Geophysical investigation of exchange between planetary oceans and rocky interior- knowledge from deep sea scenarios on Earth

Donna Blackman[1] and Andrew Fisher[1]

[1]UCSC

November 24, 2022

Abstract

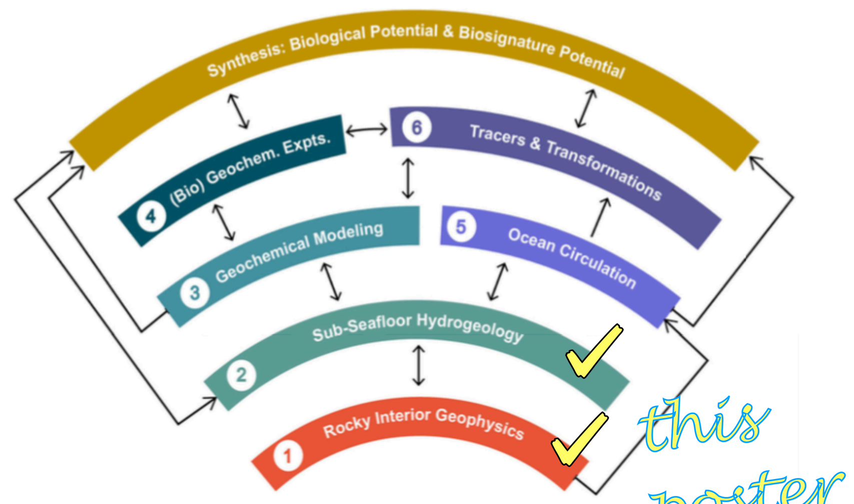
Insights from half a century investigating seafloor hydrothermal circulation on Earth can inform exploration on other Ocean Worlds. Early data/models for Earth provided useful predictions for flow at rift axes, but interpretations of the distribution of subseafloor circulation were revised significantly as data and simulations improved. Lessons learned for Earth systems elucidate how investigators might assess hydrothermal processes on other Ocean Worlds. Basin-scale morphology and heat flow indicate whether conduction explains the flux or cooling by seawater advection occurs. Detailed sonar mapping reveals areas where high flux is most likely. Seismicity patterns suggest different modes of circulation: East Pacific circulation is mapped via microseismicity within porous basaltic crust; Regional seismicity in the Atlantic highlights detachment-dominated rift segments, where faults channel circulation, sometimes within peridotite blocks that react with seawater. Exothermic serpentinization, also inferred for the lower ocean crust near subduction zones, should impart detectable temperature (T) signals. High-T/-flux circulation may be recognized with remote sensing (sonar, thermistors, chemical sensors, cameras) at the seafloor whereas low-T/-flux systems are difficult to identify. Modeling examines factors that influence hydrothermal circulation. Early models were simple single-pass cases; later data and more complex models show circulation includes multi-pass convection that can be 3D, unstable, and strongly guided by permeability patterns. Borehole observatories reveal heterogeneity in fluid chemistry and crustal microbiology. Interpreting Ocean World hydrothermal conditions will be challenging, but some fundamental inferences for Earth's seafloor hydrothermal systems have proven robust. Early studies generated testable hypotheses, advanced instrumentation and simulations, and helped focus interdisciplinary discovery.

MG24A-2190

Geophysical investigation of exchange between planetary oceans and rocky interior- knowledge from deep sea scenarios on Earth

Donna Blackman & Andy Fisher

University of California, Santa Cruz



Exploring Ocean Worlds Project Components

Leads for respective project tasks:

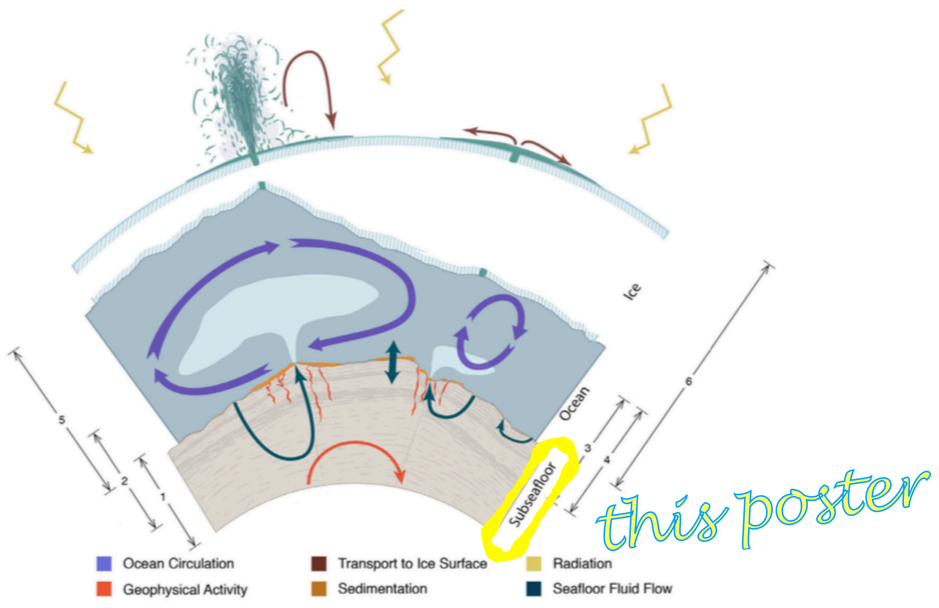
1. Donna Blackman (UCSC); Christophe Sotin (JPL)
2. Andy Fisher (UCSC)
3. Kevin Hand (JPL); Tori Hoehler (Ames); Everett Shock (U AZ)
4. Jeff Seewald (WHOI); Julie Huber (WHOI); Pete Girguis (Harvard)
5. Andreas Thurnherr (LDEO); John Marshall (MIT)
6. Brandy Toner (U MN); Hand; Hoehler; Huber

Chris German (Project & Synthesis Lead)

students/postdocs: Suyash Bire (MIT), Tucker Ely (U AZ), Adam Price (UCSC), Noah Randolph-Flagg (Ames), Adrian Wackett (U MN) & Sanjoy Som (Ames scientist/engineer)

Summary. Insights from half a century investigating seafloor hydrothermal circulation on Earth can inform exploration on other Ocean Worlds. Early data/models for Earth provided useful predictions for flow at the axis of plate spreading, but interpretations of the distribution of subseafloor circulation were revised significantly as data and simulations improved. The occurrence of hydrothermal circulation at spreading axes was predicted on the basis of heat flow measurements that were too low to be explained by conductive cooling of the young lithosphere. Seafloor mapping & sampling showed that the spreading axes were highly fractured volcanic domains amenable to porous hydrothermal flow. Eventually, hot vents hosting chemosynthetic ecosystems were discovered by submersible. More surprising has been the extent of hydrologic flow that occurs within oceanic crust in areas that are not, or no longer, volcanically active. These diffuse, low-moderate heat/flow systems may be more appropriate analogues for other Ocean World hydrothermal circulation.

Many factors differ for exploration of submarine hydrothermal flow below Earth's ocean and that which might exist on other Ocean Worlds. By examining fundamental aspects of Earth's subseafloor circulation, we can develop a set of key parameters for which values appropriate for other Ocean Worlds can be estimated and then applied in numerical flow experiments to test the likelihood of sustained activity, that might be auspicious for hosting life.

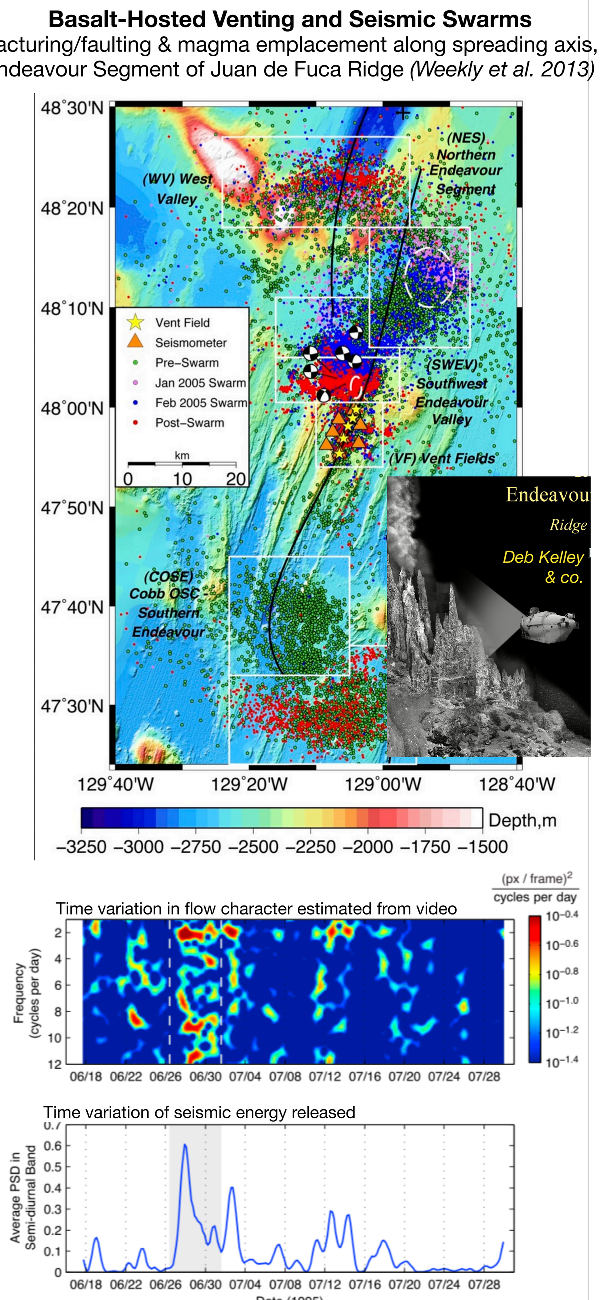


Aspects of Possible Ocean World Scenario

Key Observations from Seafloor Systems on Earth

Basalt-Hosted Venting and Seismic Swarms

fracturing/faulting & magma emplacement along spreading axis, Endeavour Segment of Juan de Fuca Ridge *(Weekly et al. 2013)*



flow rate correlates with seismicity rate

Main Endeavour Vent Field *(Crone et al. 2010)*

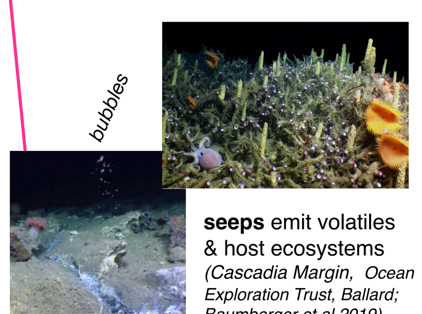
Settings of hydrothermal circulation

axis of spreading along mid-ocean ridges

ridge flanks and mature plate

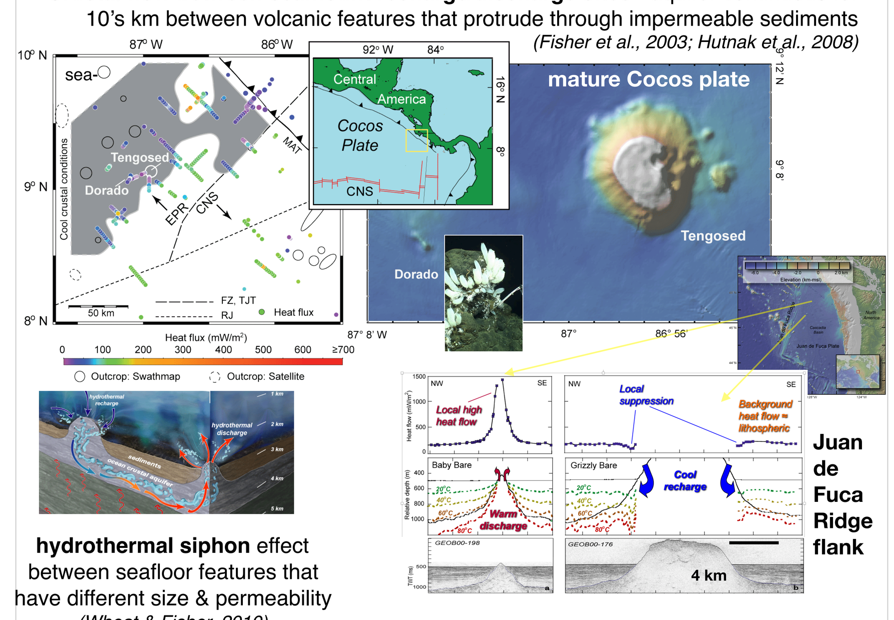
convergent margins

- seeps & methane hydrates in sediments
- mud volcanoes- evidence that subducted plate & interface between downgoing & over-riding plate are hydrated



seeps emit volatiles & host ecosystems *(Cascadia Margin, Ocean Exploration Trust, Ballard; Baumberger et al 2019)*

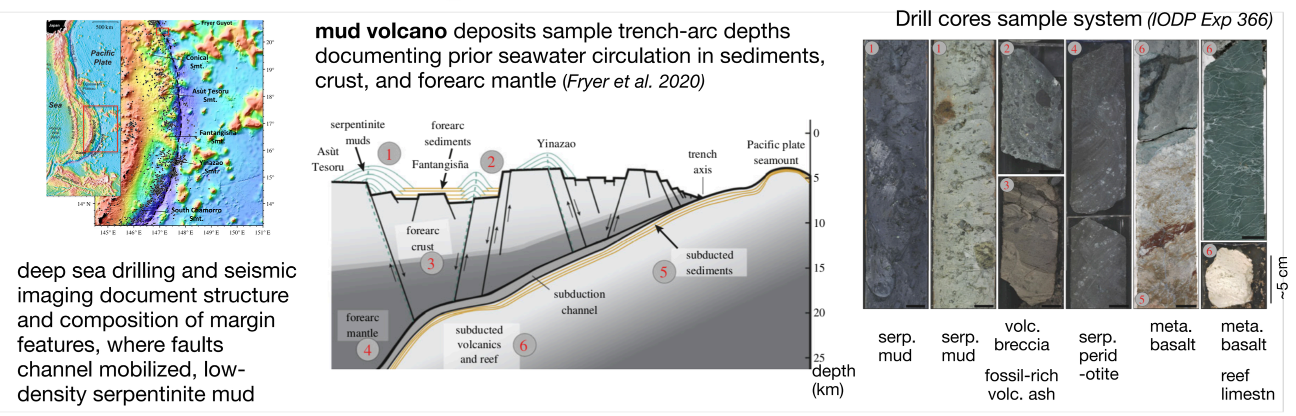
Crustal flow between seamount recharge/discharge sites- aquifer continuous for 10's km between volcanic features that protrude through impermeable sediments *(Fisher et al., 2003; Hutnak et al., 2008)*



hydrothermal siphon effect between seafloor features that have different size & permeability *(Wheat & Fisher, 2010)*

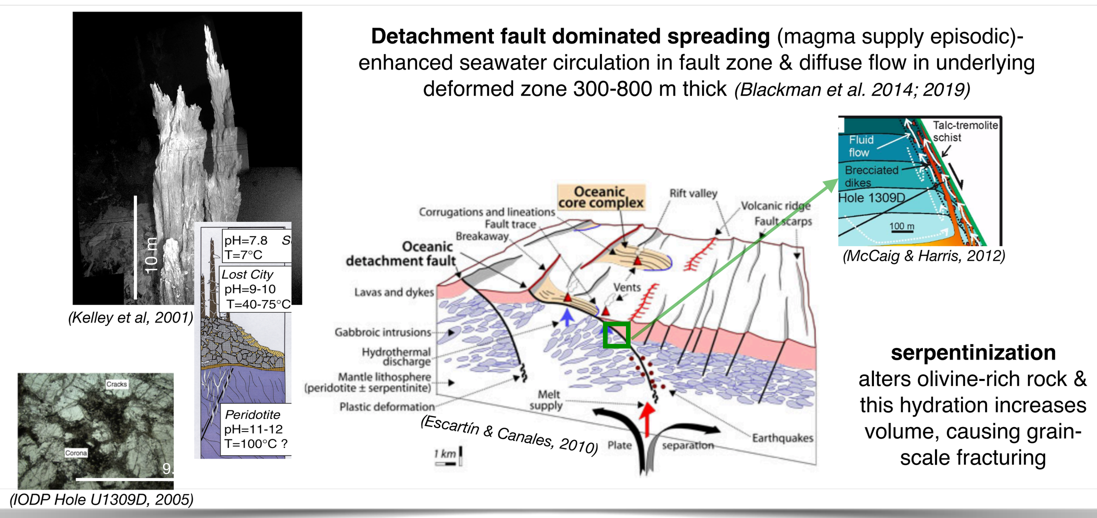
mud volcano deposits sample trench-arc depths documenting prior seawater circulation in sediments, crust, and forearc mantle *(Fryer et al. 2020)*

Drill cores sample system *(IODP Exp 366)*



deep sea drilling and seismic imaging document structure and composition of margin features, where faults channel mobilized, low-density serpentinite mud

Detachment fault dominated spreading (magma supply episodic)- enhanced seawater circulation in fault zone & diffuse flow in underlying deformed zone 300-800 m thick *(Blackman et al. 2014; 2019)*



serpentinization alters olivine-rich rock & this hydration increases volume, causing grain-scale fracturing

Fundamental Factors

mechanism to create/maintain porosity: volatiles in volcanic rock, localized deformation/fracturing, ongoing seismicity

mechanism to drive flow: heat (fluid buoyancy), pressure difference (seafloor depth variations, deformation- tectonic, tidal)

water:rock ratio sufficient for dissolution and transport

secondary mineral formation not so rapid that pores are filled/ sealed

vent fluid temperature (T) thruout range from ambient (few °) to ~400°C; higher chemical concentrations occur in (less common) venting at high T

Knowledge from Simulations of Earth's Seafloor Systems

Early models of possible heat flux

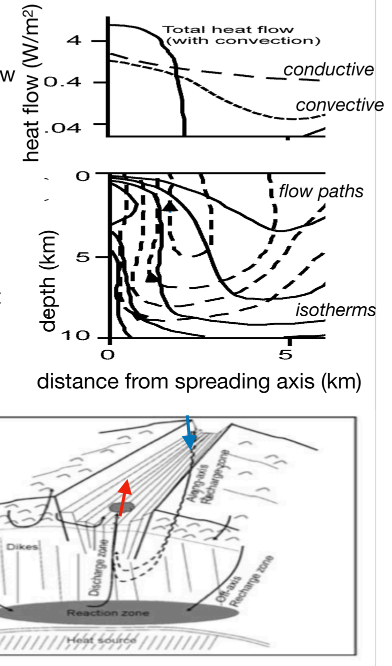
too simple to capture actual hydrothermal flow behavior:

1:1 flow cell geometry

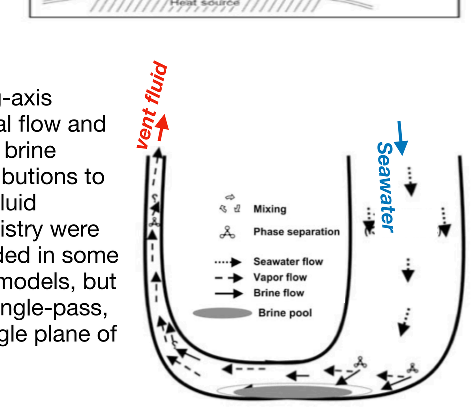
homogenous crust properties

single-pass heat engine scenario

flow only in cross-axis plane



Along-axis crustal flow and basal brine contributions to vent fluid chemistry were included in some later models, but still single-pass, in single plane of flow



Reaction zone depth inferred from vent fluid chemistry

Cl & Si concentrations in vapor-like fluid model *(Fontaine et al., 2009)*

Key Insights

flow is likely three-dimensional & unstable

low T flux significant, ~99% of systems to mine enough heat

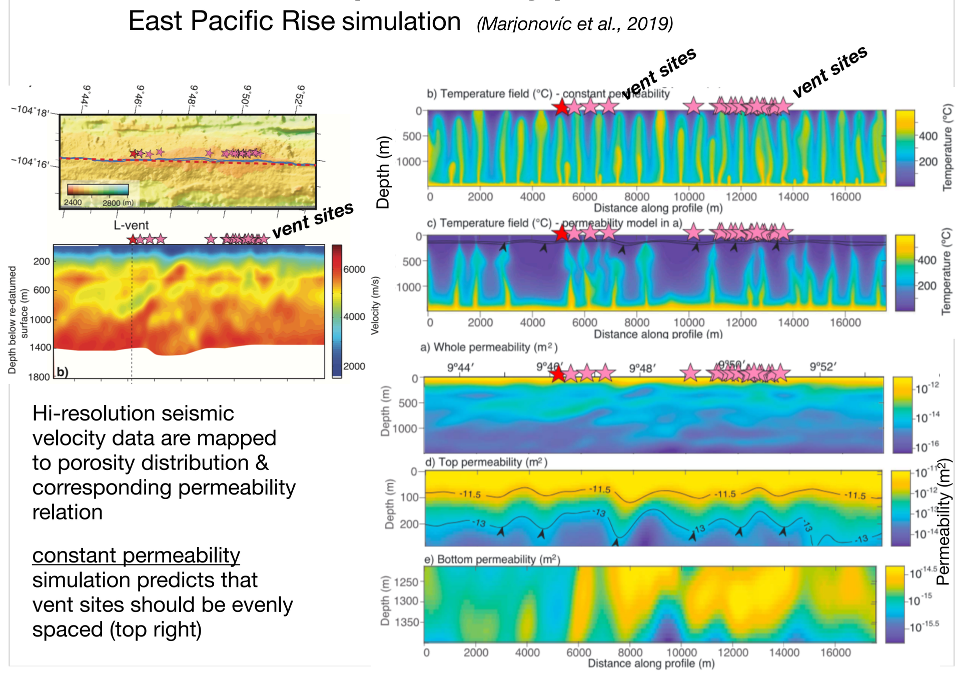
heterogeneity in properties can determine flowpaths and focus circulation

variable model domain resolution required to capture range of geologic scales within system

long term goal- **fully coupled reactive behavior** (& chemistry); short term- chemical observations guide/test physical models

2-D models & permeability pattern

East Pacific Rise simulation *(Marjanovic et al., 2019)*



Hi-resolution seismic velocity data are mapped to porosity distribution & corresponding permeability relation

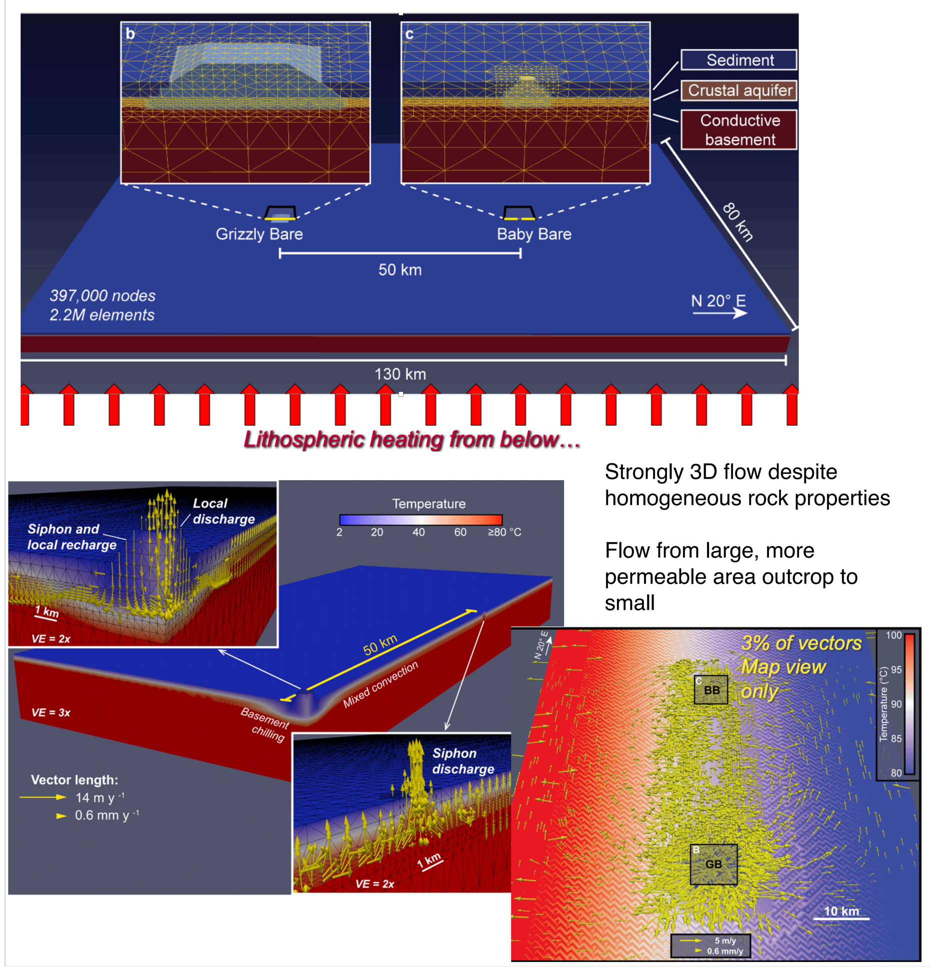
constant permeability simulation predicts that vent sites should be evenly spaced (top right)

3-D models of circulation between seamounts

(Winslow & Fisher, 2015; Winslow et al. 2016)

Narrow range of properties required to match observed flow rate (*5-20 l/s*) & heat flux (*1-2 MW*) on flank of Juan de Fuca Ridge: basement aquifer ~300 m thick, permeability 10^{-12}-10^{-13} m^2

values are much lower than prior estimates based on 2D model

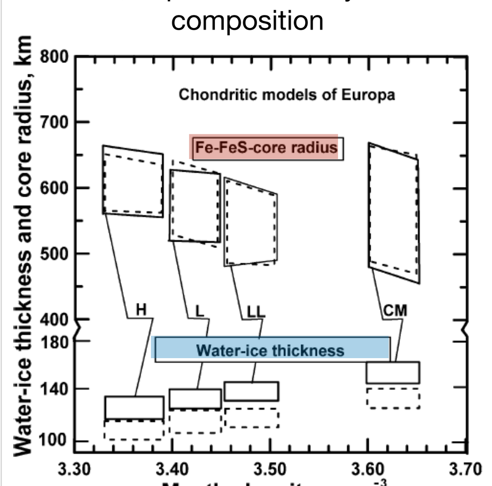


Strongly 3D flow despite homogeneous rock properties

Flow from large, more permeable area outcrop to small

Parameter Comparisons between Ocean Worlds

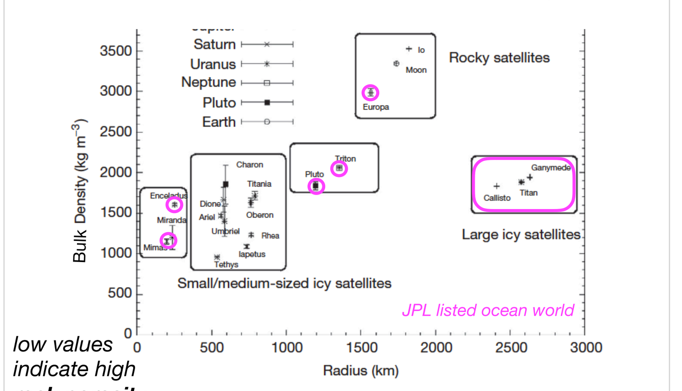
bulk density of body allows range of ocean/ice thickness & interior radius; depends on rocky interior composition



	H	L	LL	CM2
Phase composition (mol%) and density at 3 GPa and 1000 °C[a]				
Ol	31.9	37.0	42.1	73.5
Opx	35.6	30.7	25.5	0
Cpx	32.1	31.9	31.9	23.6
Gar + Ilm	0.4	0.4	0.5	0
Sp + Ilm	0	0	0	2.9
ρ (kg m^{-3})	3.381	3.428	3.463	3.611

(Kuskov & Konrod Icarus 2005)

oceans on several icy satellites in solar system



low values indicate high rock porosity

(Hussman et al., Treat. Geoph. 2015)

Earth differs notably

bulk density 5514 kg/m³

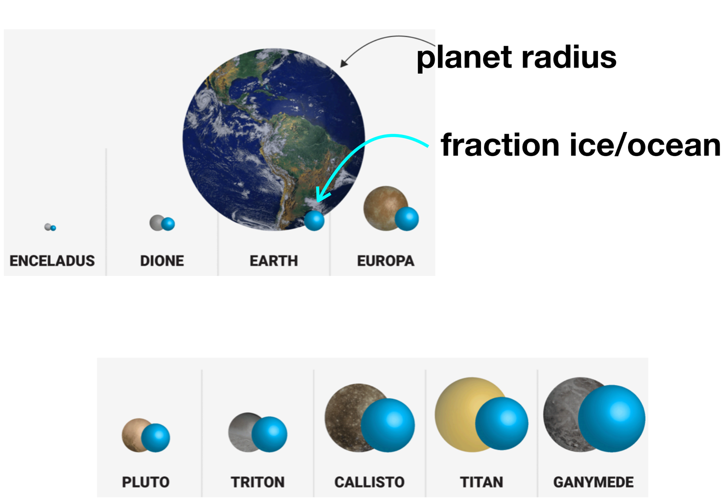
radius (core+mantle+crust) 6378 km

mantle density 3400 kg/m³

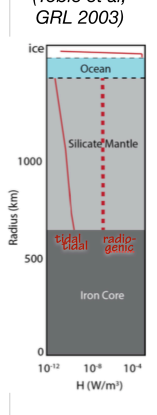
average ocean thickness 3.7 km

and, plate tectonics/volcanism are active so localization of deformation/fractures and heat sources are ongoing & determine pathways of fluid circulation

but physics of flow and chemical exchange apply



(Steve Vance JPL)



Heat Sources

radioactive decay of minerals in rocky interior (H_{rad})

dissipation of tidal forces (H_{tidal})- interior & ice shell

exothermic serpentinization reaction in olivine-rich rock

Earth's mantle radiogenic heat production H_{rad} is ~20 x 10^{12} W and H_{tidal} is negligible. Solid deformation due to tidal forcing (u_r, includes ice on icy satellites) is 0.2-0.3 m

(Vance et al, Astrobiology 2007)

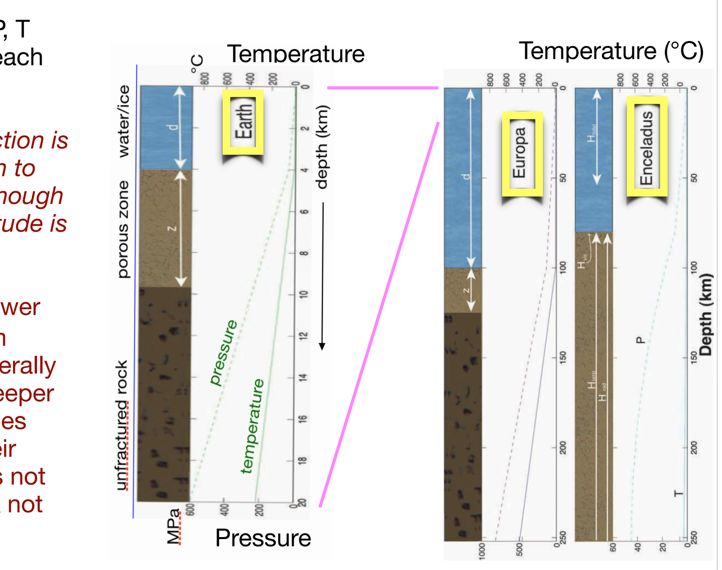
	k_2	h_2	Im (k_2)	H_{rad} ($\times 10^9$ W)	H_{tidal} ($\times 10^9$ W)	H_{tidal}/H (%)	u_r (m)
Europa	0.242	1.169	0.0054	198	2870	94	27.4
Enceladus	0.066	0.177	0.0036	0.256	5.00	95	3.8
Titania	0.034	0.096	0.0025	9.26	0.0024	0.25	0.07
Oberon	0.028	0.076	0.0032	7.34	~10^{-4}	~0	0.008
Triton	0.163	0.555	0.0052	69.40	0.17	0.25	0.24

thermal cracking via volume expansion by serpentinization

calculated for P, T conditions on each body

>> Earth prediction is not great match to observations (though order of magnitude is ok)

Porosity of lower crust (> 1 km depth) is generally negligible. Deeper fractured zones occur but their distribution is not well known & not pervasive



estimated thickness of porous interior layer

where ocean fluid might be able to circulate *(Vance et al., 2007)*

Conclusion. Interpreting Ocean World hydrothermal conditions will be challenging, but some fundamental aspects of Earth's seafloor hydrothermal systems are analogous. Sensitivity analysis across the range of possible parameter scenarios for Ocean Worlds can generate testable hypotheses, guide refinement of future simulations, suggest advances in planetary instrumentation and help focus interdisciplinary discovery.

References

Ballard, R, Ocean Exploration Trust & E/V Nautilus: the first 10 yrs, *Oceanography* Supplement p14-19, March 2019.

Baumberger, T et al., Further exploration of methane seeps on Cascadia margin, *Oceanography* Supplement, p40-41,March 2019.

Blackman, D, ASlagle, GGuerin, and AHarding , Geophysical signatures of past and present hydration within a young oceanic core complex, *GRL* doi: 10.1002/2013gl058111, 2014.

Blackman, D, NAbe, RCarlson, GGuerin, BIldefonse, AKumpf,, Seismic properties of gabbroic sections in oceanic core complexes: Constraints from seafloor drilling, *MGR* doi: 10.1007/s11001-019-09385-7, 2019.

Escartín, & PCanales, Detachments in oceanic lithosphere: Deformation, magmatism, fluid flow, and ecosystems, *Eos Trans. AGU,* doi:10.1029/2011EO040003, 2011.

Fryer P et al, Mariana serpentinite mud volcanism exhumes subducted seamount materials: implications for the origin of life. *Phil. Trans. R. Soc. A,* doi: 10.1098/rsta.2018.0425, 2020.

Hutnak, M, AFisher, RHarris, CStein, KWang, GSpinelli, MSchindler, HVillinger, ESilver, Large heat & fluid fluxes driven thru mid-plate outcrops on ocean crust, *Nat Geo*, doi: 10.1038/ngeo264, 2008.

Kelley, D et al, An off-axis hydrothermal vent field discovered near the Mid-Atlantic Ridge at 30°N, Nature. doi.org/10.1038/35084000 , 2001.

McCaig A & M Harris, Hydrothermal circulation and the dike-gabbro transition in the detachment mode of slow seafloor spreading, *Geology*, doi: 10.1130/G32789.1, 2012.

Weekly, RT, WWilcock, DToomey, EHooft, EKim, Upper crustal seismic structure of the Endeavour Segment, Juan de Fuca Ridge from travel time tomography: , *G³* doi: 10.1002/2013GC005159, 2014.

References

Crone, T, WWilcock, RMcDuff, Flow rate perturbations in a black smoker hydrothermal vent in response to a mid-ocean ridge earthquake swarm, G³ doi:10.1029/2009G002926, 2010.

Fontaine, F, WWilcock, DFoustoukos, DButterfield, A Si-Cl geothermobarometer for the reaction zone of high-temperature, basaltic-hosted mid-ocean ridge hydrothermal systems, G³ doi:10.1029/2009GC002407, 2009.

Kuskov, O & V Kronrod, Internal structure of Europa and Callisto, Icarus doi: 10.1016/j.icarus.2005.04.014, 2005.

Marjanović, M., TBarreyre, FFontaine, JEscartín, Investigating fine−scale permeability structure and its control on hydrothermal activity along a fast−spreading ridge (EPR 9°43′–53′N) using seismic velocity, poroelastic response, and numerical modeling, *GRL* doi: 10.1029/2019GL084040, 2019.

Tobie, G, GChoblet, CSotin, Tidally heated convection: Constraints on Europa's ice shell thickness *JGR* doi: 10.1029/2003JE002099, 2003.

Vance, S, JHarnmeijer, JKimura, HHussmann, BDemartin, JMBrown, Hydrothermal systems in small ocean planets, *Astrobiology* doi: 10.1089/ast.2007.0075, 2007.

Winslow, D, AFisher, P.Stauffer, CGable, GZyvoloski, 3-D modeling of outcrop-to-outcrop hydrothermal circulation on the eastern flank of the Juan de Fuca Ridge, *JGR* doi: 10.1002/2015JB012606., 2016

Winslow, D & AFisher, Sustainability and dynamics of outcrop-to-outcrop hydrothermal circulation, *Nature Comm*, 6, 10.1038/ncomms8567, 2015.