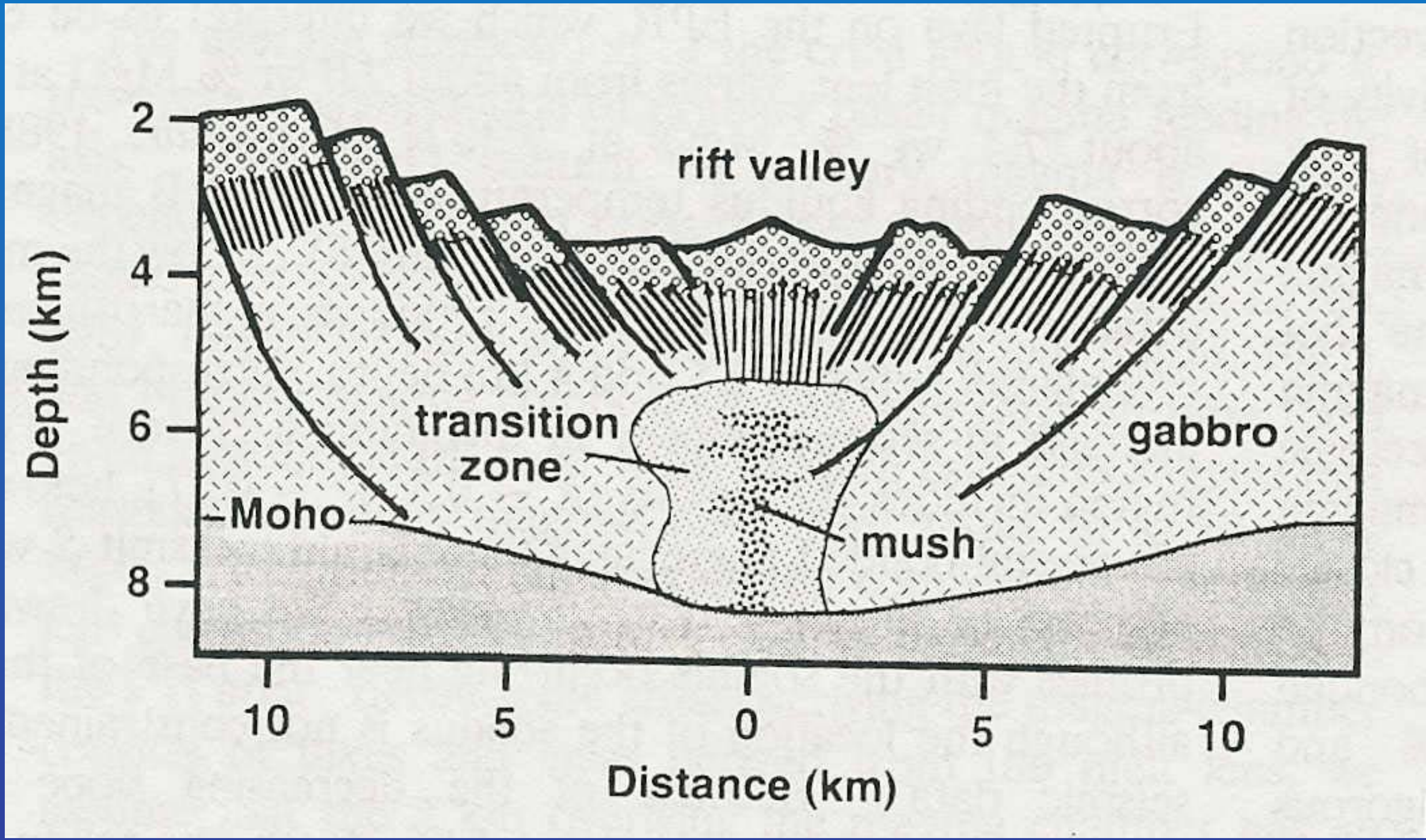
Tubeworms


Photosynthesis
SUN
GREEN PLANT
Carbon
Chemosynthesis
SULFIDE
Carbon
Hydrothermal Vent
Sulfide-fixing Bacteria

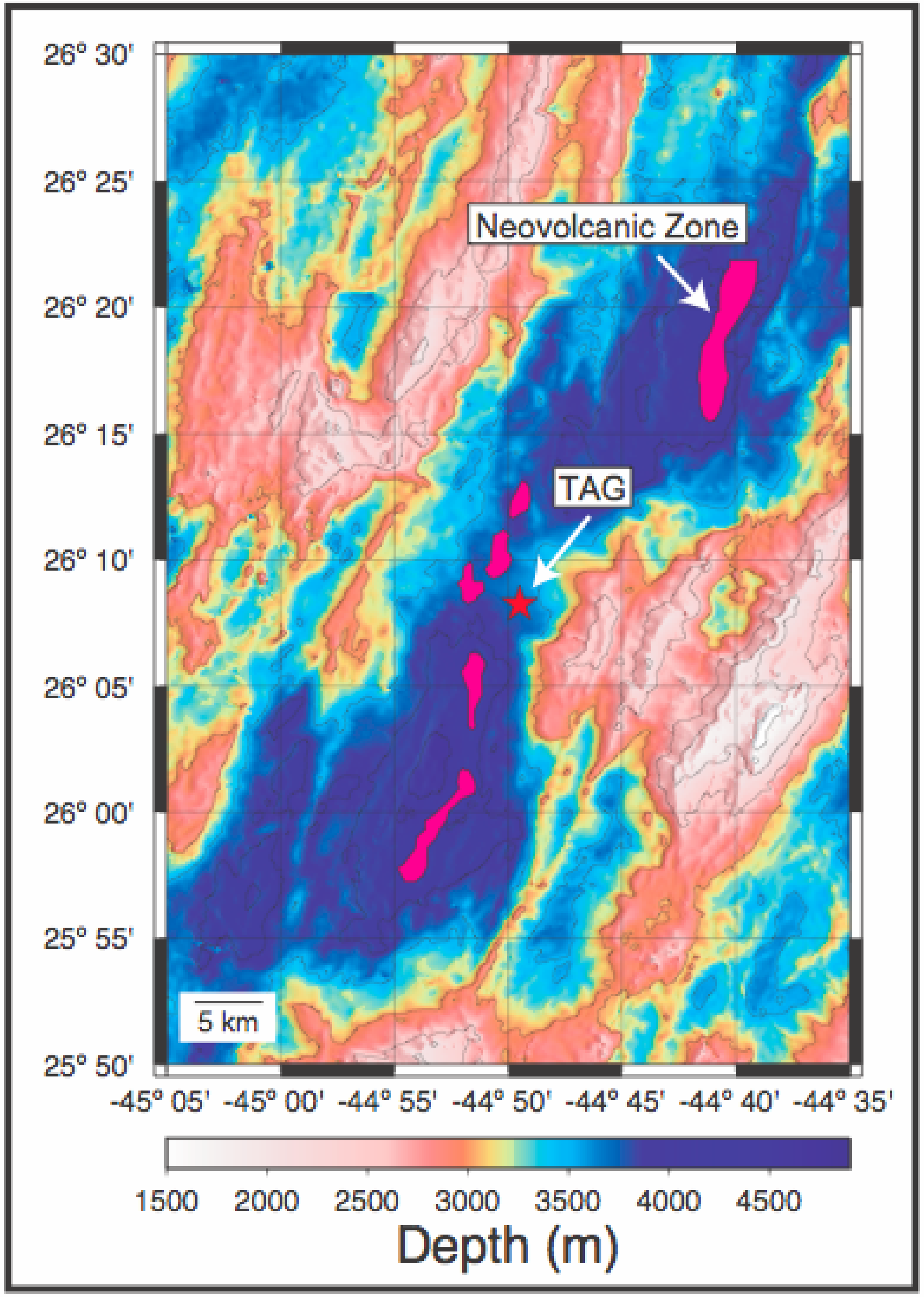

Mid-Atlantic Ridge

Model for the Crust at a Slow-Spreading Ridge

At slow-spreading ridges, magma bodies are thought to be ephemeral, cooling quickly, and no permanent melt lens resides within the crust.

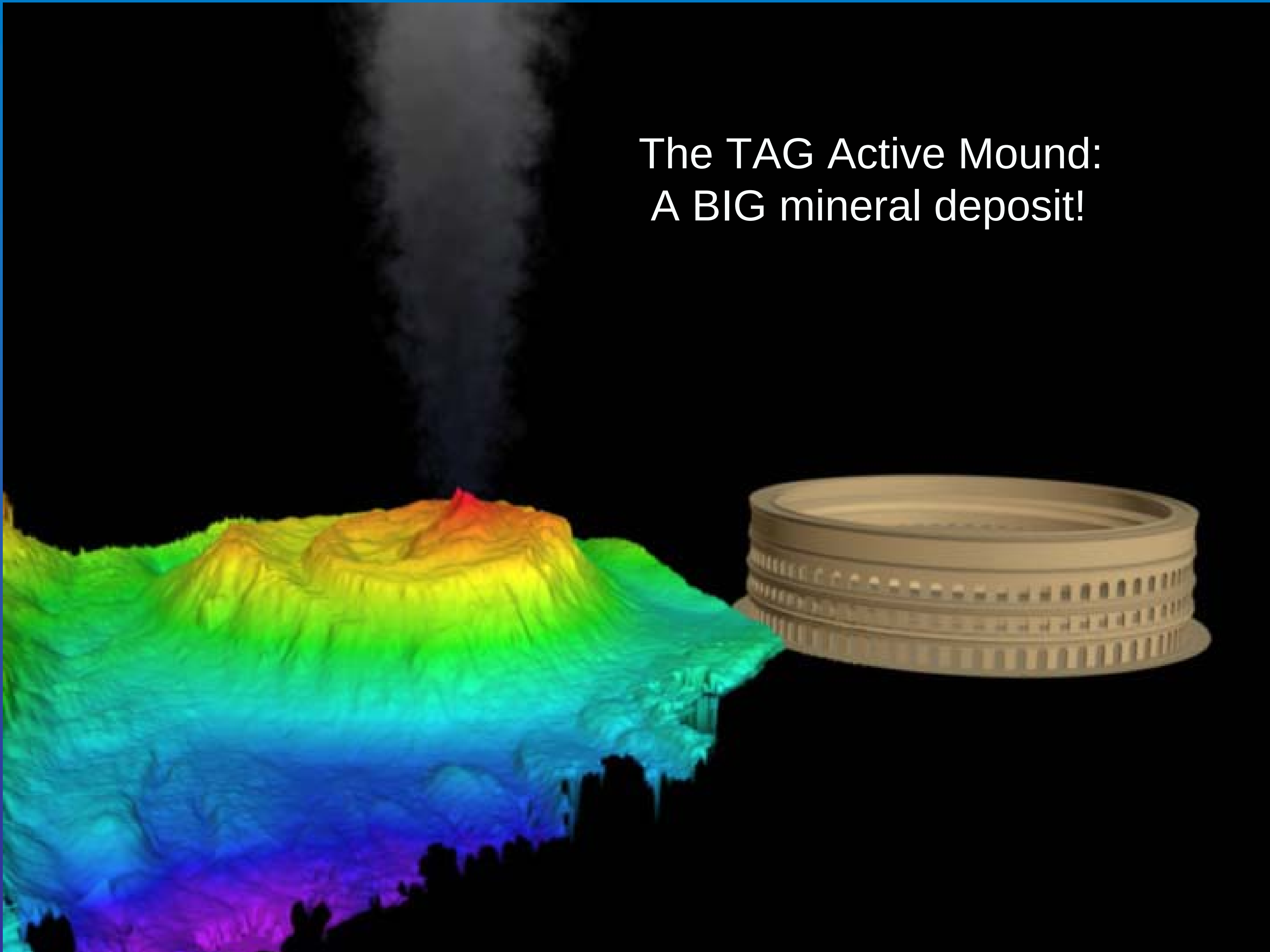


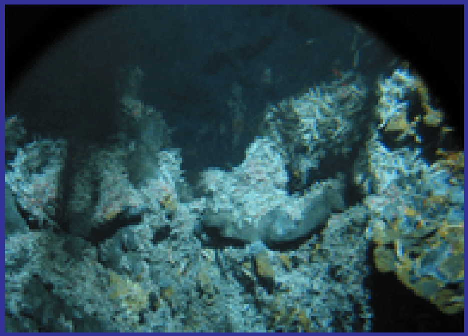
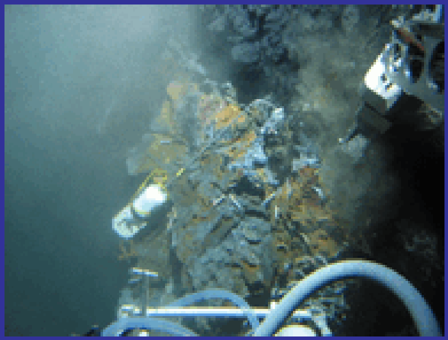
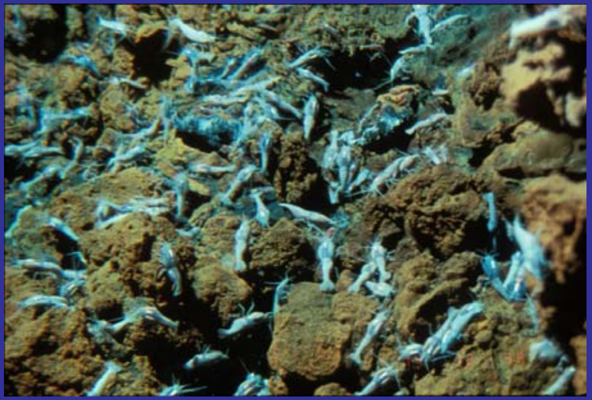
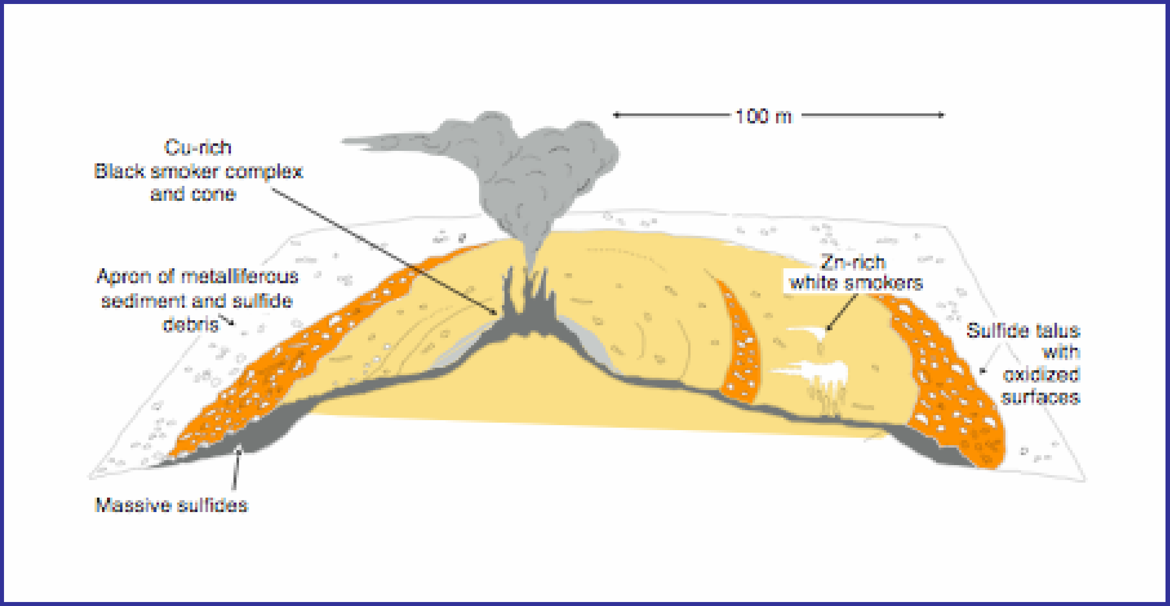
Sinton and Detrick, 1992

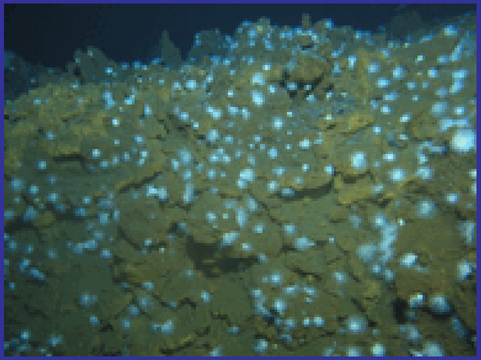
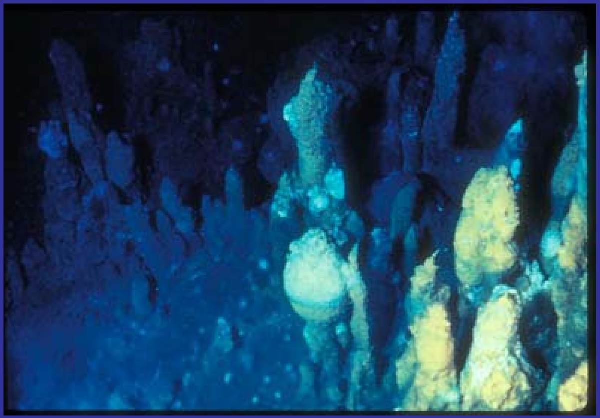


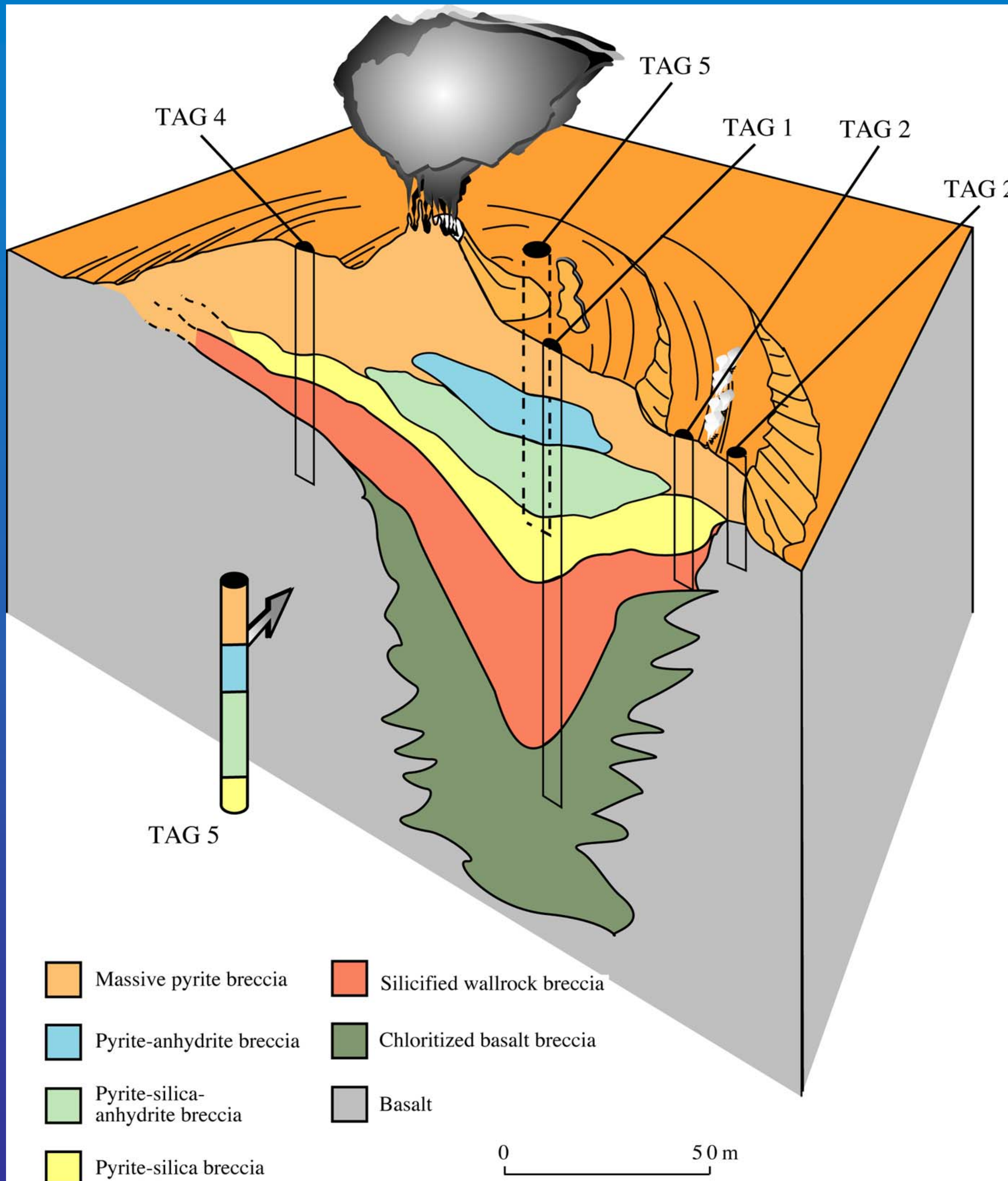
The TAG Segment

- 40 km long; hourglass shape
- Bounded by NTDs
- Axial depths >3700 m; shoals at center to 3550 m
- Asymmetric spreading:
  - ~11 mm/yr to west
  - ~13 mm/yr to east

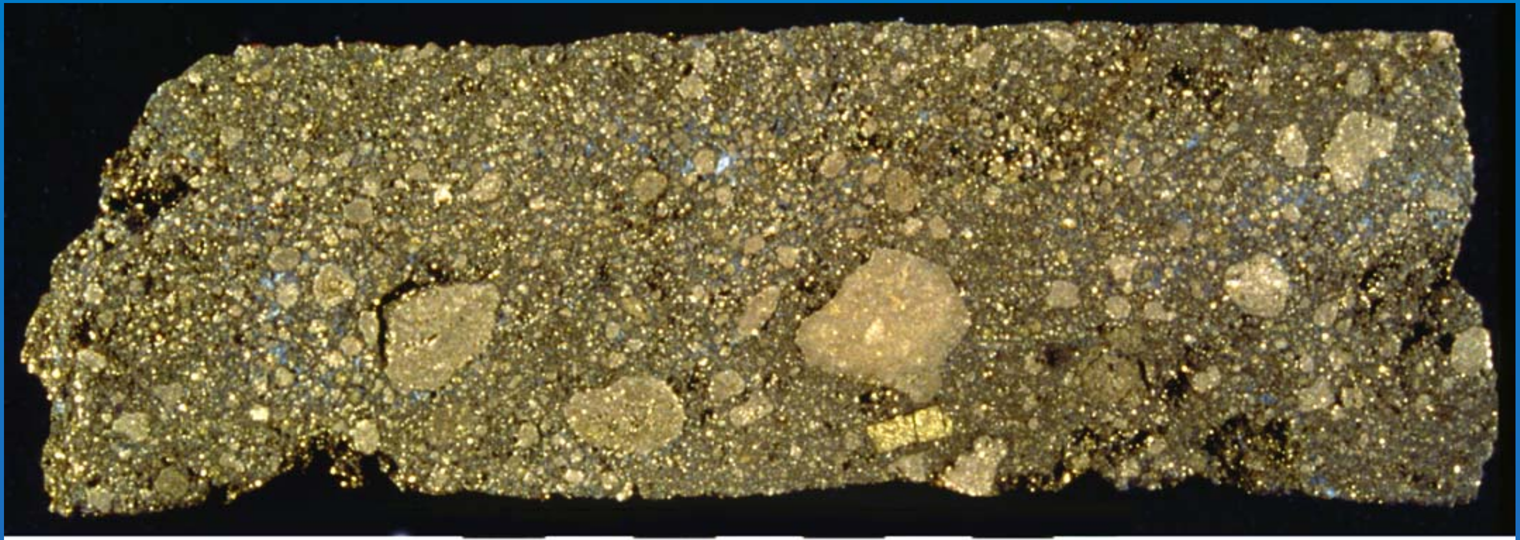

The TAG Active Mound:
A BIG mineral deposit!





100 m
Cu-rich
Black smoker complex
and cone
Apron of metalliferous
sediment and sulfide
debris
Zn-rich
white smokers
Sulfide talus
with
oxidized
surfaces
Massive sulfides



Humphris et al. (1996)

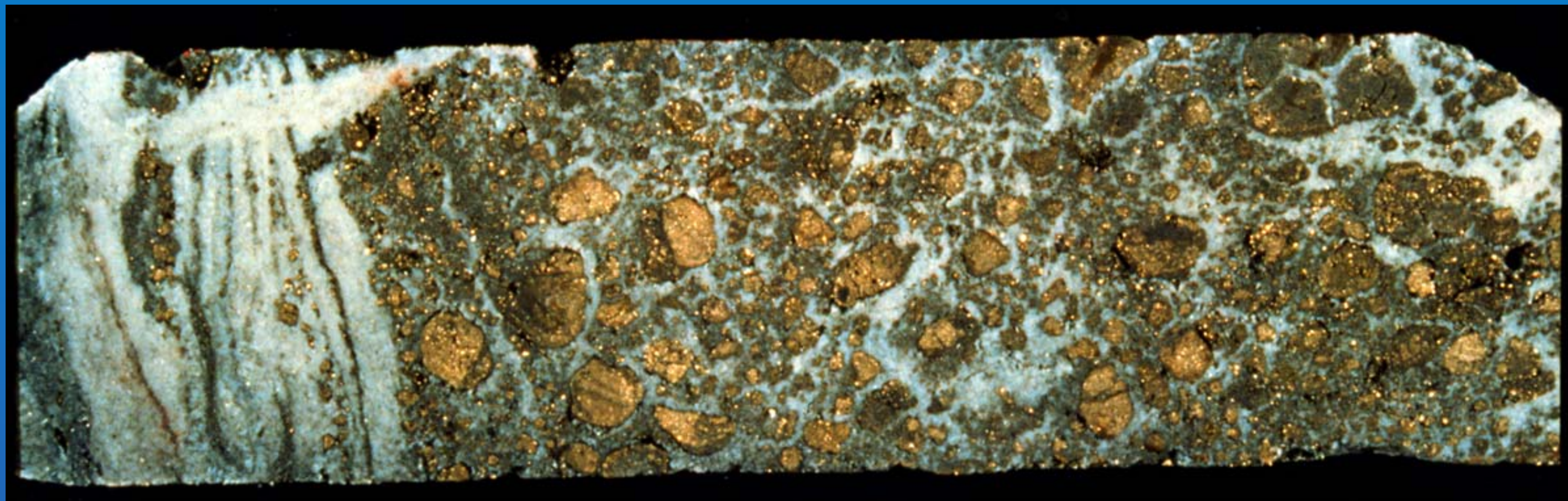


158-957F-1N-1-10B

1 cm

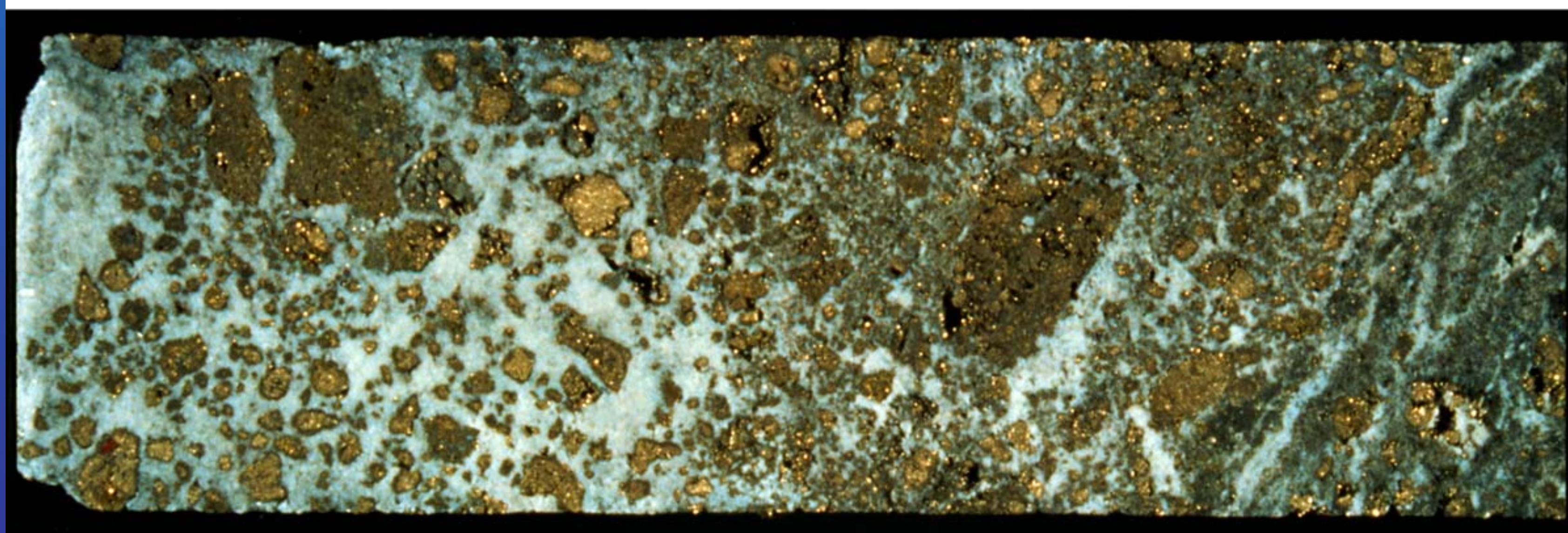
158-957M-7R-1-2

1 cm



158-957C-7N-34A

1 cm

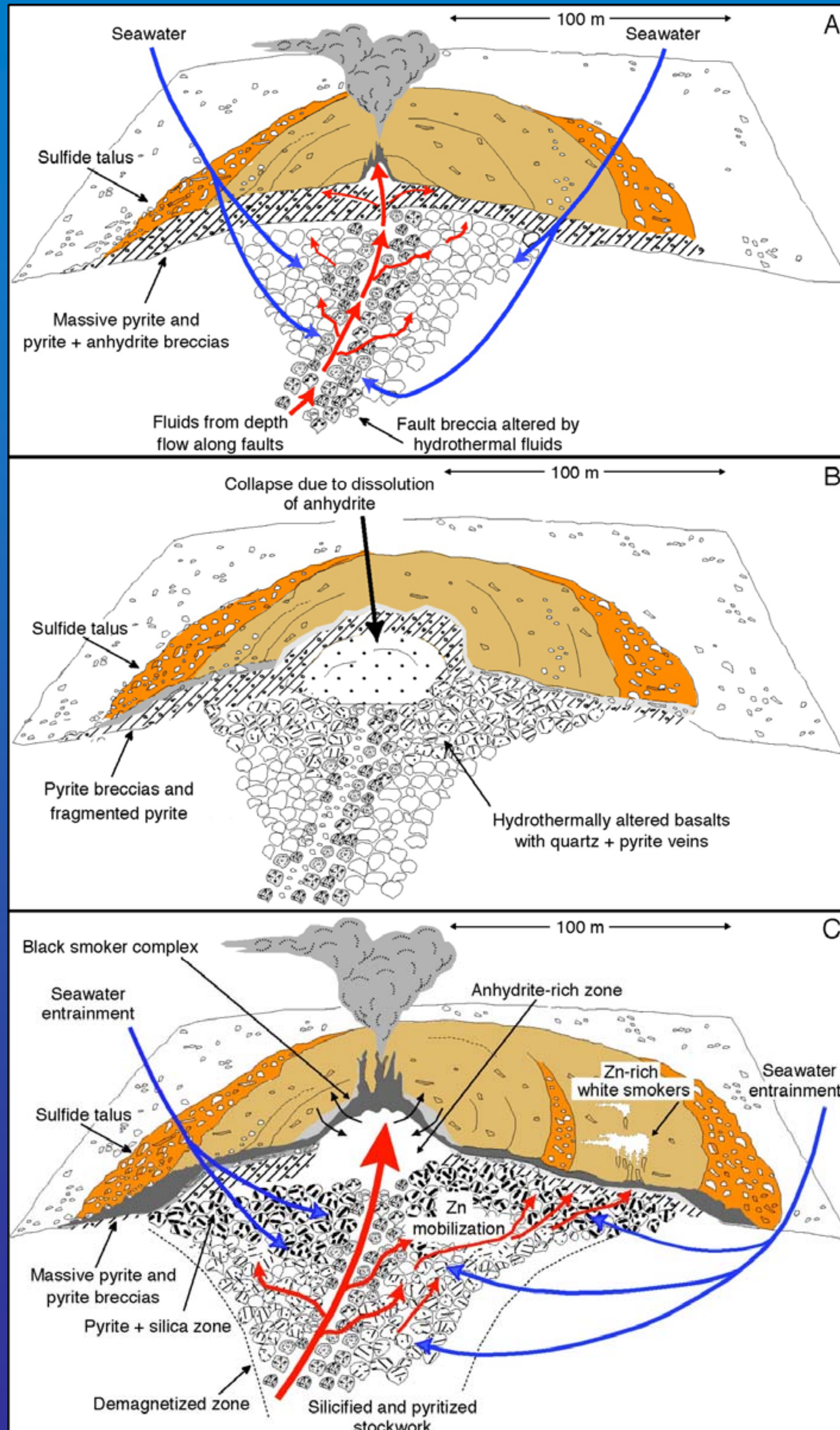


158-957C-7N-2-1K

1 cm

158-957E-17R-1-4 1 cm

158-957E-18N-1-1 1 cm



Humphris & Tivey (2000)

Estimated Tonnage of the Active TAG Mound

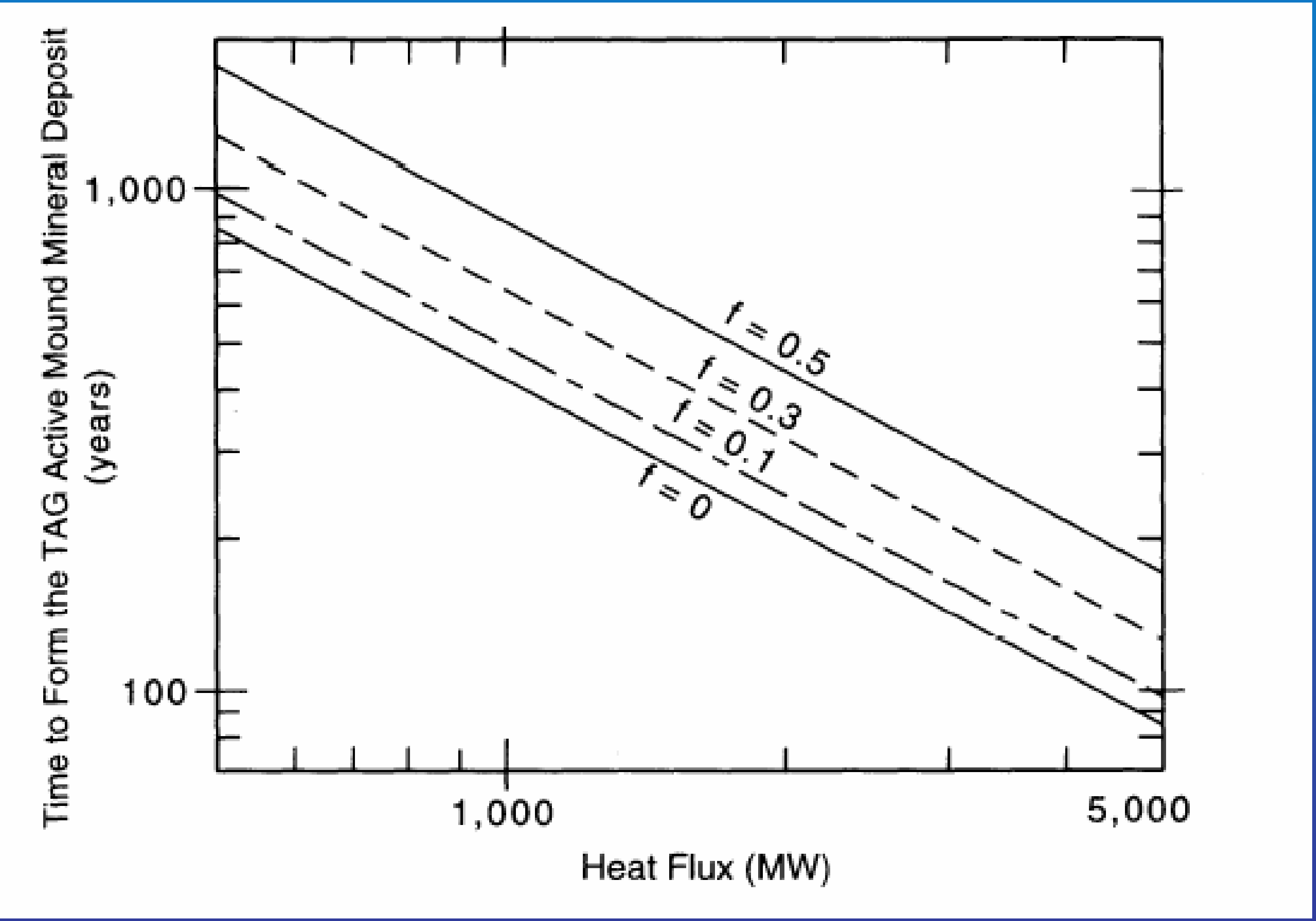
- Total Mass of Sulfide 3.9 x 10^6 tonnes

  Exposed Mound 2.7 x 10^6 tonnes
  Subseafloor Stockwork 1.2 x 10^6 tonnes

- Total Mass of Fe 2.3 x 10^6 tonnes
- Total Mass of Cu 30-60 x 10^3 tonnes
- Total Mass of Zn 15.2 x 10^3 tonnes

(Note: 1 tonne = 10^3 kg)

Based on a simple chemical mass balance model



Humphris & Cann (2000)

Other Results of Chemical Mass Balance Model

- Size of alteration zone (based on Cu budget):
  $1\text{-}2 \times 10^{12}$ kg (0.4-0.7 km^3)

- Heat to drive a 1000 MW hydrothermal system cannot be supplied from the steady state energy flux from crustal accretion

The Heat Source at TAG?

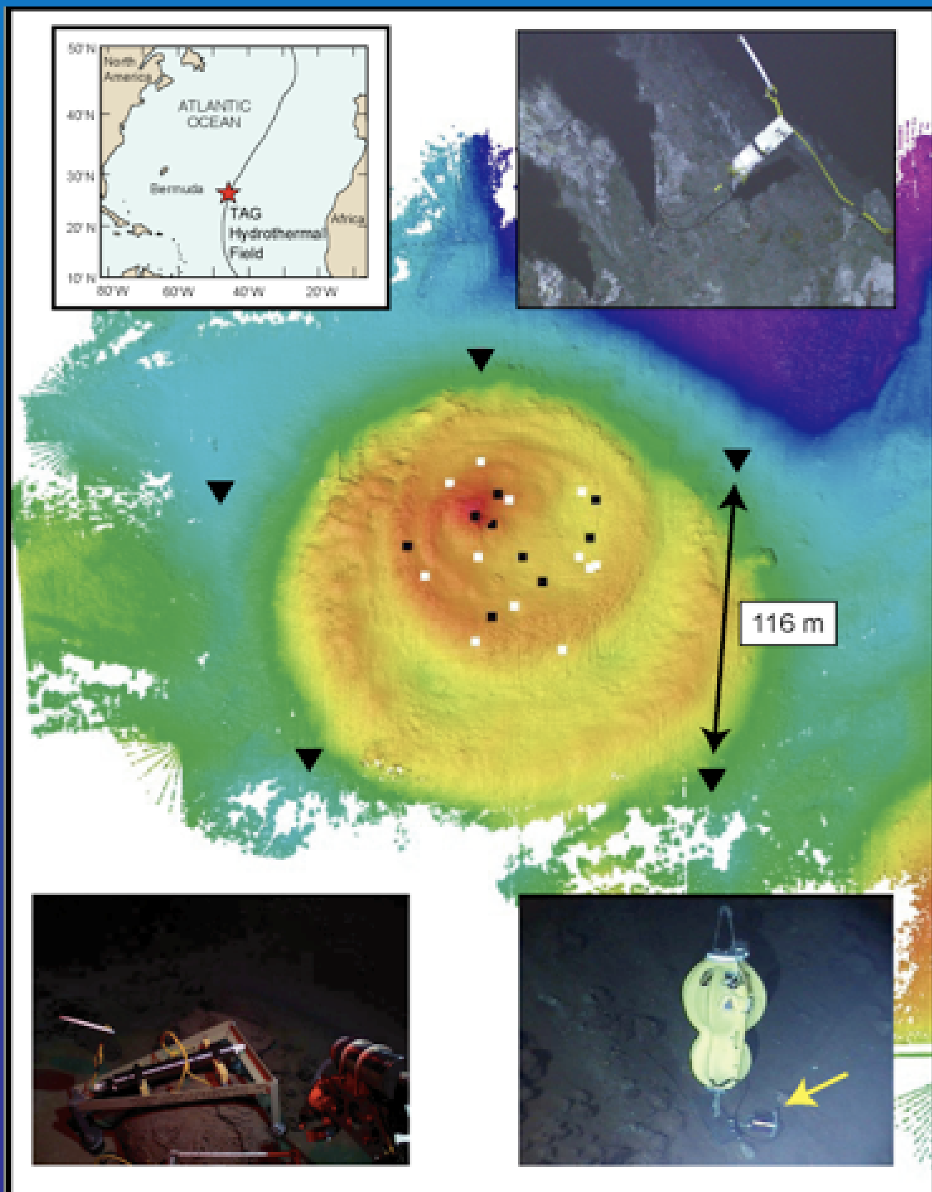
Location

- Is it in the neovolcanic zone with fluid flow pathways provided by large faults?
- Are there discrete, off-axis volcanic centers providing heat locally?

Nature

- Extraction of latent heat from magma chambers?
- Extraction of specific heat from hot rocks across cracking fronts?

The Seismics at TAG (STAG) Experiment (2003-2004)



Objectives

- To determine the location of the heat source for the TAG mound
- To investigate linkages between fluid flow, seismic activity, and tidal pressures to understand the hydraulics of the TAG mound

Components

¶ 4 oceanographic cruises

¶ Microbathymetry map of TAG mound

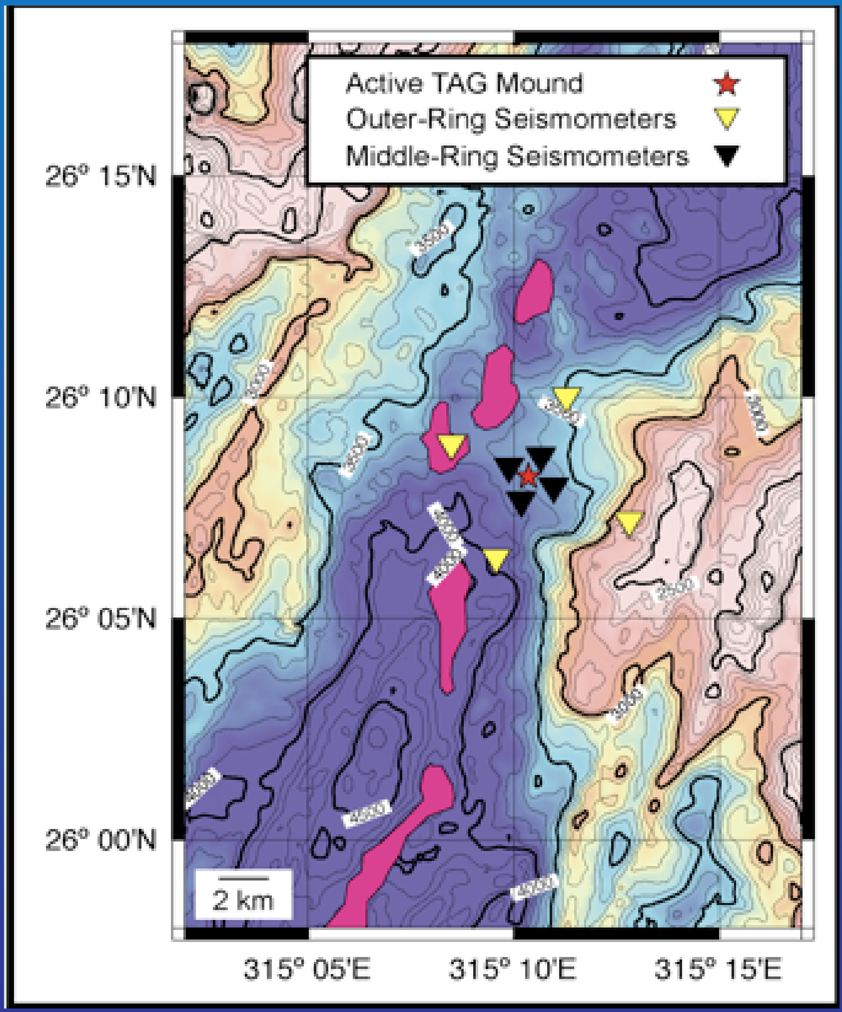
¶ 9 months seismicity data on 13 OBS

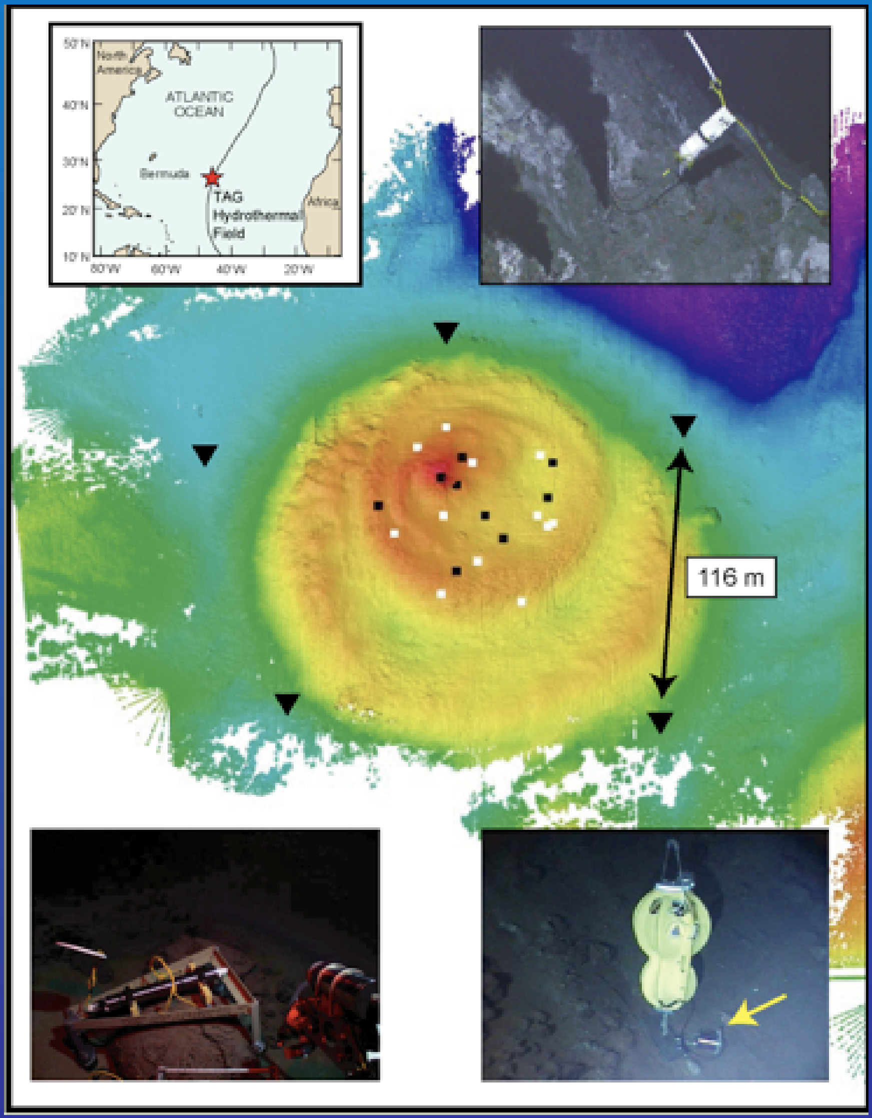
¶ 3 seismic refraction lines

¶ 12 months fluid exit T at 21 sites

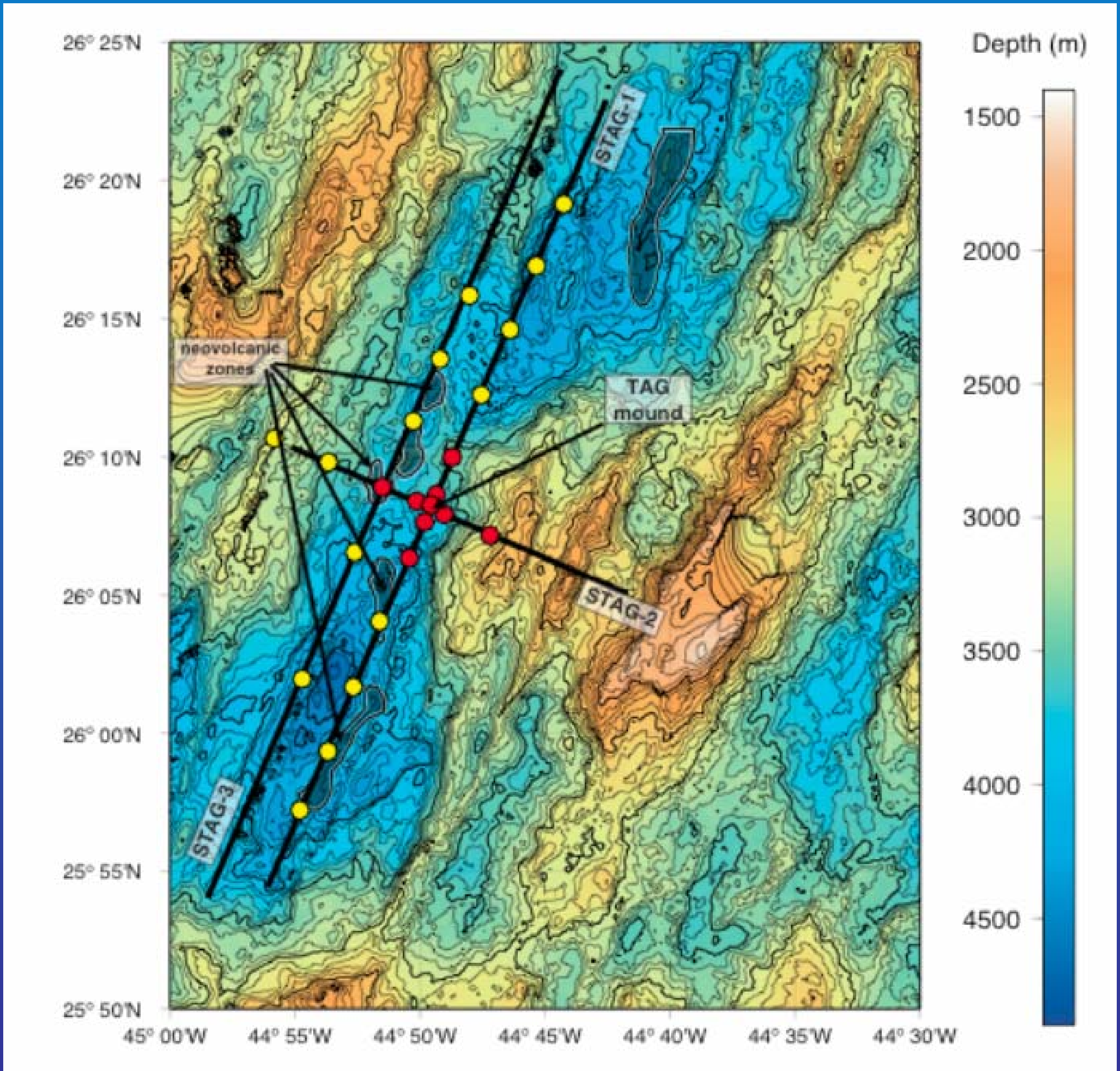
¶ 6 months tidal pressure data

OBS Deployments

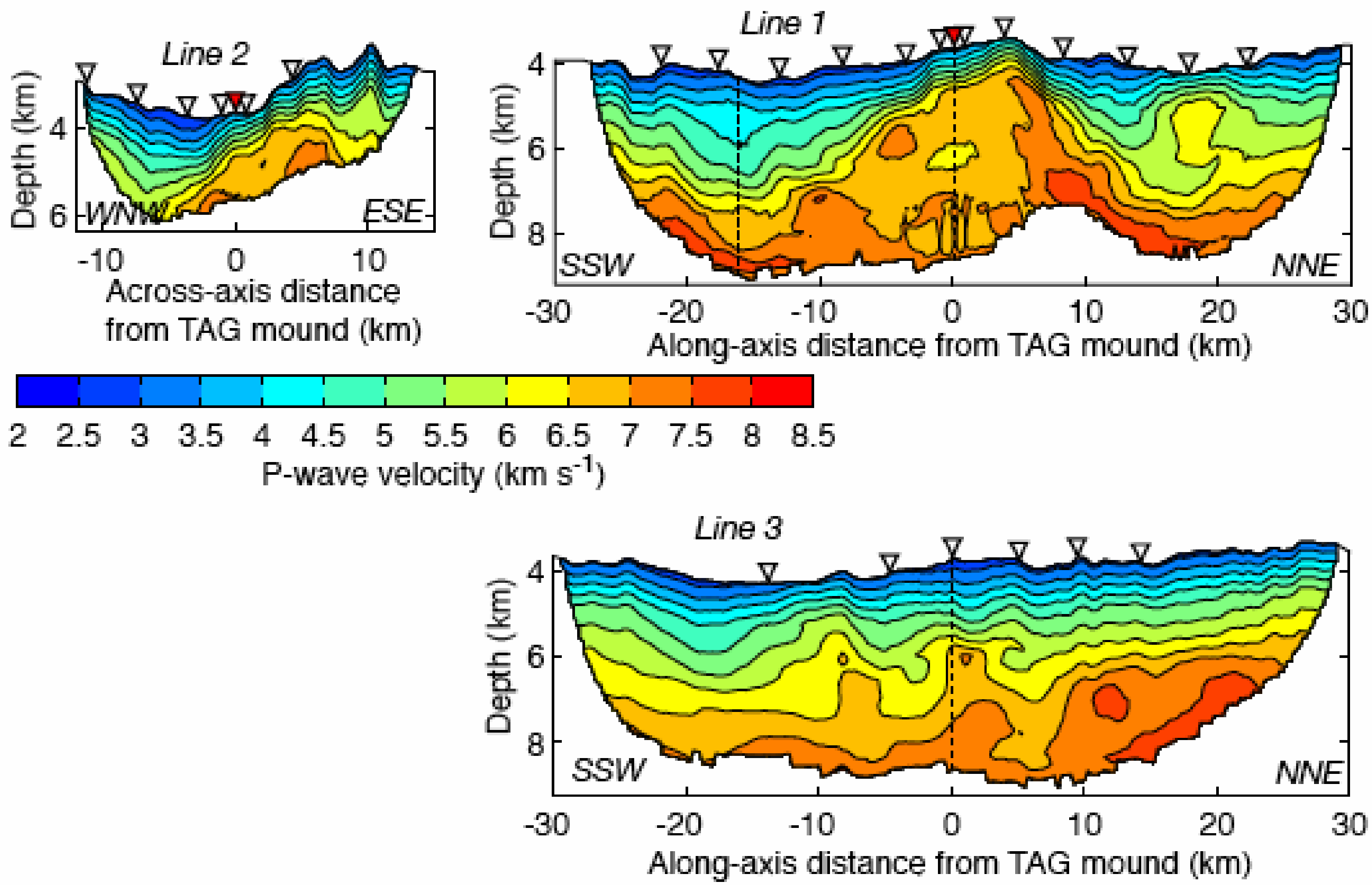




Seismic Refraction Survey

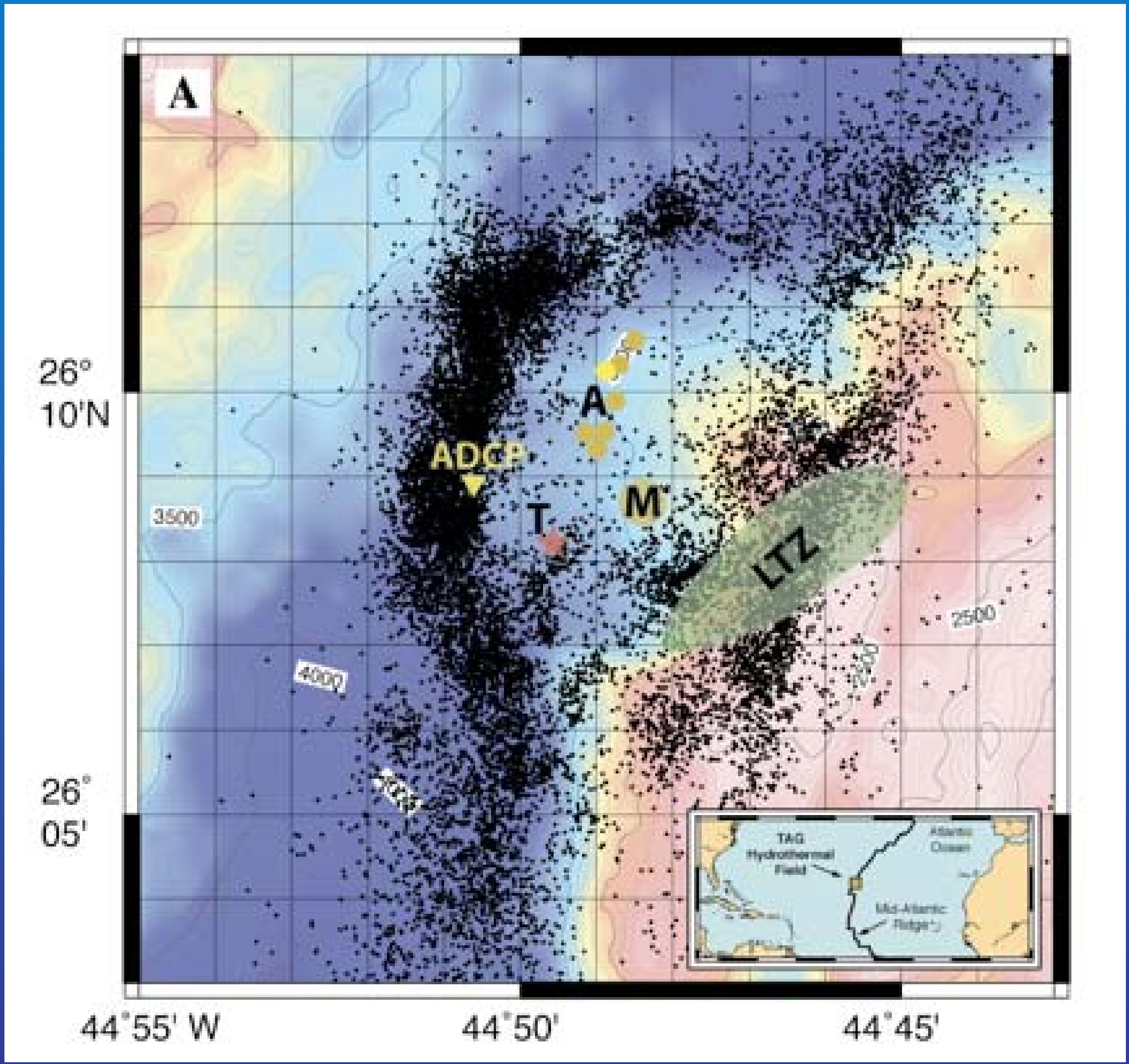


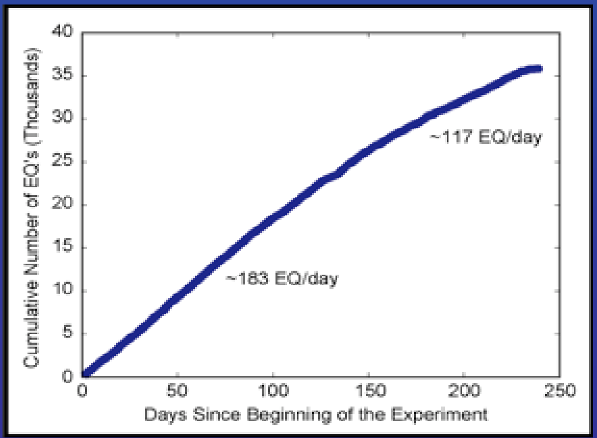
Canales et al. (2007)

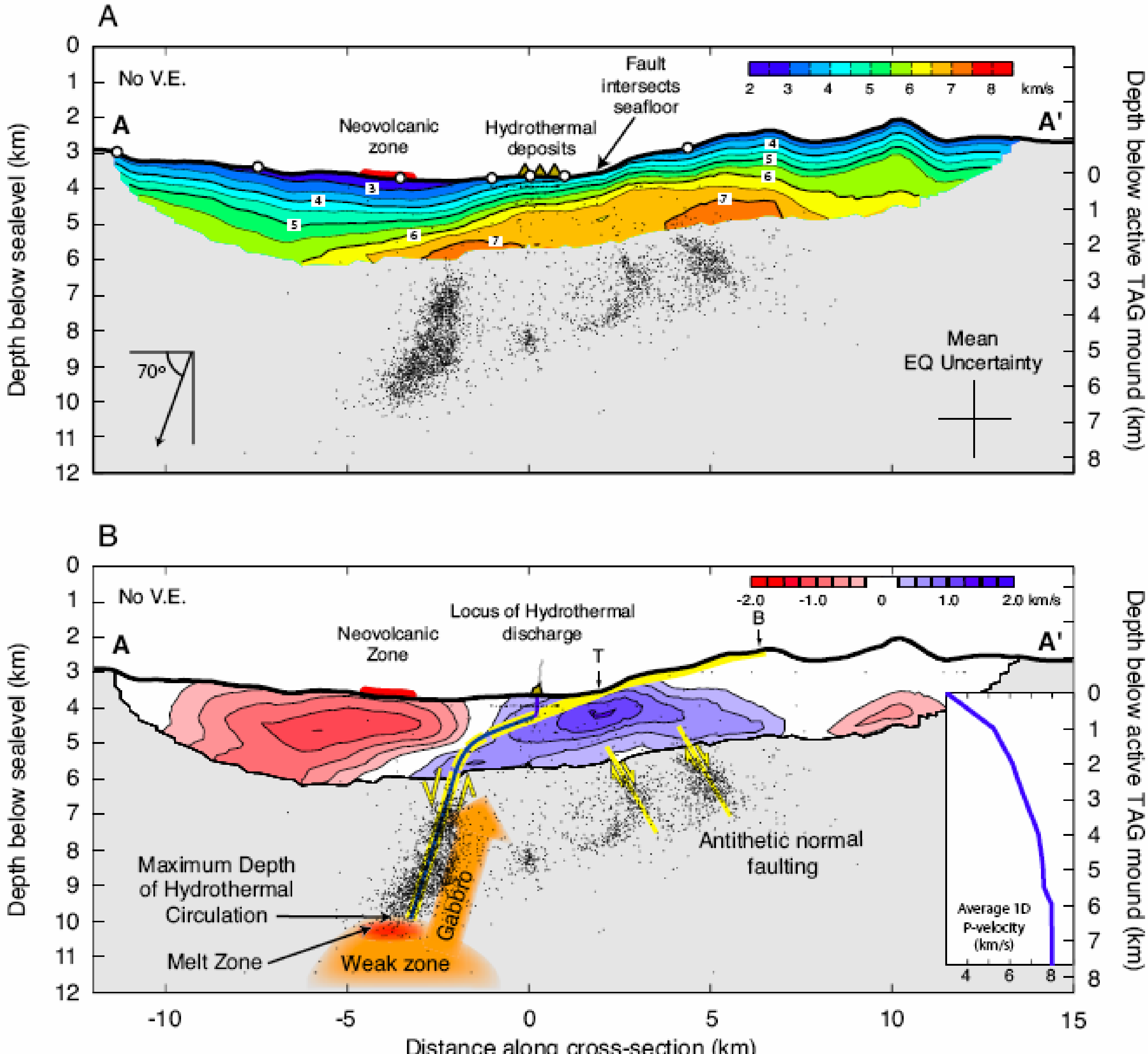


Canales et al. (2007)

• 19,232 earthquakes with magnitudes $1 \leq M_L \leq 4$ located (35,000 detected)
• 2 zones of activity:
-- arc around the eastern wall protrusion
-- parallel to ridge axis beneath eastern wall
• Focal mechanisms consistent with:
-- normal faulting around arc
-- antithetic normal faulting dipping east







DeMartin et al. (2007)

Conclusions about the TAG System

• TAG lies on the hanging wall of a detachment fault that extends >7 km below the seafloor. The large high velocity body beneath the TAG active mound is interpreted to be lower crustal rocks uplifted by tectonic extension along the detachment fault.

• The lack of a low velocity zone within the upper 4 km of crust in the vicinity of the TAG mound indicates the system extracts thermal energy from deeper crustal regions (>7 km).

• The heat source driving hydrothermal circulation is likely magmatic intrusions at the spreading axis mined by the fault.

•Hydrothermal systems could be a common feature of the hanging walls of oceanic detachment faults, which has implications for the distribution of hydrothermal activity and associated thermal and chemical fluxes.

Conclusions

• The distribution of hydrothermal systems along fast-spreading ridges is controlled dominantly by the presence or absence of a shallow axial magma chamber:

Magmatic/volcanic control more important than tectonic processes at fast-spreading ridges.

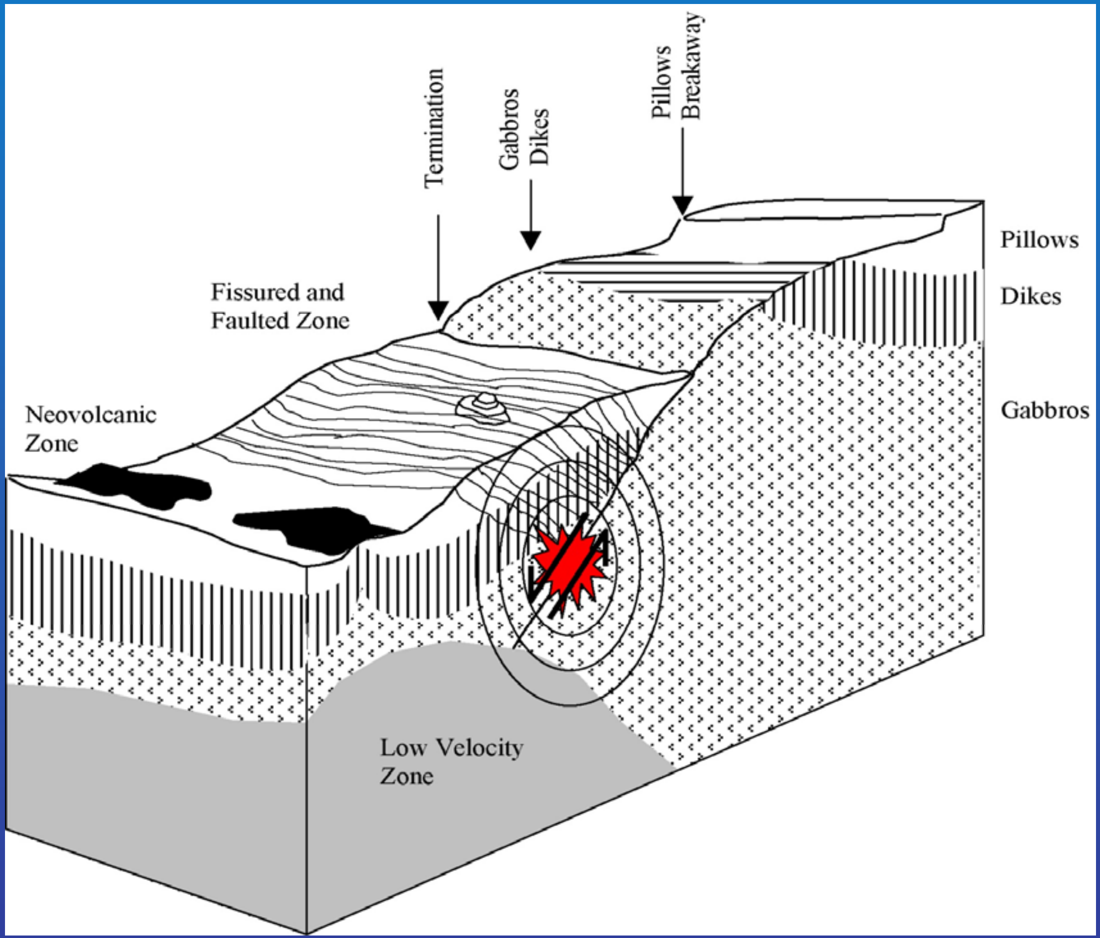
• The location of hydrothermal systems along slow-spreading ridges is controlled dominantly by faulting:

Tectonic control is more important in general than magmatic/volcanic process at slow-spreading ridges.

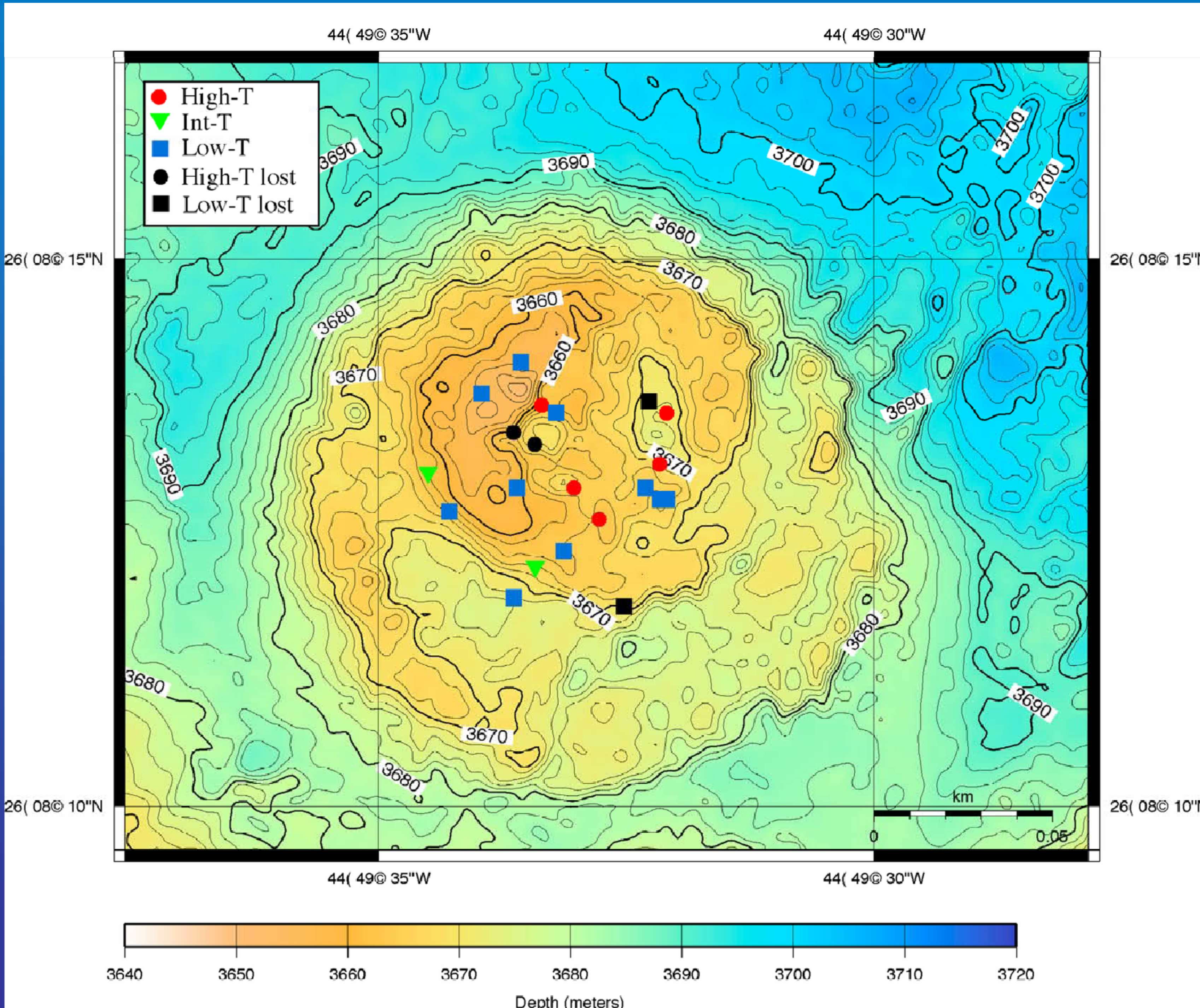
Detachment Faulting at TAG

Geophysical Evidence

- Magnetization low beneath eastern rift valley wall indicates crustal thinning
- Progression from altered gabbros through pillows along eastern valley wall



Tivey et al. (2003)



High-T
Int-T
Low-T
High-T lost
Low-T lost
44(49© 35"W
44(49© 30"W
26(08© 15"N
26(08© 10"N
3690
3700
3680
3670
3660
km
0
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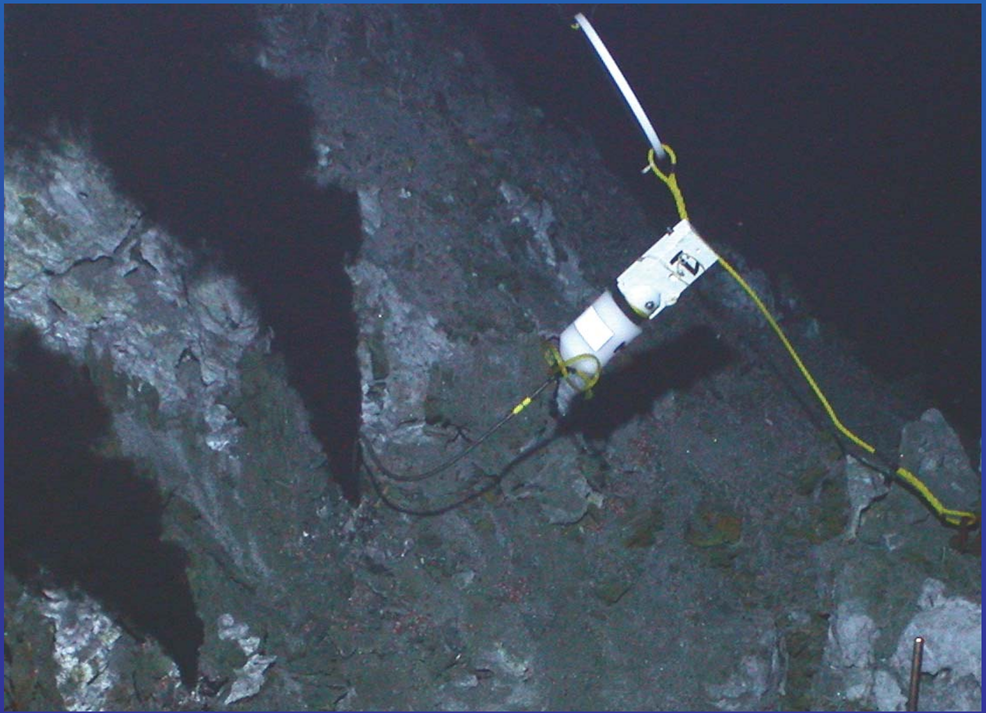
3710
3720
Depth (meters)



DSPL SeaLogger®
temperature probe:
High T: 152-460°C
Intermediate T: -2-124°C

VEMCO Minilog-T data logger: –2 to 70°C.