Fluid Flow Through Seamounts: Implications for Global Heat and Mass Flux

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Abstract

Hydrothermal circulation through the oceanic crust plays an integral role in governing the physical, chemical, and biological state of both the crust and ocean. Estimates of seafloor heat transfer indicate that fluid flow is responsible for 34% of the global oceanic heat flux, and is thermally significant, on average, to 65 Ma (Stein and Stein, 1994). Processes responsible for limiting advective heat flux between the oceanic crust and the ocean include increasing accumulations of low permeability sediments that cap relatively high permeability basement, decreasing thermal energy to drive flow, and decreasing crustal permeability with increasing crustal age.

Several factors make seamounts ideally suited to overcome these flow limiting processes. First, bathymetric relief associated with seamounts generates thermal buoyancy forces in excess of those present in flat seafloor. Second, seamount edifices are constructed mainly of extrusive basalt that is likely to have relatively high permeability. Third, seamounts tend to remain sediment free much longer than the surrounding seafloor, thereby providing areas of exposed basement where fluid can exchange with the ocean unencumbered by low-permeability sediments.

Several marine geophysical studies demonstrate that seamounts can efficiently recharge and discharge hydrothermal fluids and cool the oceanic crust. However, flow through these features is poorly understood. Numerical models of coupled heat and fluid flow illustrate how basement relief coupled with a constant bottom water temperature condition generates horizontal temperature gradients within the oceanic crust sufficient to drive flow at modest permeability. Using the global database of seamounts we show that seamounts can contribute to globally significant hydrothermal fluxes. We estimate that the mass flux associated with global database of ~15,000 seamounts is ~10^{14} kg/yr, a number comparable to mass flux through mid-ocean ridges and flanks. Seamount generated advective heat flux may be locally significant well beyond the 65 Ma average age at which advective lithospheric heat loss on ridge flanks ceases. These flows may be important for facilitating heat loss, geochemical exchange between the crust and ocean and may affect subseafloor microbial ecosystems.

Take Home Points

1. Seamounts are hydrologically active and may play a significant role in ventilating the oceanic crust across much of the seafloor, even tens of kilometers from basement outcrops.
2. The presence of topographic relief (the seamounts) stimulates convections and is effective at ventilating the oceanic crust. Fluid flow is driven by buoyancy forces.
3. Simple calculations suggest that the flux of heat and mass through seamounts are globally important.

References

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Field Examples

1. East Pacific Rise

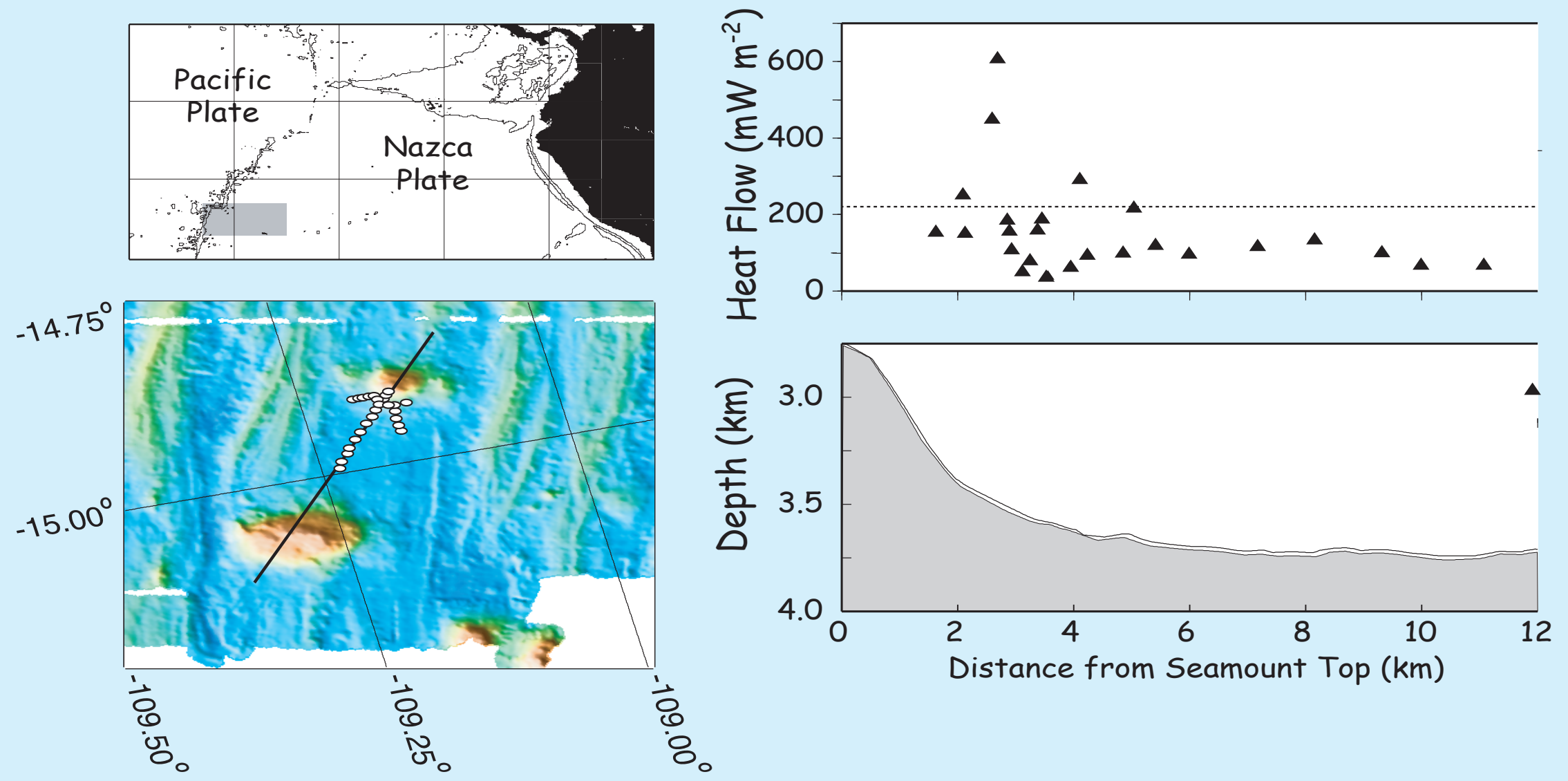


Figure 1. Heat Flow data across a thinly sedimented ridge flank on 4 Ma oceanic crust [Villinger et al., 2002]. Heat flow observations are consistent with advective fluid flow toward the seamount and discharge through it.

2. Juan de Fuca

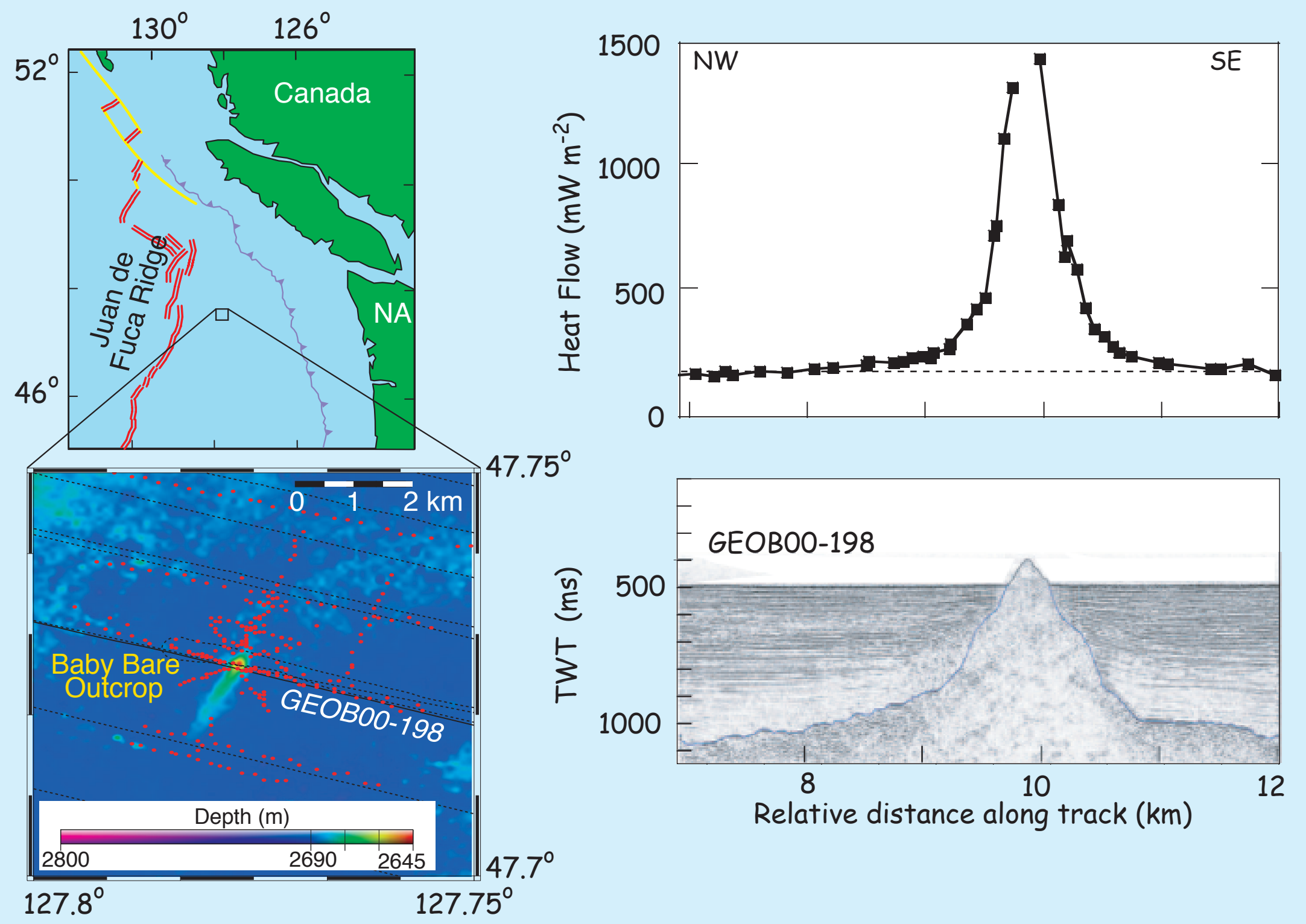


Figure 2. Heat flow data across a thickly sedimented ridge flank on 3.5 Ma crust [Fisher et al., 2003].

3. Costa Rica

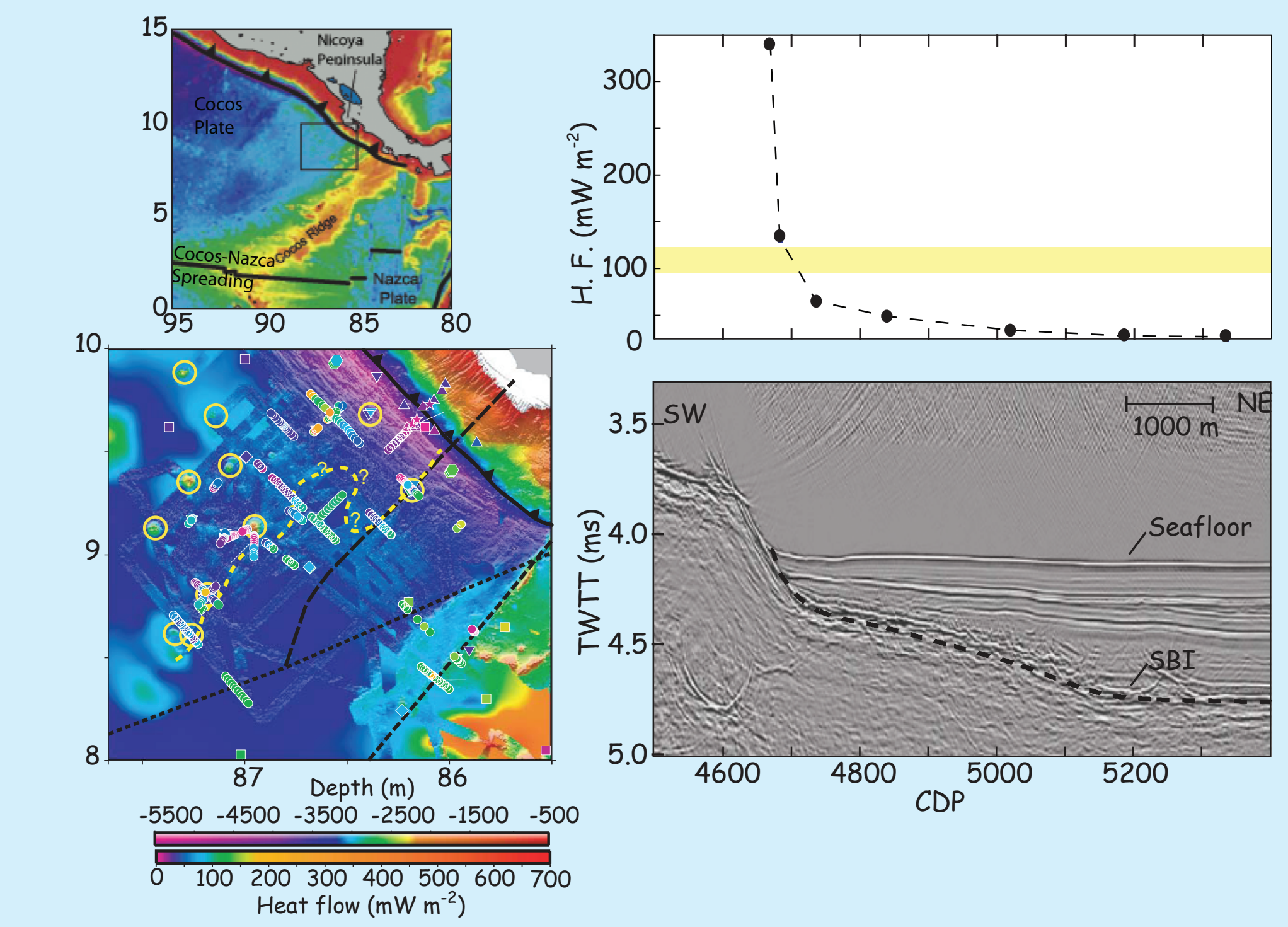


Figure 3. Heat flow data across a thickly sedimented ridge flank on 20-25 Ma crust [Huntnak et al., 2006].

Distribution and Geometry of Seamounts

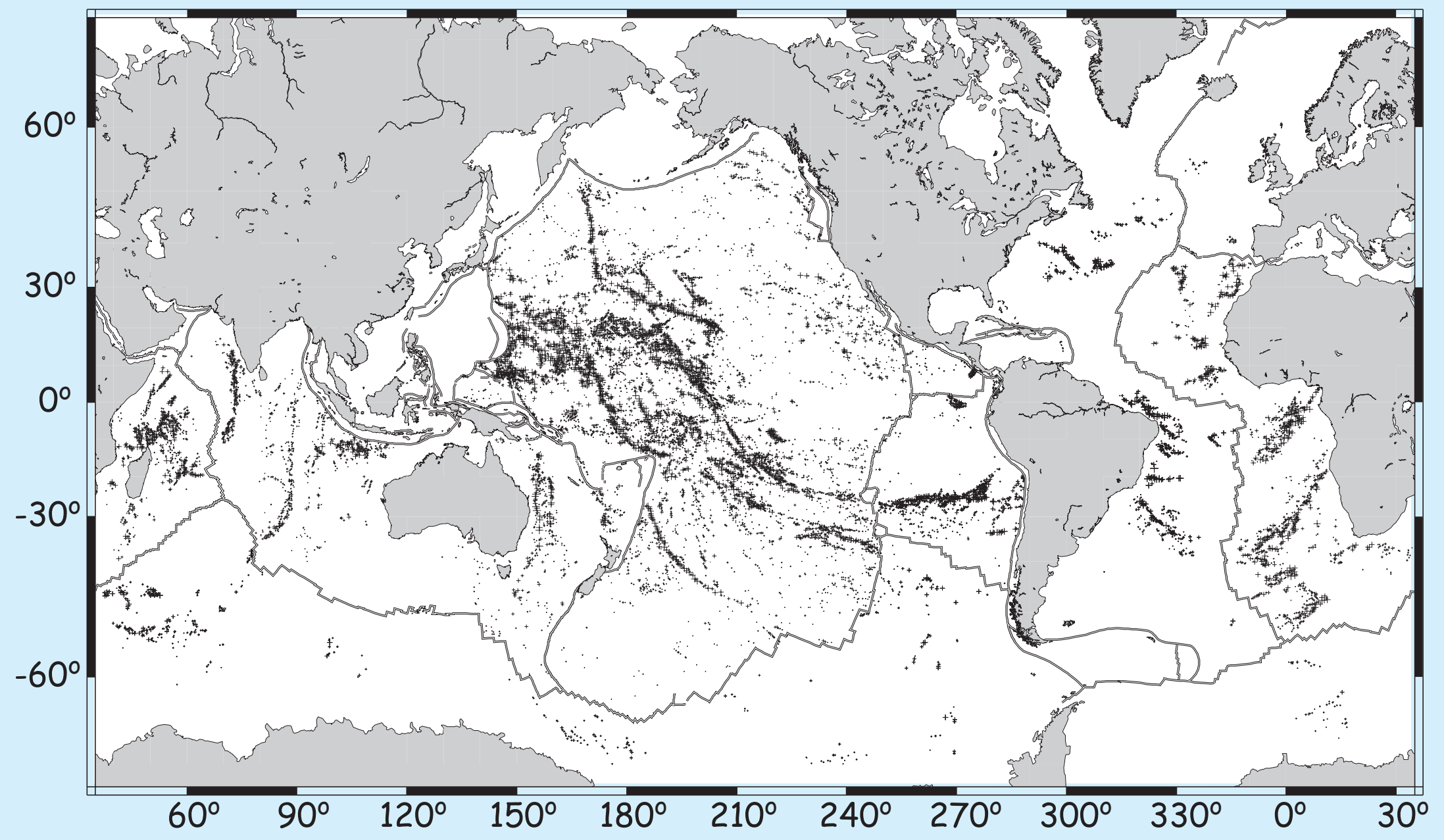


Figure 4. Global distribution of seamounts based on satellite gravimetry between 72° north and south. Seamounts are a globally common phenomena with seamounts in all of the oceans. Slightly fewer than 15,000 seamounts with heights greater than about 2 km are catalogued [Wessel, 2001].

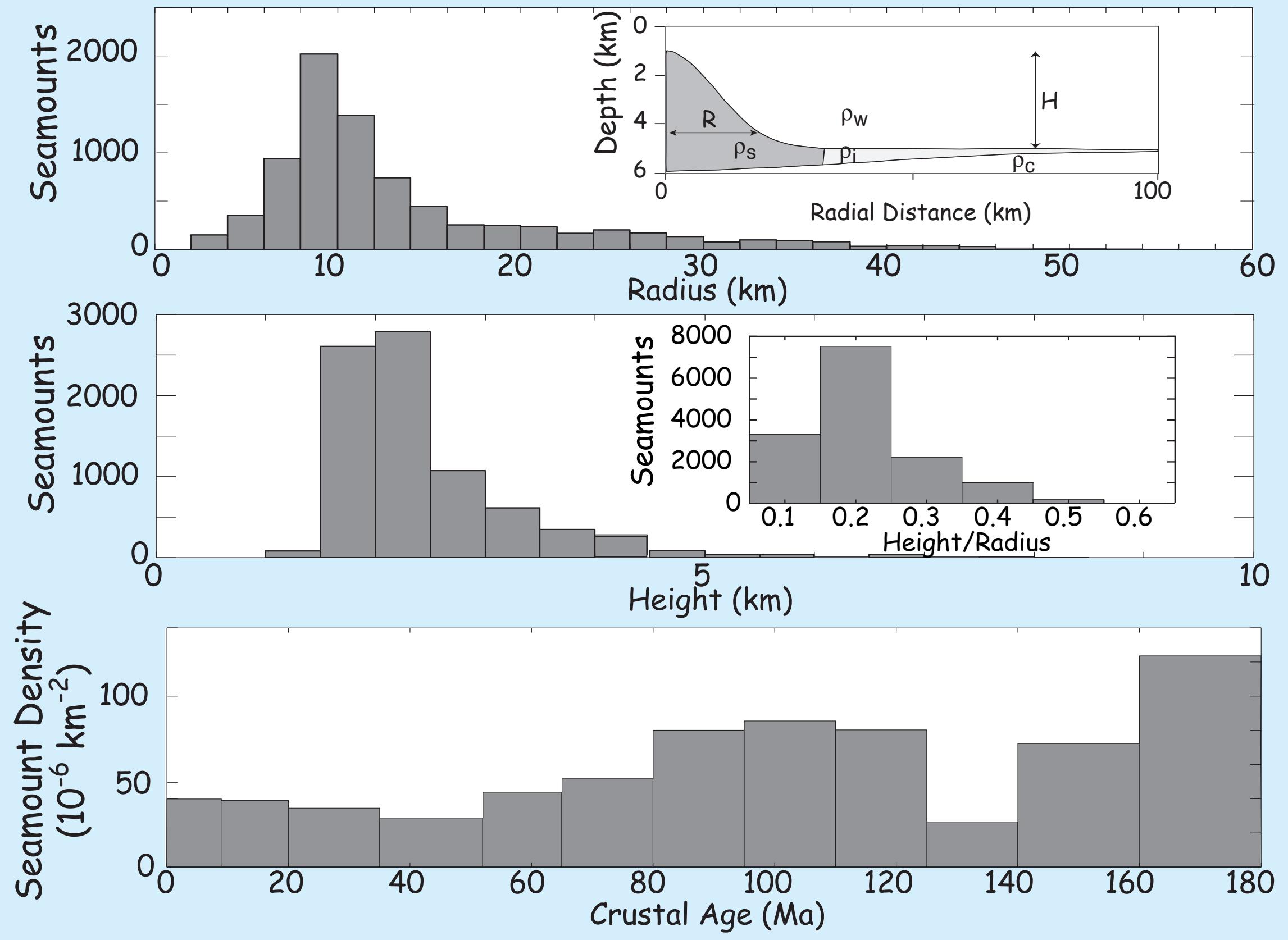
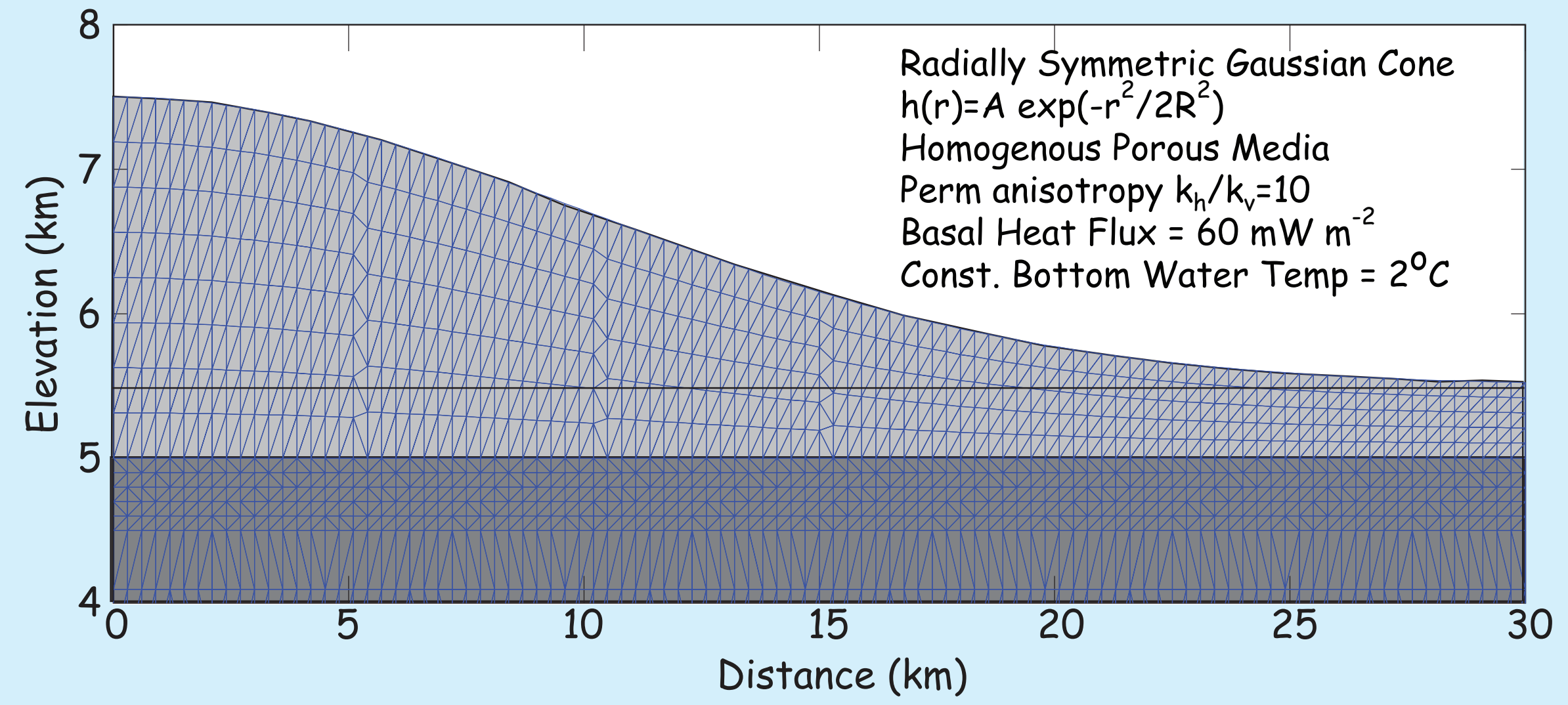


Figure 5. Geometry and age distribution of seamounts. Histograms of seamount geometry are long tailed and well characterized by a power-law distribution such that the actual number of seamounts may be on the order of 100,000, most being too small to be detected by altimetry data [Wessel, 2001]. Observations from several settings suggest that many of these undetected seamounts could be hydrogeologically and thermally important.

Coupled Heat and Fluid Flow Simulations



Radially Symmetric Gaussian Cone
$h(r)=A\exp(-r^2/2R^2)$
Homogenous Porous Media
Perm anisotropy $k_h/k_v=10$
Basal Heat Flux = 60 mW m^{-2}
Const. Bottom Water Temp = 2°C

Figure 6. Finite element mesh used for simulations. The algorithm (FEHM) solves equations appropriate for porous media that approximate fractured rock at a large scale. Fluid properties vary with temperature and pressure.

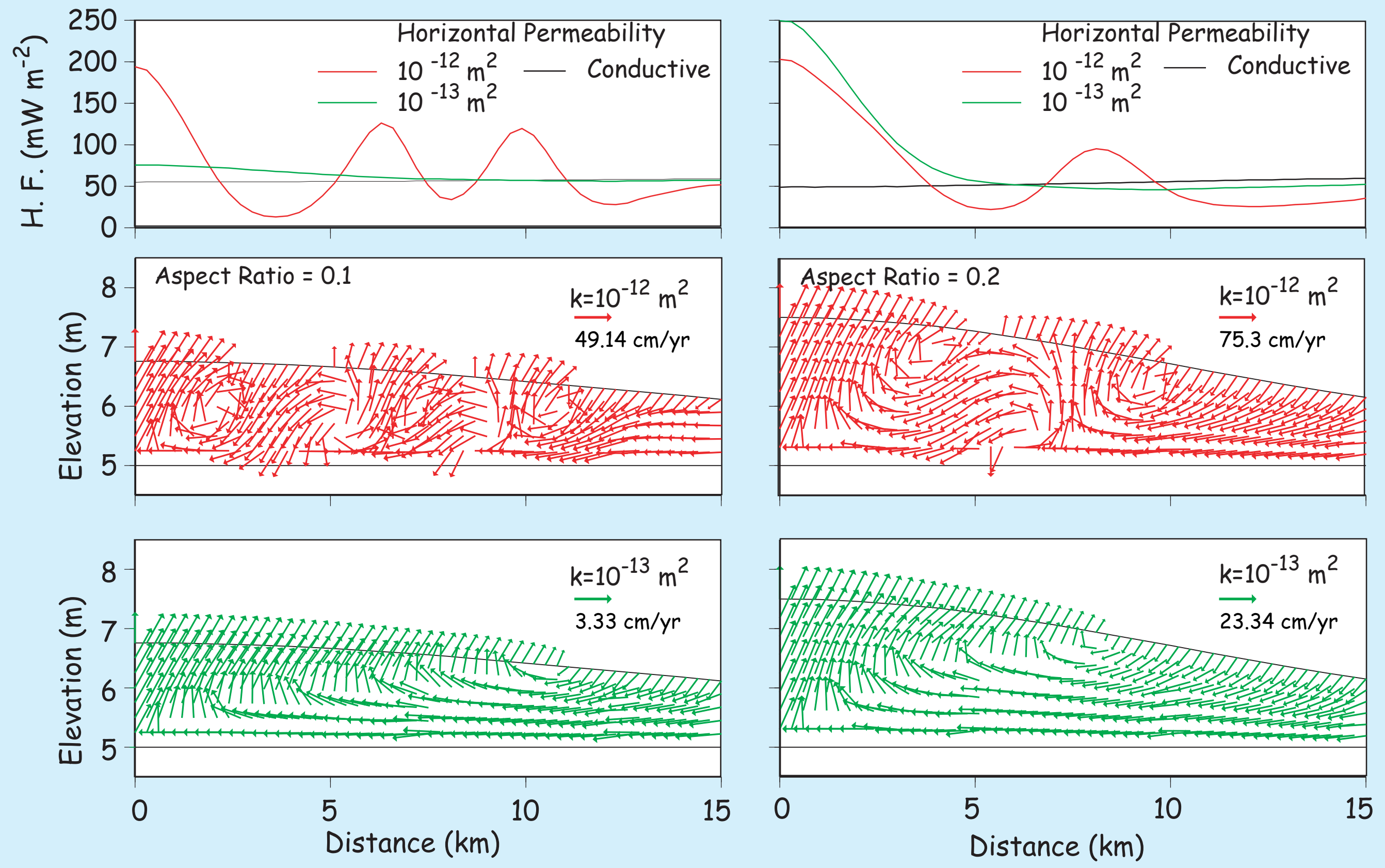


Figure 7. Results of coupled heat and fluid flow for seamounts as a function of permeability and aspect ratio. Note differences in the scales of flow vectors.

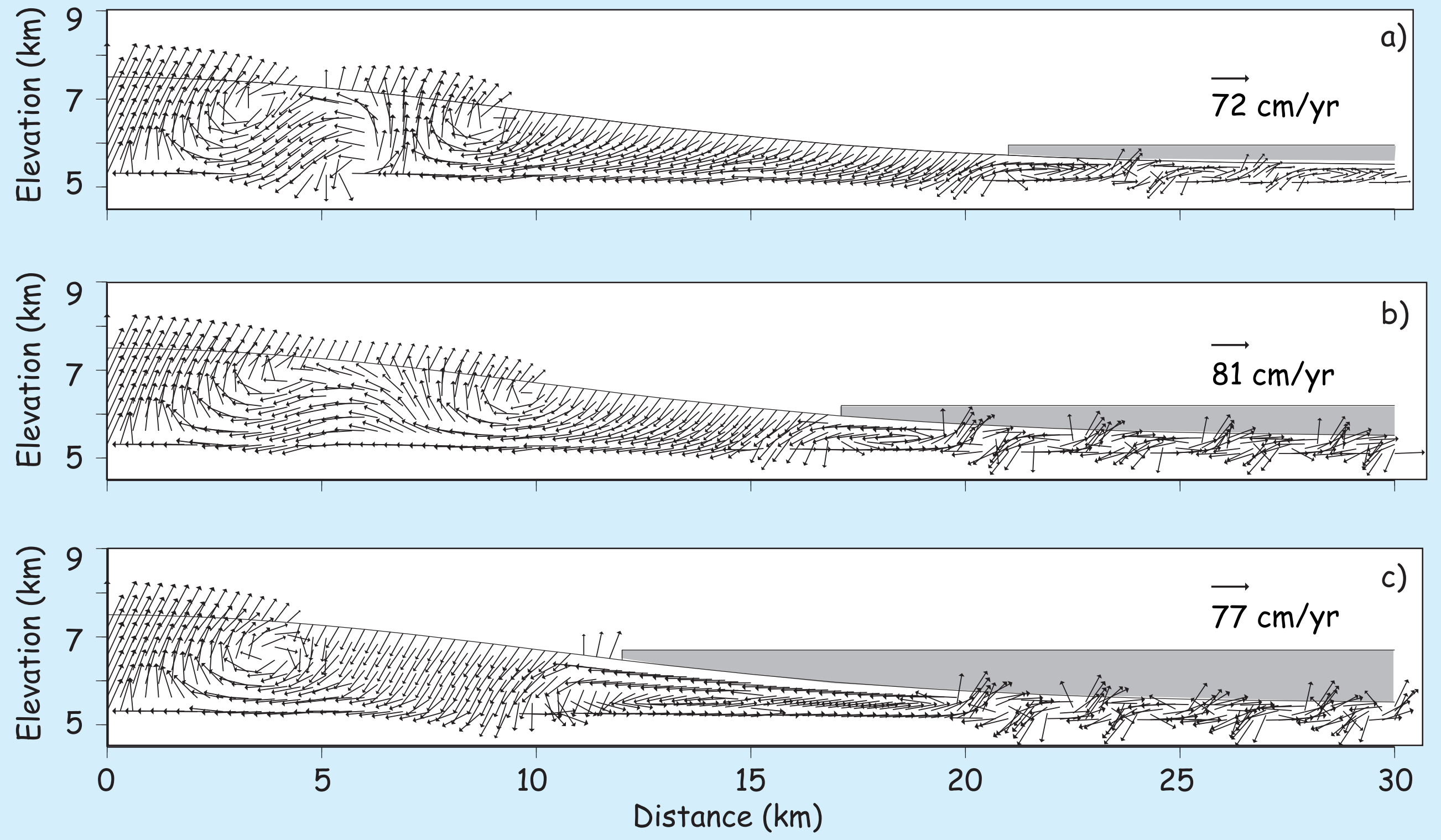


Figure 8. Effect of sediment cover on fluid circulation through seamounts. Effective sediment height: a) 1.5 km, b) 1.0 km, c) 0.5 km.

Estimates of global marine heat and mass fluxes.

Environment	Power W	Mass Flux kg yr^{-1}
Ridge Axis[1] (< 1 Ma)	$1.8 - 3.3 \times 10^{12}$	$3.7 - 8.5 \times 10^{13}$
Ridge Flank[1] (> 1 Ma)	$7.7 - 9.3 \times 10^{12}$	$1.2 - 2.4 \times 10^{15}$
Seamounts (1-180 Ma)	4.1×10^{11}	5.0×10^{14}

[1] Numbers represent ranges of values from Stein and Stein (1994), Schultz and Elderfield (1997), and Mottl (2003).