Mantle helium reveals Southern Ocean hydrothermal venting

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Abstract

Hydrothermal venting along the global mid-ocean ridge system plays a major role in cycling elements and energy between the Earth's interior and surface. We use the distribution of helium isotopes along an oceanic transect at 67°S to identify previously unobserved hydrothermal activity in the Pacific sector of the Southern Ocean. Combining the geochemical information provided by the helium isotope anomaly with independent hydrographic information from the Southern Ocean, we trace the source of the hydrothermal input to the Pacific Antarctic Ridge south of 55°S, one of the major global mid-ocean ridge systems, which has until now been a 'blank spot' on the global map of hydrothermal venting. We identify three complete ridge segments, a portion of a fourth segment and two isolated locations on the Pacific Antarctic Ridge between 145°W and 175°W (representing ~540 km of ridge in total) as the potential source of the newly observed plume.

1. Introduction

The observation of submarine hydrothermal vents along the global mid-ocean ridge system in the late 1970s [*Corliss, et al.*, 1979; *Spiess, et al.*, 1980] remains among the most important discoveries in modern earth science [*German and Von Damm*, 2003]. Hydrothermal circulation impacts global cycling of elements [*Elderfield and Schultz*, 1996], including economically valuable minerals, and provides extreme ecological niches that host unique chemosynthetic fauna [*Lutz and Kennish*, 1993; *Van Dover, et al.*, 2002]. Additionally, trace elements emanating from hydrothermal vents such as ^{3}He are uniquely suited for mapping deep ocean circulation and mixing [*Lupton*, 1998; *Lupton and Craig*, 1981; *Naveira Garabato, et al.*, 2007].

During 30 years of seafloor exploration, more than 220 active vent sites have been identified along the ~ 58,000 km of global mid-ocean ridge crests, over half of them along spreading ridges in the eastern Pacific Ocean [*Baker and German*, 2004]. However, no active venting has been observed south of 38°S in the Pacific Ocean or the Pacific Sector of the Southern Ocean along the Pacific Antarctic Ridge, which traverses 7000 km from the Chile Triple Junction through the Southern Ocean to the Macquarie Triple Junction south of New Zealand.

Here, we use water column measurements of helium isotopes to identify and map a novel source of hydrothermal venting into the Pacific sector of the Southern Ocean. Hydrothermal fluids are enriched by about a factor of 10 in the light isotope of helium, ^{3}He, relative to the atmospheric helium ratio [e.g., *Jenkins, et al.*, 1978; *Lupton and Craig*, 1981]. The source of this ^{3}He excess is mantle ^{3}He trapped in the Earth's interior during its formation and released mainly through volcanic processes at mid-ocean ridges

[*Lupton*, 1983; *Welhan and Craig*, 1979]. Ascending from the seafloor, the hydrothermal fluids entrain ambient seawater, rise until becoming neutrally buoyant and form ^{3}He – tagged hydrothermal plumes [*Helfrich and Speer*, 1995].

Vertical mixing in the ocean is inhibited by density stratification. Thus, dispersion of trace element signals strongly follows isopycnal surfaces along which the energy required for transport is minimized. These surfaces of maximal dispersion have been labeled by a system of neutral density coordinates (γ_n) [*Jackett and McDougall*, 1997], and are nearly horizontal over most of the ocean. They carry conservative tracers over long distances with relatively little diapycnal dispersion. Because it is biologically and chemically inert and has a high signal-to-noise ratio, ^{3}He is uniquely suited as a marker of the neutral density layer into which the hydrothermal signal is injected. Conversely, the presence of a ^{3}He plume can be used to identify and trace hydrothermal activity in the deep ocean over thousands of kilometers.

2. Methods

Helium isotope data used in this study were collected as part of the WOCE hydrographic program and are available from the CLIVAR (Climate Variability and Predictability) & Carbon Hydrographic Data Office (http://whpo.ucsd.edu). Sample collection followed standard WOCE protocols, with helium samples being drawn immediately after opening the seals of the 10-liter Niskin bottles in a multi-bottle sampling rosette. Samples were stored in copper tubes for laboratory analysis, with tritium measured on all samples to correct for ^{3}He ingrowth during storage. P16S samples shallower than about 1500 m were measured at the Woods Hole Oceanographic Institute (PI Jenkins). P16S samples deeper than about 1500 m were measured at the NOAA Pacific Marine Environmental

Laboratory (PI Lupton). S4P samples were measured at Lamont Doherty Earth Observatory (PI Schlosser). Helium isotope ratios are reported as δ^3He, which is the percent deviation of the ^{3}He/^{4}He ratio of the sample (R_{sample}) from that of atmospheric air (R_{air}), defined as $\delta^3\text{He} = [R_{sample}/R_{air} - 1]*100$. All three laboratories report a 1σ precision of approximately 0.2% in δ^3He.

The neutral densities along P16S and S4P were calculated from salinity, temperature and pressure data collected on-board. For locating potential vent sites, the depth of the 28.2 neutral density surface was calculated using the Southern Ocean Database (SODB, available at http://woceSOatlas.tamu.edu [*Orsi and Whitworth III*, 2005]), which is a compilation of hydrographic data from approximately 93,000 stations south of 25°S. The algorithms of Jackett and McDougall (1997) were applied to the salinity, temperature, pressure, and position of the station data to calculate the neutral density. Neutral density surface depths were interpolated linearly in the vertical to the 28.2 surface and, using a cubic spline, in the horizontal to a 1°-grid for comparison with the TBASE bathymetry from the National Geophysical Data Center [*Row and Hastings*, 1999].

3. Results and Discussion

We evaluate the distribution of ^{3}He along two ocean transects from the WOCE hydrographic program [*Talley*, 2007]: the meridional WOCE line P16S at 150°W and the zonal transect S4P at 67°S in the Pacific sector of the Southern Ocean (Figure 1a).

The meridional transect along WOCE line P16S at 150°W displays the well-known major South Pacific helium plume [*Lupton*, 1998; *Lupton and Craig*, 1981] with δ^3He values of up to approximately 35%. The helium plume emanating from the Southern East Pacific Rise (S-EPR) is well-mapped [*Lupton*, 1998; *Takahata, et al.*, 2005] and its primary source vent fields have been investigated [*Auzende, et al.*, 1996; *Baker, et al.*, 2002; *Urabe, et al.*, 1995]. The S-EPR helium plume is centered on the γ_n=27.9 surface (Figure 1b). This density surface, and the center of the S-EPR plume, can be identified at about 2500 m water depth throughout most of the South Pacific Ocean. It rises sharply south of 45°S as a result of large-scale wind-driven upwelling in the Antarctic Circumpolar Current (ACC).

Along transect S4P at 67°S (Figure 1c), the γ_n=27.9 surface has shoaled to between 50 and 700 m depth. It carries a remnant ^{3}He anomaly that can be traced back to the S-EPR plume. However, at this latitude, wind-driven upwelling in the ACC has vented most of the ^{3}He from the S-EPR plume to the atmosphere. Neutral density surfaces less than about 27.8 have outcropped north of the S4P transect, and even those in the center of the plume have been exposed to the winter mixed layer which has dramatically reduced peak δ^3He values on the γ_n=27.9 surface at this latitude.

In the same transect a second deeper δ^3He maximum with δ^3He values of about 11% is clearly visible (Figure 1c). While exhibiting a smaller anomaly than the main S-EPR plume to the North, the deep plume is present at all stations of the S4P transect. It follows the contours of the γ_n=28.2 surface across the entire 4500 km transect and represents the most distinguished feature in the ^{3}He distribution over much of the Pacific sector of the Southern Ocean. The γ_n=28.2 surface, and the δ^3He maximum, lie at about 1500 m water depth in the west and tilt downward to about 3000 m at the eastern end of the transect, which is consistent with the pattern of on- and off-shore currents along the Antarctic continental slope. At all longitudes, the δ^3He maximum sits well below the remnant signal of the S-EPR plume. This implies that the Southern Ocean plume is fed from a hydrothermal source distinct from the main S-EPR plume. This source must interact with the very dense γ_n=28.2 water mass that is characteristic of the region along the Antarctic continental slope, unequivocally locating the source to be in the Pacific sector of the Southern Ocean. The different magnitude of the δ^3He anomaly between the SO plume and the S-EPR plume reflects the combined effect of the strength of the hydrothermal flux, which is thought to be a function of the local spreading rate [*Farley, et al.*, 1995] and the mean residence time in the South Pacific basin or the Southern Ocean, respectively [*Schlosser and Winckler*, 2002].

What is the source of the Southern Ocean plume? To obtain a three-dimensional perspective of the possible source regions of the Southern Ocean plume, we used hydrographic data from the Southern Ocean Database [*Orsi and Whitworth III*, 2005] to map the depth of the γ_n=28.2 neutral density surface, which carries the ^{3}He maximum marking the SO plume onto the bathymetry of the Southern Ocean. In the eastern Pacific sector of the Southern Ocean, east of about 145°W, the surface does not extend to the crest of the Pacific Antarctic Ridge, dead-ending on its southern flank, which excludes this section of the ridge as a source of the Southern Ocean plume. West of 145°W the surface crosses the Pacific Antarctic Ridge close to the seafloor. Along the meridional transect P16S at 150°W, for example, the γ_n=28.2 surface terminates at about 55°S on the northern flank of the ridge (Figure 1b). The Southern Ocean plume is found at this transect over the Pacific Antarctic Ridge at the southernmost two stations (Figure 1b).

The section of the PAR west of 175°W consists almost entirely of fracture zones. Because fracture zones typically have low magma budgets [*Cormier, et al.*, 1984], and any helium anomaly would likely originate from a hydrothermal system driven by magmatic heating, the fracture zone-dominated PAR west of 175° is an unlikely source of the observed helium plume. Thus, we focus our analysis on the spreading center between 175°W (Erebus Fracture Zone) and 145°W (Udintsev Fracture Zone), identified in Figure 1a as red dashed line.

As revealed by satellite gravity data and detailed swath bathymetry, the axial morphology of the PAR between 175°W in this region changes from a rift valley in the western part (from 175°W to ~ 157°W) to an axial dome in the eastern part (157°W and 145°W) of the section, reflecting the along-axis increase in spreading rate from slow to fast [*Géli, et al.*, 1997; *Ondréas, et al.*, 2001]. As is typical for slow spreading centers, the western part of the section is characterized by a rough sea floor with many well-marked fracture zones. The eastern part of the section is smooth sea floor, typical for fast spreading centers [*Géli, et al.*, 1997].

To localize potential source regions along the Pacific-Antarctic Ridge, we contoured the neutral density distribution along the ridge crest of the PAR between 175°W and 145°W (Figure 2) and identified the height of the $\gamma_n = 28.2$ surface above the ridge (black line). Because chronic hydrothermal plumes typically rise about 250-300 meters into the water column before becoming neutrally buoyant and spreading laterally along isopycnals [*Baker and German*, 2004], we mapped all areas along the PAR section where the γ_n=28.2 surface clears the ridge crest by less than 300 m (Figure 3). This is a somewhat conservative approach which accounts for the possibility that the venting might occur below the ridge crest, for example on a side wall of the rift valley, or that the hydrothermal fluid rises to less than 300 m. The candidate source locations are constrained to three complete ridge segments, a portion of a fourth segment, and two additional isolated locations. In the transition zone between the slow and fast spreading parts of the ridge we identify two potential source candidates, including a ridge segment between about 170°W and 168°W and a location at about 162°. In the fast spreading part of the ridge we identify four potential sources: a prominent segment between 151°W and 153°W, two smaller ridge sections at 148°W and 146.5°W, and a location at about 145°W. Overall, our mapping approach allows us to localize the probable venting region to approximately 540 kilometers of ridge extent constituting less than 30% of the total ridge length.

The finding that the PAR may be hydrothermally active is not unexpected. Hydrothermal venting is common along the global chain of seafloor volcanoes. However, the factors influencing their location and extent are not well understood [e.g., *Fisher*, 2004; *Tolstoy*, 2009]. So far, only a small fraction of the global mid-ocean ridge system has been systematically surveyed for indications of venting. Our approach, combining the geochemical information provided by the helium isotope anomaly in the water column with independent hydrographic information from the Southern Ocean Database (SODB) and sea-floor topographic data allows us to both trace the source of a far-field hydrothermal plume to the Pacific Antarctic Ridge, one of the major global mid-ocean ridge systems, and provide locations to focus a future search for venting along the ridge crest. This information may be valuable to prioritize future exploration of the hydrothermal venting systems of the Pacific Antarctic Ridge.

4. Conclusions

We document mantle ^{3}He and, by inference, hydrothermal activity on the Pacific-Antarctic Ridge far south in the Southern Ocean. Our results confirm the assumption of ^{3}He injection into the Southern Ocean, as postulated by basin inventories and General Circulation Models [*Farley, et al.*, 1995]. Interestingly, the Southern Ocean Plume seems to be unique to the Pacific sector; we have not found comparable features along Indian or Atlantic sector transects. In addition to its intrinsic geochemical significance, the hydrothermal signal, since it is injected at depth into a particularly dense water mass primarily present south of the Pacific Antarctic Ridge and observable across the width of the basin, provides a unique signal for tracing abyssal circulation and ventilation processes south of the ACC, such as the formation of Antarctic Bottom Water or mixing across the ACC. This is particularly important because this region is the locus of the strongest coupling between the atmosphere and abyssal ocean, and has been implicated in past climatic changes. Understanding its ventilation patterns and timescales is one of the most pressing problems in modern physical oceanography.

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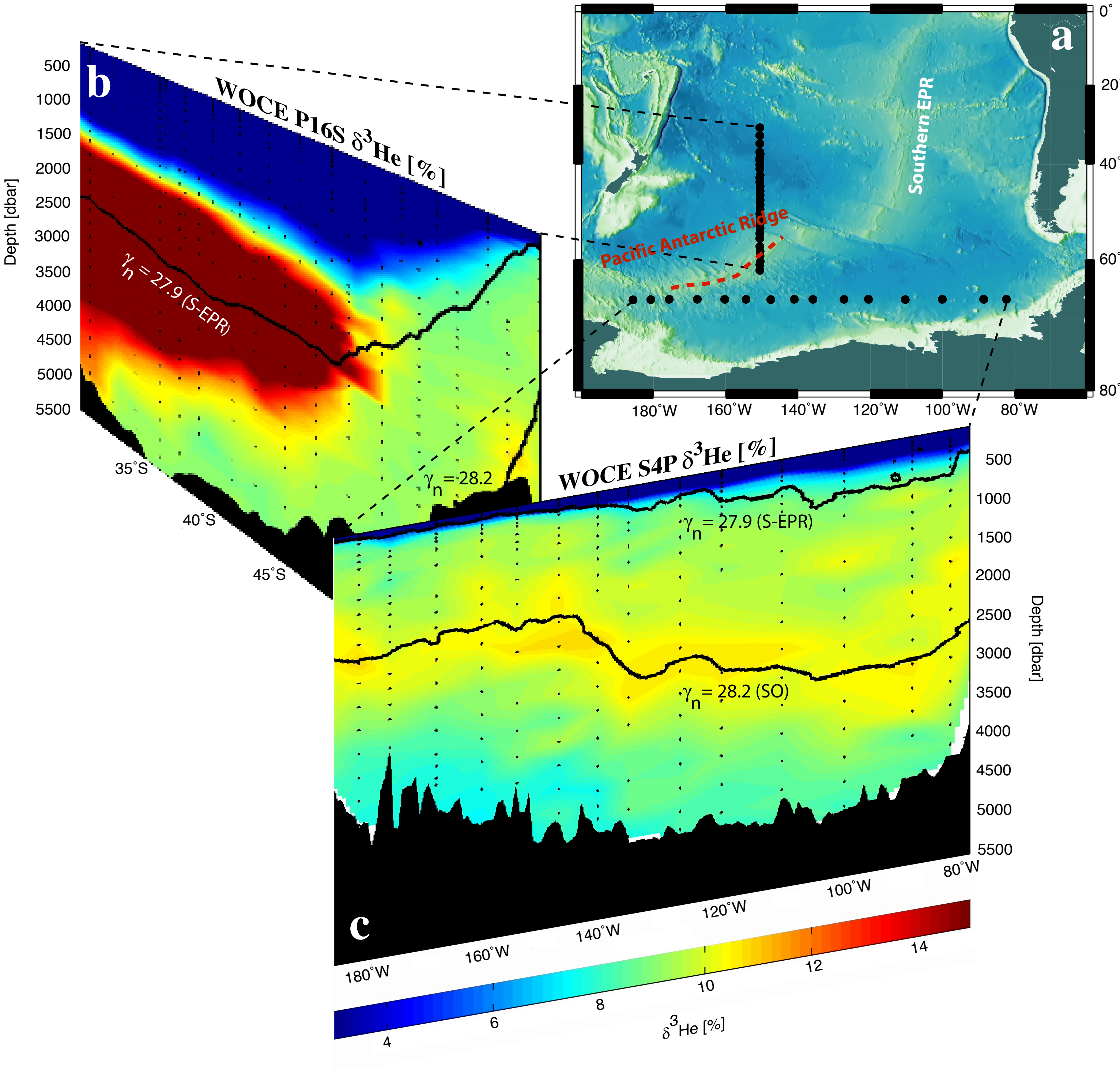
Figure Legends

Figure 1: Helium isotope distribution as marker of hydrothermal activity in the South Pacific and Southern Ocean. a: Map of the South Pacific with WOCE sections P16S at 150°W and S4P at 67°S (black dots). The red stippled line identifies the potentially active portion of the Pacific Antarctic Ridge between 175°W to 145°W. b: Vertical section of δ^3He along P16S marking the Southern East Pacific Rise (S-EPR) plume. c: Vertical section of δ^3He along S4P marking the Southern Ocean (SO) plume.

Figure 2: Neutral density distribution along the Pacific Antarctic Ridge from 175°W to 145°W (red stippled line in Figure 1a). The thick black line marks the depth of the γ_n=28.2 surface that carries the ^{3}He anomaly. High resolution swath bathymetry of the ridge is from *Géli, et al.* [1997]. The blanked areas mark fracture zones. We map locations where the height of the γ_n = 28.2 surface is less than 300 m above the ridge to identify potential sources of the Southern Ocean plume (Figure 3).

Figure 3: Map showing the Pacific Antarctic Ridge from 175°W to 145°W (red stippled line in Figure 1a) with the height of the γ_n = 28.2 neutral density surface above the ridge indicated with colored dots. Locations where the vertical distance between the 28.2 surface and the ridge crest is below 300 m are colored in shades of yellow and red and indicate potential sources of the Southern Ocean plume. Locations where this surface is above 300 m height are colored in shades of blue.



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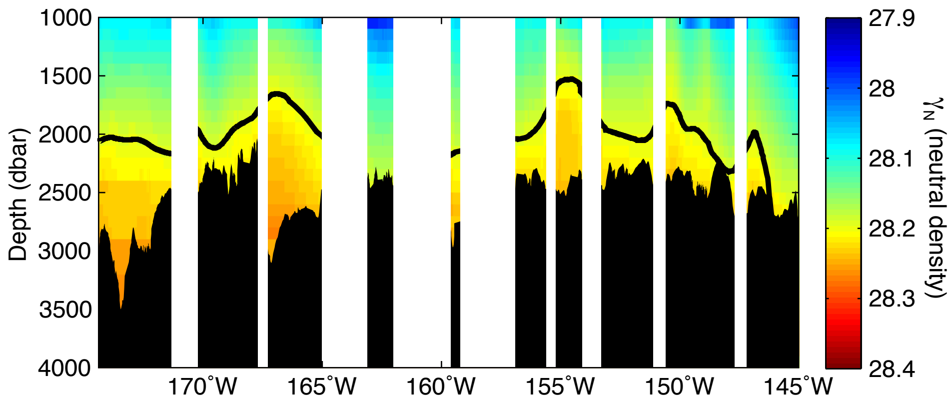

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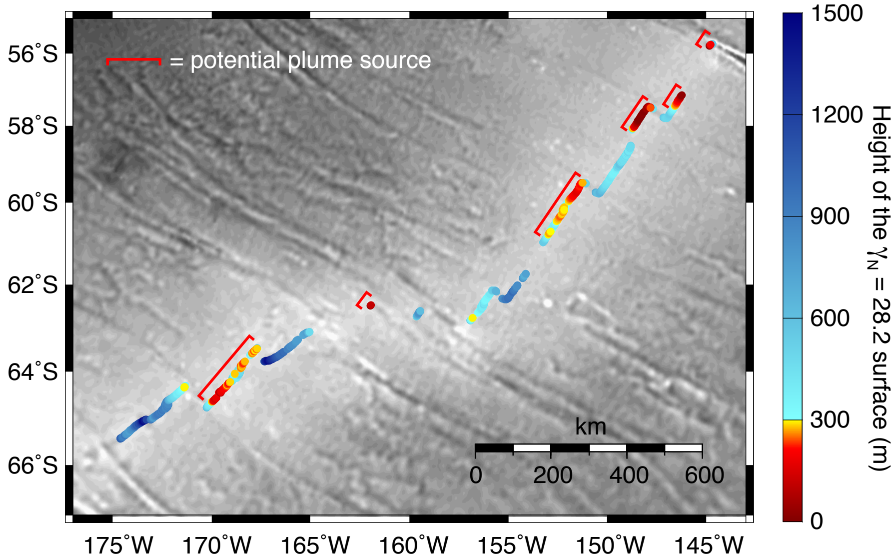

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