A global assessment of deep-sea basalt sites for carbon sequestration

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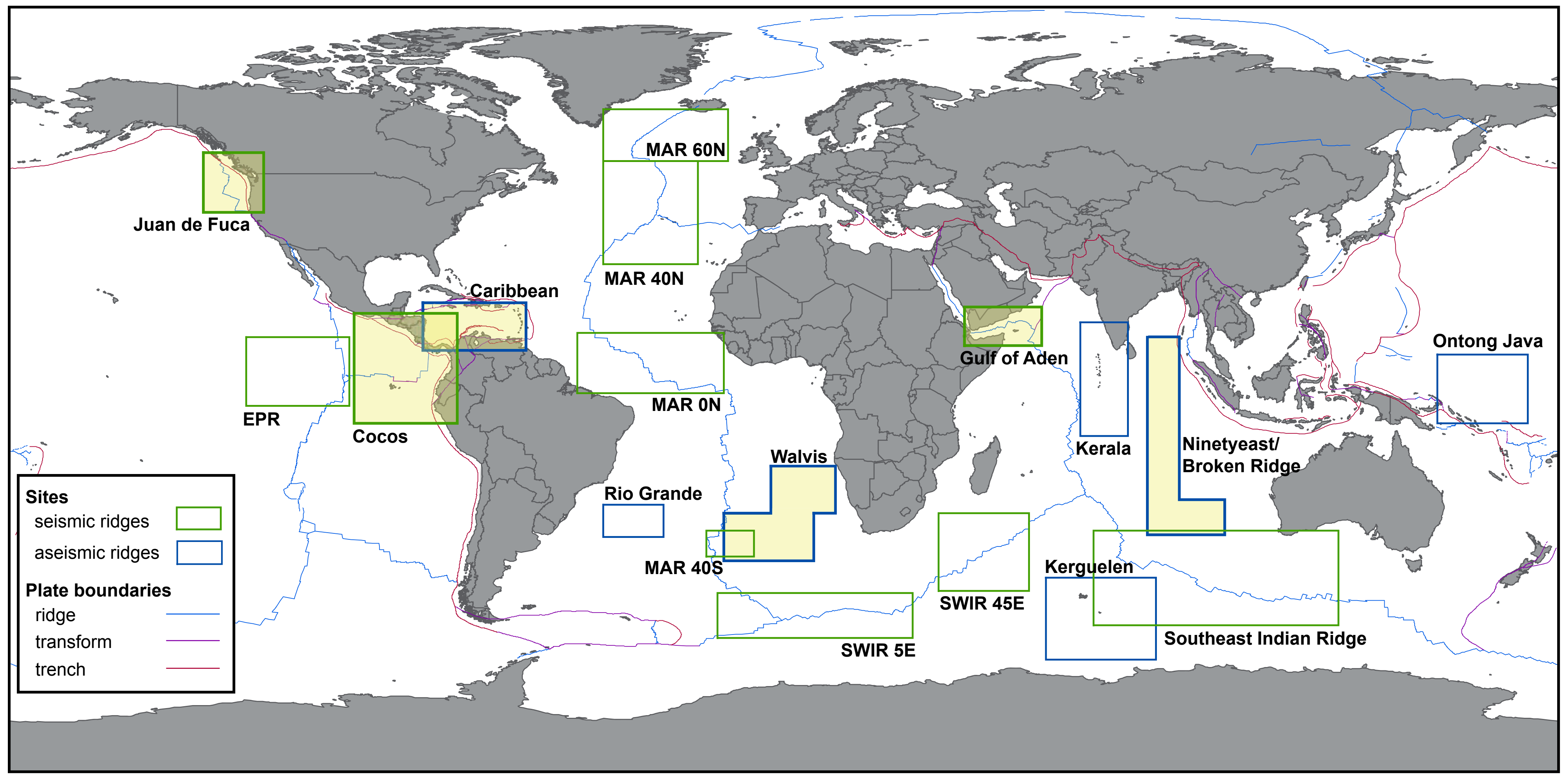
Sites investigated for potential deep-sea carbon sequestration



Global sites considered in our assessment for deep-sea basalt CO_2 sequestration. Eleven seismic ridge sites (green boxes) and seven aseismic ridge sites (blue boxes) were identified with sediment thickness ≥ 200 m for this study. The sites highlighted in yellow are detailed below.

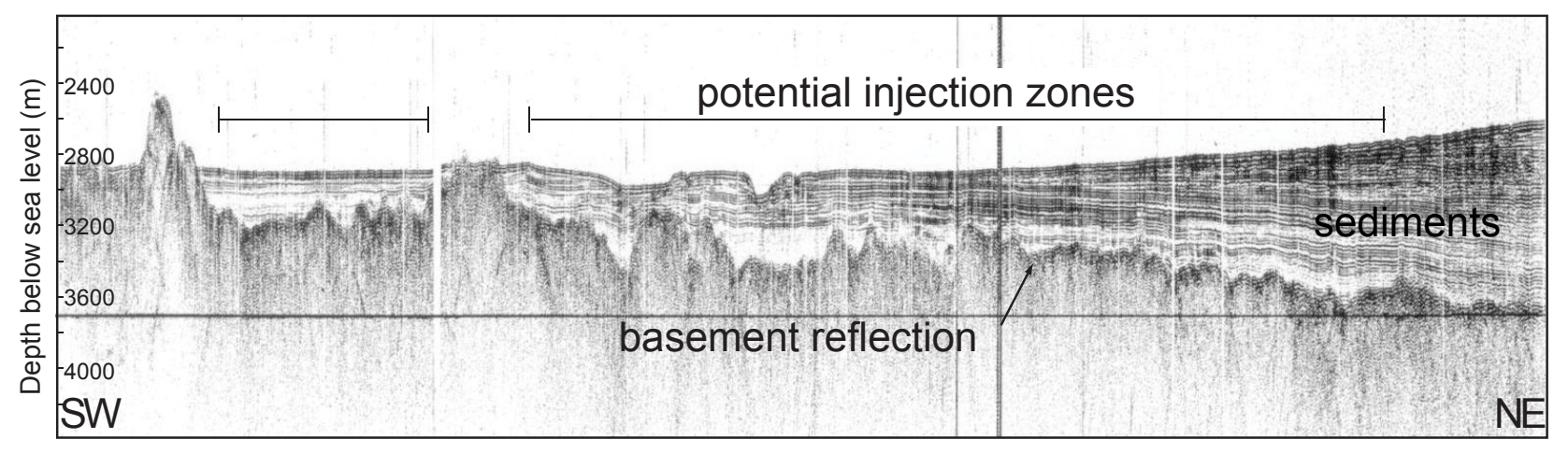
Abstract

In recent years, the debate over the most effective means to stabilize greenhouse gas concentrations in the atmosphere has endorsed multiple approaches and a variety of technologies. Assuring secure storage of anthropogenic carbon dioxide is one of our most pressing global scientific challenges that may contribute to achieving a stable solution over the next several decades. Geological sequestration by injection into deep-sea basalt formations provides unique and significant advantages over other potential storage options, including: (a) vast reservoir capacities with high porosity and permeability, sufficient to accommodate centuries-long U.S. production of fossil fuel CO_2 at locations within a few hundreds of kilometers of populated areas; (b) chemical reactivity of CO_2 with basalt and in situ fluids to produce stable, non-toxic carbonates; and (c) significant risk reduction for post-injection leakage by geological, gravitational, and mineral trapping mechanisms. We compare independent trapping mechanisms available in deep-sea basalts to those in saline aquifers, which have also been proposed as potential storage environments for anthropogenic carbon dioxide. We suggest that deep-sea basalts offer significant advantages over saline aquifers, in terms of reduced risk of post-injection leakage and storage capacity. Using a global site assessment strategy to highlight the most secure oceanic basalt sites that provide all trapping mechanisms, we initially identify potential target regions that occur in deep-sea basalt and calculate the potential injection volume for each. The largest volumes and most secure basalt sites occur in regions adjacent to intermediate- to fast-spreading seismic ridges as well as deep aseismic ridges. We then use site-specific criteria, such as abundance of ODP and IODP drill sites with basement penetration, permeability and/or porosity data, to refine volume calculations and to prioritize these target regions as promising locations to securely accommodate carbon dioxide injection. Pilot injection studies in deep-sea basalts are necessary to establish the viability of these reservoirs for future CO_2 sequestration. We suggest that basaltic crust at deep ocean sites offers vast capacity and potential for permanent sequestration of carbon dioxide to mitigate atmospheric build-up of this greenhouse gas.

Benefits of Deep-Sea Geological Sequestration in Basalt

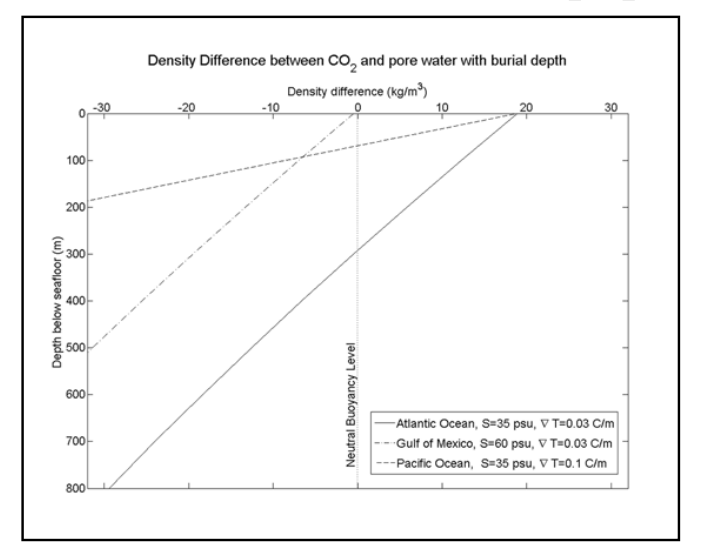
- High porosity and storage capacity
- High permeability and injection potential
- Safe and secure long-term CO_2 sequestration: Hierarchy of multiple trapping mechanisms

1. Physical Trapping



Seismic line across Juan de Fuca Plate (R/V Conrad 1501)

2. Gravitational Trapping



Levine et al. (2007); House et al. (2006)

3. Mineral Trapping

Natural Analog: Magnesite filled fractures in Oman

$CaAl_2Si_2O_8 + CO_2 + 2H_2O = CaCO_3 + Al_2Si_2O_5(OH)_4$

(Matter et al., 2006)

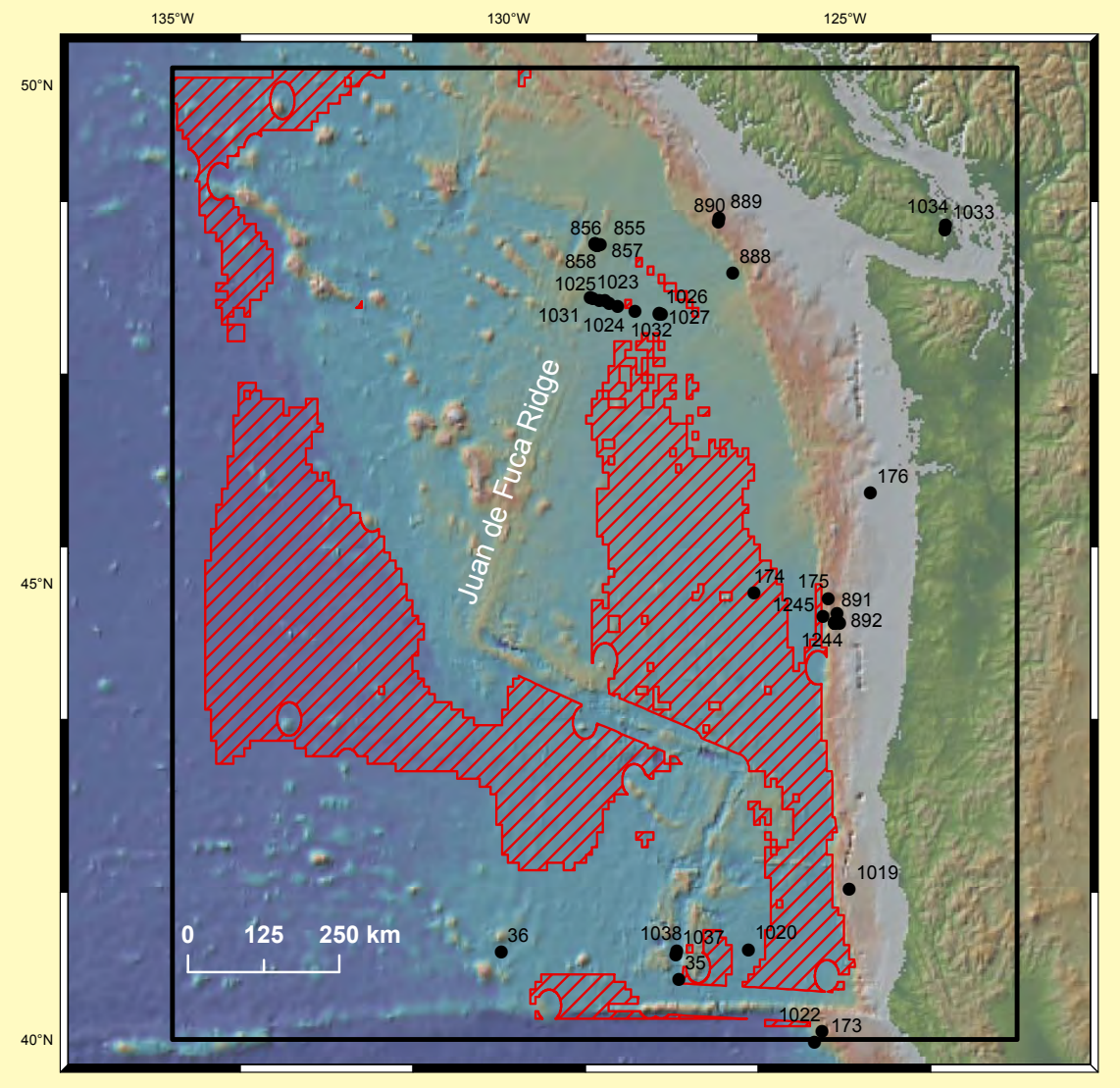
Site Assessment Strategy - Identify deep-sea basalt sites that provide all trapping mechanisms.

1. **≥ 200 meters of sediment cover provides physical trapping** (from Divins, 2007).
2. **≥ 2700 meters of water depth provides gravitational trapping** (from the Marine Geoscience Data System, http://www.marine-geo.org; Smith & Sandwell, 1997).
3. **Oceanic basalt provides high permeability layers** (e.g. Spinelli and Fisher, 2002) **and mineral trapping potential** (Goldberg, 1999).

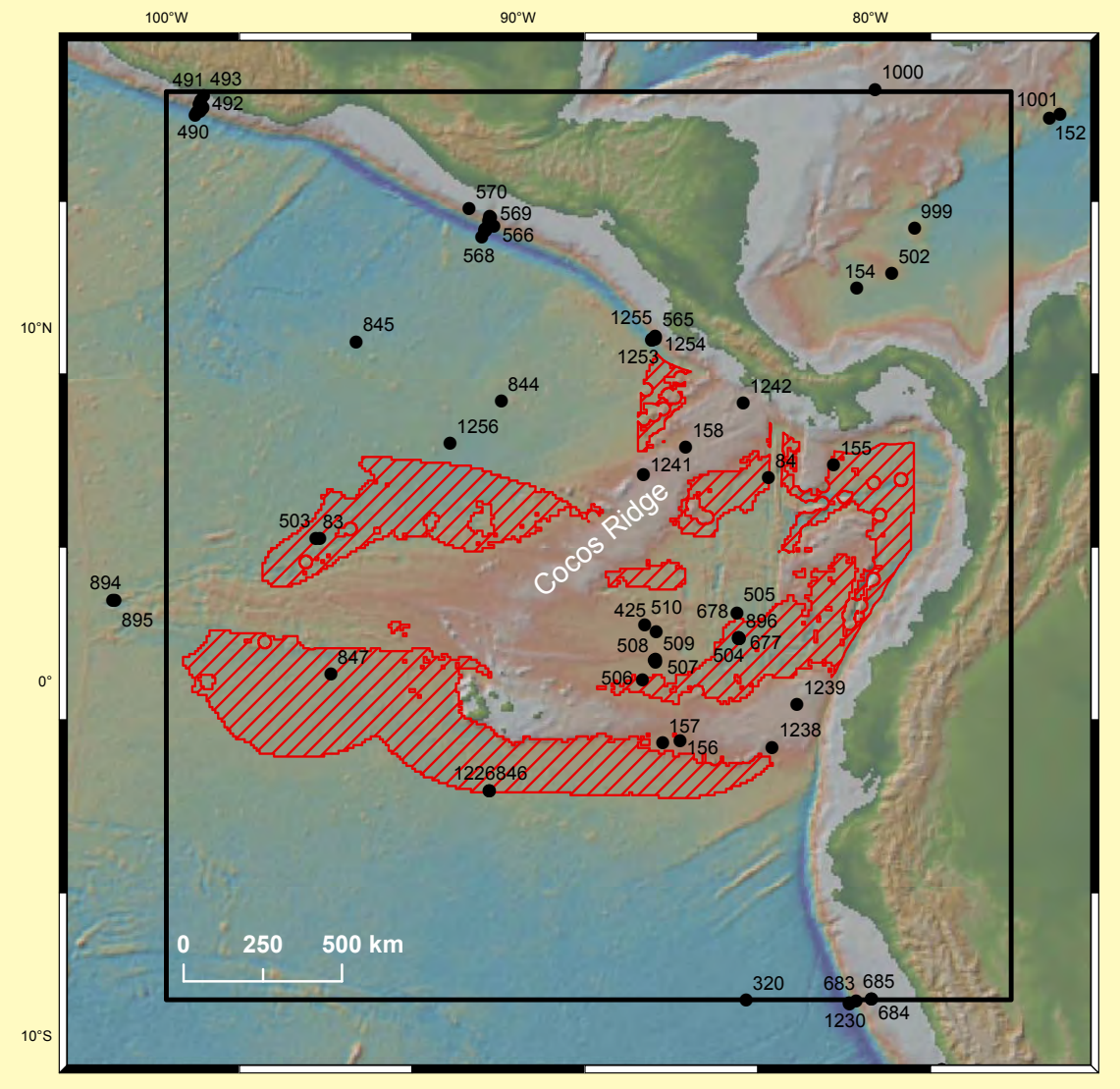
Seismic Ridge Sites

Location maps of potential seismic ridge sites. For each site, the red hatched area represents water depths ≥ 2700 m and sediment thickness ≥ 200 m, excluding 20 km distance from seamounts and plate boundaries (Goldberg et al., 2008; Goldberg and Slagle, 2008).The outer boundaries are constrained within 15-my crust, beyond which > 50% of intergranular-scale pore space is filled by crustal alteration (Jarrard et al., 2003). DSDP, ODP, and IODP drillsite locations are indicated by black circles.

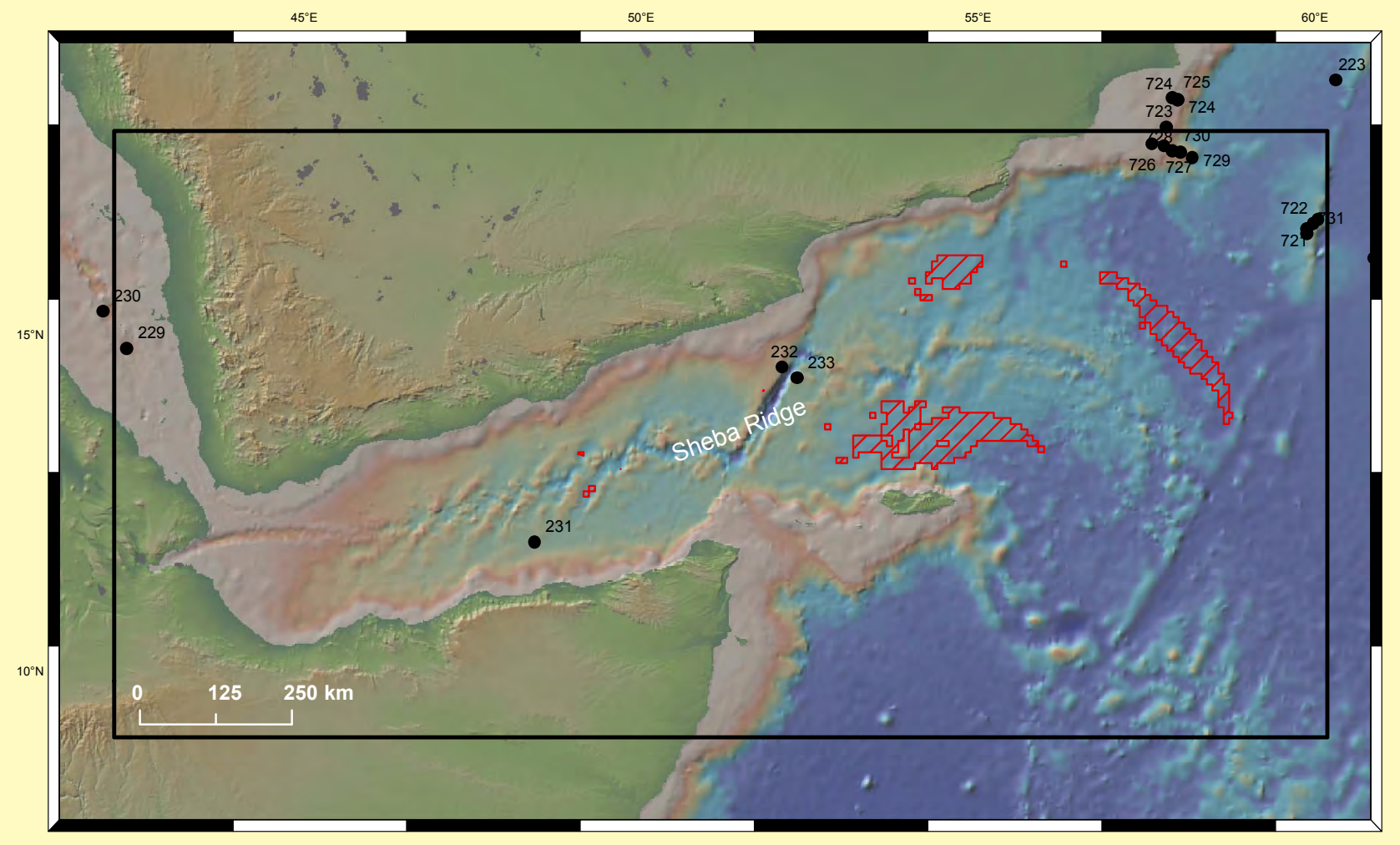
Juan de Fuca Ridge



Cocos Ridge



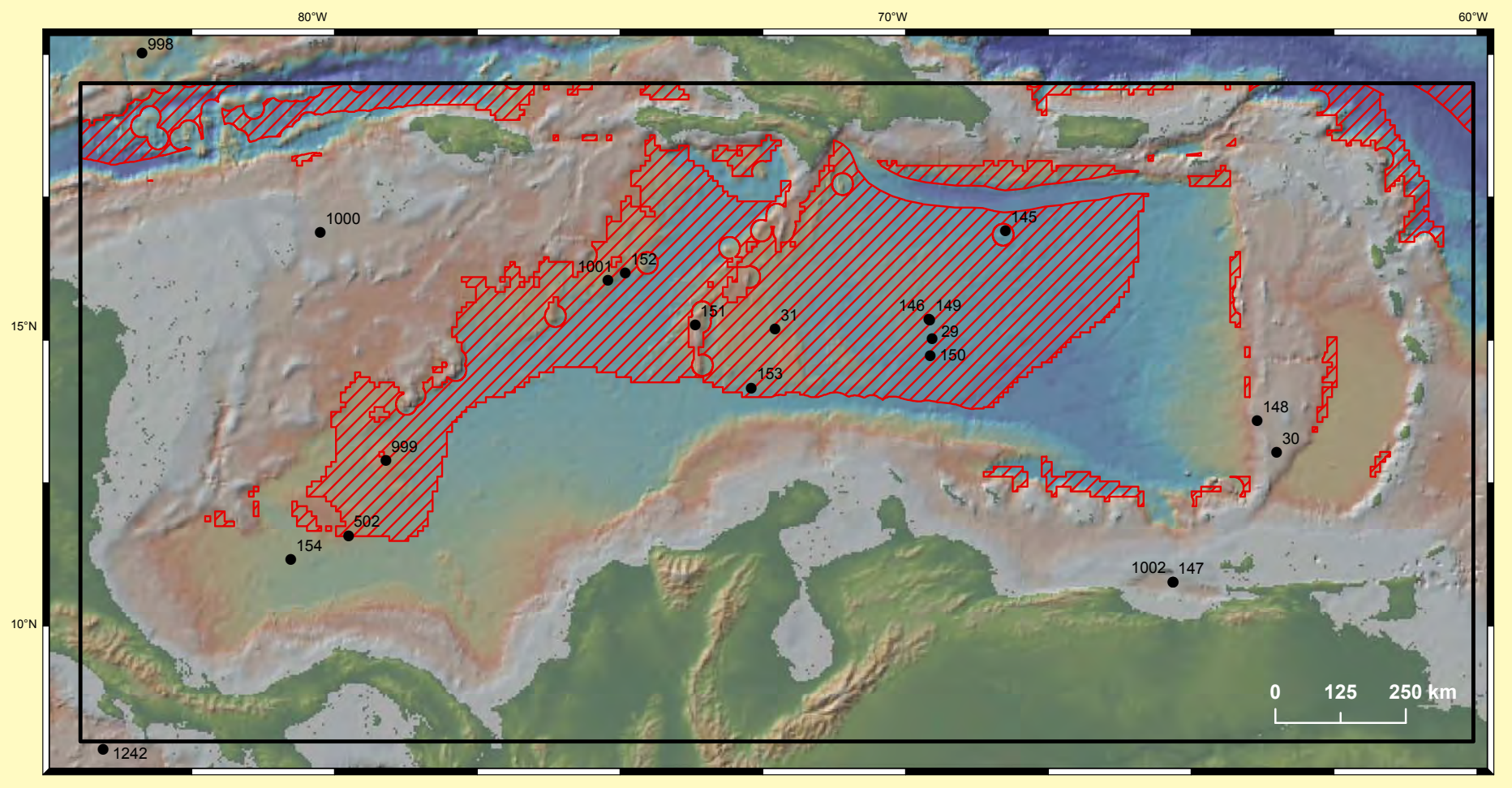
Gulf of Aden



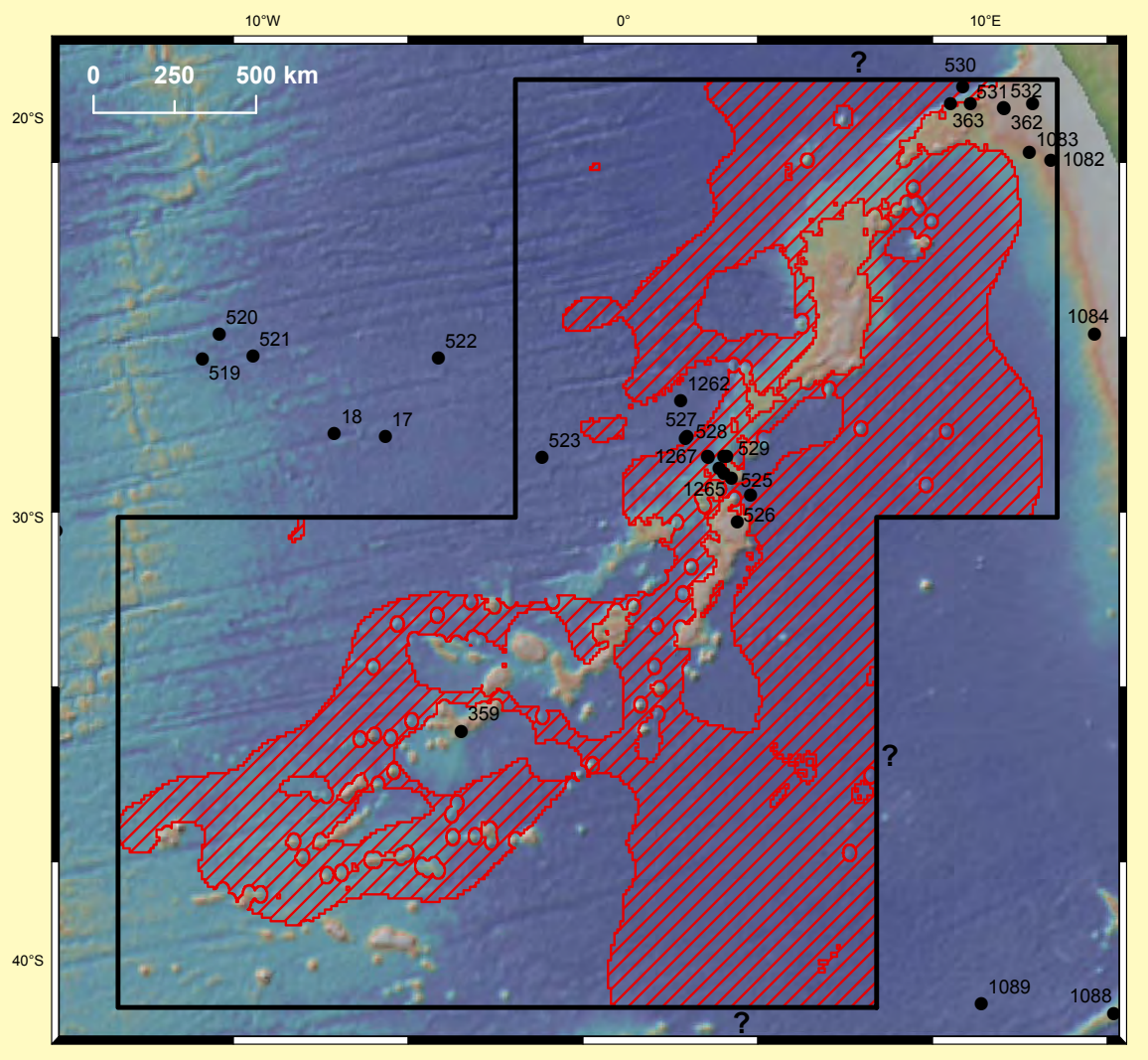
Large Igneous Provinces (Aseismic Ridge Sites)

Location maps of potential aseismic ridge sites (large igneous provinces, in Coffin & Eldholm, 1994). For each site, the red hatched area indicates water depths ≥ 2700 m and sediment thickness ≥ 200 m, and excludes 20 km distance from seamounts and plate boundaries (Goldberg and Slagle, 2008). Unconstrained boundaries at each site are indicated ("?"). DSDP, ODP, and IODP drillsite locations are indicated by black circles.

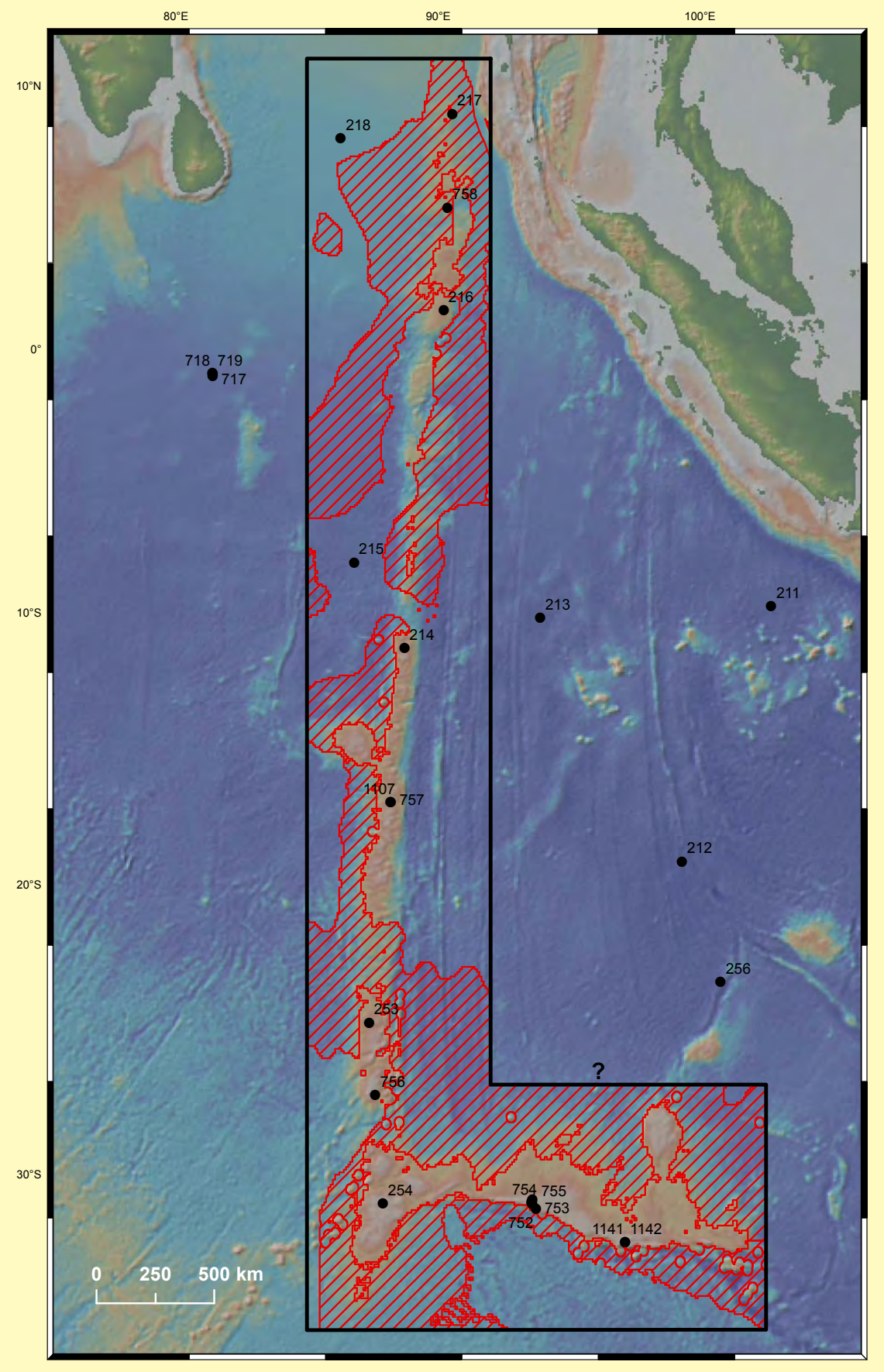
Caribbean flood basalt



Walvis Ridge



Ninetyeast and Broken Ridges



		Computed Reservoir Volume (km^3)				
		20 m net thickness	20 m net thickness	100 m net thickness	100 m net thickness	
Region	**Area (km^2)**	5% eff. porosity	10% eff. porosity **	5% eff. porosity	10% eff. porosity	**Carbon Min.(Gt)*** **
Juan de Fuca Ridge	244,963	**245**	490	1,225	2,450	**67**
East Pacific Rise	491,561	**492**	983	2,458	4,916	**134**
Cocos Ridge	891,510	**892**	1,783	4,458	8,915	**243**
Mid-Atlantic Ridge 60N	52,734	**53**	105	264	527	**14**
Mid-Atlantic Ridge 40N	139,141	**139**	278	696	1,391	**38**
Mid-Atlantic Ridge 0	220,842	**221**	442	1,104	2,208	**60**
Mid-Atlantic Ridge 40S	3,778	**4**	8	19	38	**1**
Southwest Indian Ridge 5E	81,329	**81**	163	407	813	**22**
Southwest Indian Ridge 45E	15,757	**16**	32	79	158	**4**
Gulf of Aden	30,763	**31**	62	154	308	**8**
Southeast Indian Ridge	2,068,304	**2,068**	4,137	10,342	20,683	**564**
Caribbean flood basalt	541,611	**542**	1,083	2,708	5,416	**148**
Rio Grande Rise	831,818 *	**832**	1,664	4,159	8,318	**227**
Walvis Ridge	1,933,711 *	**1,934**	3,867	9,669	19,337	**527**
Kerala Basin	952,761	**953**	1,906	4,764	9,528	**260**
Ninetyeast Ridge/Broken Ridge	2,198,757	**2,199**	4,398	10,994	21,988	**600**
Kerguelen Plateau	1,788,834 *	**1,789**	3,578	8,944	17,888	**488**
Ontong Java Plateau	2,616,646 *	**2,617**	5,233	13,083	26,166	**714**

* LIP boundaries not well-constrained by bathymetry or sediment cover

** based on in situ density logs (e.g. Goldberg, 1999)

*** Carbon calculation using minimum reservoir volume; assumes CO_2 liquid fills pore space; if $CaCO_3$ fills pore space, capacity increases by ~ one third

Total Seismic Sites	**1,156 Gt**
Total Aseismic Sites	**2,963 Gt**
Total for All Sites	**4,119 Gt**

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Implications

- At current U.S. annual emission rates of 1.7 Gt Carbon, even individual oceanic basalt ridges have sufficient capacity for tens to hundreds of years of safe and secure sequestration of anthropogenic CO_2.
- The worldwide total volume potential is 4.1 Tt-C, assuming the minimum reservoir thickness estimates (see Table). These estimates may be as much as ten times greater than the minimum calculation, for higher porosity and greater reservoir thicknesses.
- Large volumes exist at seismic ridges in reasonable proximity to CO_2 sources along continental margins, such as the **Cocos Ridge**, **the Juan de Fuca Ridge**, and the **Sheba Ridge in the Gulf of Aden**.
- Aseismic ridge sites may provide three times greater capacity than seismic ridge sites. However, pore volume estimates and area assessments are significantly less well-constrained.
- Further investigations are needed to measure in situ properties at specific sites. A pilot injection study in deep-sea basalt would establish the viability of these reservoirs for CO_2 sequestration.