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Deepwater mantle 3He plumes over the Northern Mid-Atlantic Ridge (36°N - 40°N) and the Azores Platform

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Abstract:

As part of a multidisciplinary project aimed at studying mid-ocean ridge processes near the Azores, fifty water column profiles were analysed for 3He/4He ratios in dissolved helium (a well known hydrothermal tracer) from 36°N to 40°N along the Mid-Atlantic Ridge (MAR) and over the Azores Plateau. As expected, large δ3He anomalies could be observed over the Rainbow, Lucky Strike and Menez Gwen hydrothermal sites. The main finding of the present study is the discovery of a large hydrothermal 3He plume north of the Açor Fracture Zone (north AFZ site), with a CH4/3He ratio indicative of a basaltic-hosted hydrothermal system. Clear 3He and CH4 anomalies, likely corresponding to unknown venting sites too, were also detected in the Amar Minor segment and south of the Kurchatov Fracture Zone. Evidence for substantial mantle helium degassing was also observed in the deep nodal basins along the Terceira Rift. Based on 3He plumes over the total length of the surveyed segments, the distribution of hydrothermal sites corresponds to a site frequency of 1.3 ± 0.2 site/100 km, in good agreement with the global vent field statistics of Baker and German (2004). For the Rainbow, Lucky Strike and Menez Gwen sites, the application of a plume model based on the conservation of mass, heat and momemtum shows that the heat output computed by the model is only an estimation of the heat released by the focused part of the flow imputable to one single vent. Applied to the north AFZ venting site for which the height of the plume is not known precisely, the model does not allow to discriminate between a Menez Gwen / Rainbow type of venting or a more focused vent complex as the one observed at the TAG site (26°N).

Keywords: mid-ocean ridges; helium-3; hydrothermal processes.

1. Introduction

$^3He/^4He$ values in the deep sea are significantly higher than the atmospheric ratio $R_a = 1.38\times10^{-6}$ (Clarke et al., 1969; Jenkins et al., 1972; Craig et al., 1975). This excess ^3He is due to the leakage into the ocean of mantle helium with distinctively higher isotopic ratio, $^3He/^4He \sim 8\times R_a$ (Lupton, 1983). Most of this ^3He is injected into the ocean at discrete hydrothermal vent sites scattered along mid-ocean ridges, as part of the processes generating new oceanic crust (Craig and Lupton, 1981). It is then advected by the prevailing currents, creating characteristic ^3He anomalies extending for thousands of kilometers across the ocean basins (Lupton and Craig, 1981; Jamous et al., 1992; Ruth et al., 2000; Schlosser and Winckler, 2002). The magnitude of the anomaly varies among the main ocean basins. The large-scale distribution of ^3He, which is determined by the strength and spatial distribution of the helium sources and by the ocean dynamics (circulation, ventilation and mixing), is a powerful oceanic tracer (Jean-Baptiste, 1992; Farley et al., 1995; Dutay et al., 2004; Jean-Baptiste et al., 2004). Large ^3He excesses, up to 40%, occur in the Pacific ocean (Lupton and Craig, 1981; Sano et al., 1995; Lupton, 1996; Lupton, 1998). Similar but much smaller anomalies (only a few percent on average) are observed in the Atlantic (Jenkins and Clarke, 1976; Lupton, 1976; Jean-Baptiste et al., 1991), due to the expected weaker hydrothermal activity on the Mid-Atlantic Ridge (MAR) and also to the efficient deep ventilation by the North Atlantic Deep Waters (NADW).

At the local and regional scales, ^3He anomalies can be used to trace hydrothermal activity and locate active venting sites (Lupton, 1979; Jenkins et al., 1980; Belviso et al., 1987; Charlou et al., 1991; Jean-Baptiste et al., 1990; 1992; Lupton et al., 1993; Lupton et al., 2004). The lowest probability of occurrence pertains to slow spreading ridges (Baker et al., 1996, 2004; Jean-Baptiste and Fourré, 2004), such as the Mid-Atlantic Ridge. Nevertheless, a substantial number of hydrothermal sites have been discovered on the MAR over the last two decades thanks to intensive scientific activity. And new sites have yet to be discovered.

This paper is concerned with ^{3}He excess data collected from depth profiles between 36°N and 40°N on the MAR and in the Azores area as part of the EU Framework Programs FP4 and FP5 in the Azores region (the data set is available from the first author's web page at http:// www.lsce.ipsl.fr). The purpose of our study is to examine the distribution of ^{3}He anomalies in this region of the North Atlantic in relation to hydrothermal activity.

2. Geological setting of the studied area

The Azores region is the site of the triple junction between the North American, Eurasian and African plates. Its morphology and tectonic patterns have been studied in detail using geophysical data (Searle, 1980; Freire Luis et al., 1994; Detrick et al., 1995). The depth profile of the MAR axis between 36°N and 40°N is strongly influenced by the presence of the Azores hotspot. Between the Oceanographer transform at 35°N and the Pico Fracture Zone (37.5°N), the studied area comprises several major topographic units including the South Amar, Amar Minor, Amar, Famous, North Famous and Lucky Strike segments. They consist in deep rift valleys offset by fracture zones. Their length is variable, ranging from ~15 km to ~60 km.

North of the Pico fracture zone, the central axis runs across the western extension of the Azores platform. The well developed rift valley disappears and is replaced by a shallow rifted axial high that more nearly resembles that of a fast spreading ridge (Searle, 1980).

North of 39.5°N, between the North Azores and the Kurchatov fractures zones, the ridge axis deepens again rapidly and the median valley redevelops, bounded by 600 to 1000 m high scarps about 12 km apart.

On the East side of the MAR, the volcanic islands of Graciosa, Terceira and Sao Miguel and a series of deep basins form a linear structure known as the Terceira Rift. Present patterns of seismic activity favour the idea of the Terceira Rift being the third arm of the Azores Triple Junction (Krause and Watkins, 1970; Fernandes et al., 2006).

3. Experimental methods

Water samples were collected over four years at fifty stations (Fig. 1) occupied by the RRS Charles Darwin (CD-89 and CD-97 cruises in 1994-1995), the RRS Discovery (Flame-1 cruise, 1997), the R/V Atalante (Flores cruise, 1997) and the R/V Poseidon (Flame-2 cruise, 1998). Sampling was performed on vertical casts using Niskin-type bottles on a CTD rosette. Water for helium isotope analysis was drawn into 10 ml copper tubes tightly sealed with steel pinch-clamps.

The water samples were processed at the helium isotope facility in Saclay (Jean-Baptiste et al., 1992). Each copper tube was attached on top of a high vacuum line via an o-ring Cajon fitting. When the pressure in the line was less than 10^{-6} Torr, the lower clamp was removed and the water was transferred by gravity to a glass flask placed in a ultrasonic bath. The dissolved gases were transferred into a low He-permeability glass bulb (Jean-Baptiste et al., 1989) placed in liquid nitrogen and equiped with a capillary which prevents any back-diffusion in the line. The system acts as a diffusion pump, gases being transported from the warm to the cold part of the line by the flow of water vapour which passes through the capillary and freezes into the bulb. After 15 mn, the bulb was flame-sealed.

The bulb was then attached to the inlet line of a VG-3000 dual-collector noble gas mass spectrometer for helium isotope analysis. The gas was introduced in the mass spectrometer through a series of traps (a water trap and a charcoal trap, both in liquid nitrogen, and a Ti-getter to remove hydrogen). ^{4}He was measured on a Faraday cup. ^{3}He was detected by ion counting using an electron multiplier.

The overall uncertainty in the ^{3}He excess, $\delta^{3}He\% = (R/R_a-1)\times 100$ (where R is the isotopic ratio of the sample and R_a is the atmospheric ratio) was better than 0.4%.

4. The time-evolution of the ^{3}He background in the Azores region

Atlantic Ocean deep and bottom waters contain much less mantle ^{3}He than those of the Pacific (Jenkins and Clarke, 1976; Lupton, 1976) due to a lower ^{3}He flux at ridge axis (because of the lower spreading rate) and to a faster ventilation of the deep waters. This is particularly true for the North Atlantic, where the influence of the Antarctic circumpolar waters tagged with ^{3}He of Pacific origin (Jean-Baptiste et al., 1991; Well et al., 2003) is vanishing and where well ventilated North Atlantic deep waters dominate. However, in addition to the hydrothermal (mantle) ^{3}He component, ^{3}He is also produced in the ocean by the radioactive decay of tritium fallout from atmospheric nuclear tests of the 50's and early 60's (Weiss and Roether, 1980). For the past four decades, tritium input to the North Atlantic has been particularly high : in fact, most of the nuclear devices were detonated in the northern hemisphere, and in addition to direct precipitation and vapour exchange at sea surface, tritium fallouts over Eurasia were discharged into the Arctic and then into the North Atlantic by river runoff (Doney et al., 1993). Due to this tritium delivery, North Atlantic intermediate and deep waters have been progressively tagged with tritium and tritiugenic ^{3}He (Ostlund et al., 1974; Jenkins and Rhines, 1980; Andrié et al., 1988; Ostlund and Rooth, 1990;), thus gradually increasing the Atlantic ^{3}He background.

4.1. Tritiugenic ^{3}He in thermocline waters

Fig. 2 shows vertical δ^3He profiles over the Azores Plateau obtained in 1981 - TTO/NATS section at 36.°25N (Jenkins, pers. comm.) - and in 1997 - WOCE/A24 cruise (Schlosser, 2003). The 1981 profiles display a sharp δ^3He maximum of 9-10% between 500 m and 700 m. This value is much higher than the 3-4% maximum for thermocline waters recorded in 1972 at GEOSECS station 27 located at 42°N - 42°W (Jenkins and Clarke, 1976). Between 1981 and 1997, this tritiugenic ^{3}He maximum has widened and deepened to reach 10-11% at 1250 m in 1997. On the 1981 TTO-NATS profiles, a broad secondary maximum (indicated by a circle in Fig. 2) is visible at the stations in the Azores domain (in red in Fig.2) in the depth range 1000 m - 2000 m. This feature is most likely the signature of mantle ^{3}He inputs in the Azores region (see results below). In 1997, this maximum is masked by the deepening of the tritiugenic ^{3}He peak and cannot be identified any longer.

4.2. Tritiugenic ^{3}He in deep waters

Between the 1972 GEOSECS survey and the 1981 TTO/NATS cruises, the δ^3He value of the deep waters between 2000 m and 3000 m has remained stable at 2-3%, in agreement with the North Atlantic tritium data (Ostlund and Rooth, 1990) which show that at 40°N the tritium transient had not yet reached these depths. The situation radically changed during the next decade however, with a significant increase of the δ^3He value which reaches 5-7% in 1997 (Fig. 2).

5. ^{3}He anomalies related to hydrothermal activity

5.1. MAR south of the Azores Triple Junction (36°N-38°N)

Only a few casts were devoted to the Menez Gwen and Lucky Strike segments due to the fact that hydrothermal vents had already been discovered and studied there (Charlou et al., 2000). Both venting sites create a sharp δ^3He anomaly reaching 27% and 50.5% respectively (Fig. 3). A secondary anomaly (~12%) centered around 1800 m is also observed at several stations towards the southern end of the Lucky Strike segment (indicated by a circle in Fig. 3), suggesting an additional ^{3}He source deeper than the one already identified in the central part of the Lucky Strike segment. This anomaly probably corresponds to the Menez Hom site (37.13°N), where seeping fluids with sightly elevated temperature have been observed at ~1790 m (J.L. Charlou, unpublished data). Further south, the Famous segment do not show any specific anomaly. Both in South Lucky Strike and in the Famous segments however, the δ^3He values are significantly above the δ^3He regional background outside the rift valley (Fig.3). This is in agreement with previous measurements made from horizontal hydrocasts (Bougault et al., 1998) which show that hydrothermal tracers anomalies are ubiquitous all along this part of the MAR. These ^{3}He anomalies are likely brought from nearby active segments (Lucky Strike to the north and Amar to the south) by the strong and variable currents within the axial rift (Jean-Baptiste et al., 1998; Turnherr et al., 2002). Some minor hydrothermal inputs may also occur at various places such as Mount

Saldanha (36.57°N) where low temperature diffuse venting associated with methane anomalies have been observed (Dias and Barriga, 2006).

South of the Famous segment, the Amar segment hosts the Rainbow hydrothermal site discovered during the course of this project (German et al., 1996). This large vent field creates a well defined δ^3He anomaly between 2000 m and 2250 m, which reaches a maximum value of 39% above the site (Fig.4). Plume dispersion study (German et al., 1998) and current meter monitoring (Thurnherr et al., 2002) at the Rainbow site have shown that water within the rift valley is moving steadily towards the northeast. Hence the Rainbow ^{3}He signal is not expected to spread into the adjacent Amar Minor and South Amar segments. Nevertheless, a clear ^{3}He signal (δ^3He = 13.9%), correlated with a methane peak of 148 nl/l, is seen at 2075 m (Fig.5) just north of the offset between Amar Minor and South Amar (station Flame2-17 at 35.89°N), thus pointing to the presence of an unkown hydrothermal venting site in the area. A weaker signal is also observed at the adjacent station Flame2-15 located at 36.99°N.

5.2. MAR north of the Azores Triple Junction (38°N-40°N)

Several vertical CTD-casts were lowered in this northern section of the study area. The measured δ^3He vertical profiles are shown in Fig. 6. The most striking feature is the sharp δ^3He anomaly north of the Açor Fracture Zone, reaching a maximum of 24% at 38.98°N (station CD97-07). The anomaly, which is also be observed at the two adjacent stations CD97-06, CD97-05 (red profiles in Fig.6a) located at 38.81°N and 38.83°N respectively, is correlated with a methane peak at the same depth (fig. 6). The neutrally-buoyant plume, which spreads at a depth of ~ 970 m, is not confined within the walls of the rift (see bathymetric map in Fig.7) and hence may be rapidly lost to the open ocean. The origin of the anomaly is as yet unknown. However, the fact that it is restricted to the three stations between the fracture zone and 38.98°N, and not seen further north at station CD97-15 at 39.37°N (blue profile in Fig.6) points to an injection of mantle ^{3}He by a local hydrothermal venting site. The size of the anomaly is less than the one recorded at Lucky Strike or

Rainbow but comparable to the one at Menez Gwen. However, since the plume is not confined within the rift valley wall (as it is the case for the Rainbow and Lucky Strike plumes), the recorded anomaly may nevertheless be indicative of substantial hydrothermal fluid release.

Further north, between the North Azores and the Kurchatov Fracture Zones, the vertical profiles at three adjacent stations between 39.67°N and 39.97°N (CD97-09, CD97-12 and CD97-13) show elevated δ^3He values (up to 14-15%) at various depths between 1750 m and 2150 m (indicated by a circle in Fig. 6). This layer also displays a methane enrichment up to 60 nl/l (fig. 6), again pointing to some nearby hydrothermal release.

5.3. The Azores domain

The Azores domain is located to the east of the MAR. This triangular shape zone of anomalously shallow topography corresponds to the Azores hotspot. It comprises a series of deep enclosed basins running along the Terceira Rift (Fig.1). From East to West, we find : (1) the Hirondelle basin, between Sao Miguel and Terceira, (2) the East Graciosa basin, between Terceira and Graciosa, and (3) the West Graciosa basin, located West of Graciosa. Vertical CTD casts were lowered in each of these basins (Fig. 8). The two vertical δ^3He profiles in the Hirondelle basin are characterized by a progressive ^{3}He enrichment reaching a maximum value of 26-27% at depth. The East and West Graciosa basins also display significant δ^3He enrichments compared to the North Atlantic background. Since the islands of the Azores archipelago are the siege of numerous present-day active geothermal and volcanic manifestations, the occurrence of a mantle ^{3}He signature at depth along the Terceira Rift does not come as a surprise. It is interesting to note that none of these ^{3}He enrichments corresponds to any methane anomaly (J.L. Charlou, unpublished results). Hence, the ^{3}He inputs along the Terceira rift may rather correspond to a direct release of volcanic gases than to hydrothermal inputs.

6. Discussion

6.1. Large scale ^{3}He distribution

Figure 9 displays a δ^3He vertical section from 36°N to 40°N along the MAR which summarize the various geographic patterns of the ^{3}He distribution. The ^{3}He field is strongly influenced by the various hydrothermal inputs in the rift valley. Besides the known sites of Menez Gwen, Lucky Strike and Rainbow, which create well defined ^{3}He anomalies at the level of the neutrally-buoyant plume, a ^{3}He plume is observed in the Amar Minor segment, corresponding to an unkown venting site. Weaker ^{3}He excesses also occur in South Lucky Strike in the vicinity of the Menez Hom seepage site.

North of the Azores Triple Junction, the main feature is the ^{3}He plume at about 1000 m north of the Açor Fracture Zone (in the following “north AFZ plume”), clearly pointing to another yet unkown venting site. A second active site is also present further north between the North Azores and the Kurchatov Fracture Zones.

Based on ^{3}He anomalies over the total length of the surveyed segments, the distribution of hydrothermal sites corresponds to a site frequency F_s between 1.1 and 1.5 site/100 km (depending on whether the Saldanha and Menez Hom seepage sites are included or not). With an average full spreading rate of 24mm/yr for the studied area, this figure is in good agreement with the global vent field statistics of Baker and German (2004) : $F_s=1.01+0.0023\times V_m$, where V_m (in km^3/Myr.km) is the magmatic budget, i.e., the product of the full spreading rate by the nominal thichness of the crust (6.3±0.9 km).

On the Azores plateau, the present survey also points to substantial ^{3}He inputs in the deep nodal basins along the Terceira Rift, especially in the Hirondelle basin, between the islands of Sao Miguel and Terceira (Fig. 8). These ^{3}He anomalies may correspond to direct volcanic degassing since no corresponding methane anomaly could be detected.

6.2. Methane / ^{3}He ratios

The $CH_4/^3He$ ratio for the Lucky Strike, Menez Gwen and Rainbow sites have been determined from the analysis of the hydrothermal fluids and are 65x10^6, 85x10^6 and 108x10^6

respectively (Charlou et al., 2000; Jean-Baptiste et al., 2004). Intensive measurements of CH_4 and ^3He in the Rainbow plume (Jean-Baptiste et al., 2004) have also shown that the ratio of the two tracers in the dispersing plume and in the end-member fluid is identical within experimental uncertainties. These ratios are among the highest for unsedimented ridges due to the production of abiogenic methane by serpentinization reactions in the ultramafic bedrock (Charlou et al., 2002). Based on the maximum anomaly in the tracer enriched layer (see Fig. 5 and 6), the $CH_4/^3He$ ratios are $33x10^6$ and $11x10^6$ for the Amar Minor and South Kurtchatov sites respectively. Surprisingly, the $CH_4/^3He$ ratio in the north AFZ plume (Fig. 6) is only $0.8x10^6$, a value close to the MAR basaltic ratio of $0.7x10^6$ (Welhan and Craig, 1983). This indicates that the north AFZ site differs from the ultramafic-hosted systems discovered further south between 36°N and 38°N and is more likely a pure basaltic-hosted system outgassing juvenile carbon like those on the East Pacific Rise.

6.3. Plume height and thermal budget

The heat output of a vent can be estimated from the height of its rising plume by solving the conservation equations for mass, heat and momentum averaged over the width of the plume (Speer and Rona, 1989; Rudnicki and Elderfield, 1992). In this set of equations, the entrainment of ambient seawater into the plume is proportional to the upward velocity (Turner, 1986), with a (dimensionless) entrainment constant of the order of 0.1 (see Baker et al., 1989 and references therein). The plume model requires that the end-member fluid temperature and salinity are known, as well as the background vertical density profile (inferred from T-S profiles) throughout the depth range of the plume. In the studied area, these requirements are met for the Rainbow, Lucky Strike and Menez Gwen plumes. One strong limitation of this approach is that it applies to a plume created by a single source. Thus, in case of multiple sources, the application of the plume model will only give a lower bound of the total thermal budget of the site, unless the vents are close enough to coalesce at an early stage in a single larger plume (Rudnicky and Elderfield, 1992). Besides, the plume model does not take into account the contribution of diffuse flows to the thermal budget.

The set of conservation equations for mass, heat, salinity and momemtum was integrated numerically until the velocity of the plume drop to zero. The thermodynamic data were taken from Bishoff and Rosenbauer (1985) for the hot hydrothermal fluid and from the standard algorithms describing the equation of state of seawater, below 40°C (UNESCO, 1983). The model was first checked against the TAG results of Rudnicky and Elderfield (1992) to detect any computational error that might occur. Then, it was applied to the Rainbow, Lucky Strike and Menez Gwen plumes to calculate the heat flux corresponding to their respective plume height. As an example, Fig.10 displays the relationship between the heat output and the plume height for the Rainbow site. It shows that, as expected from the analytical solution of Morton et al. (1956), the heat output is proportional to the power 4 of the plume height. For each site, the results displayed in Table 1 show that the heat output deduced from the plume model is much lower than the total thermal budget inferred from the ^{3}He budget for the site and ^{3}He/heat ratio in the hydrothermal fluid (Jean-Baptiste et al., 1998; 2004). As a matter of fact, it represents only a fraction of the average heat released by one individual vent (i.e., the total heat output divided by the number of vents for the site). Even for the Rainbow site, which has the highest density of vents per unit area, the plumes released by the different vents are too distant (~ 50 m) to interact before reaching their equilibrium height where they spread horizontally and mix with one another.

However, horizontal currents have a strong effect on the height of rise due to plume bending in response to ambient currents. For instance, Lavelle (1997) calculates that plume height is reduced by a factor of 2 when ambient current velocity increases from 0.015 m/s to 0.06 m/s. At Rainbow, ambient currents are relatively low (0.01 m/s to 0.03 m/s – Thurnherr et al., 2002), so this effect should be small in agreement with the observation (German et al., 1998) that plume height is constant over the whole area (a result which would not be expected in the case of plume bending). On the other hand, at Lucky Strike, where discrepancy between the plume model heat flux and the data is maximum (see Table 1), plume bending may be substantial due to the strong horizontal currents (up to 0.15 m/s) in the axial valley (Jean-Baptiste et al., 1998).

With regards to the north AFZ venting site, the above limitations show that the plume model is of little help to infer the strength of the hydrothermal activity. Moreover, the height of the plume is not known accurately : a closer look at the bathymetric map of the area (fig. 7) suggests that the venting site is probably located somewhere between 1200 m and 1000 m on the wall of the shallow central graben. Fig. 11 displays the heat output calculated by the plume model as a function of plume height for a fluid end-member temperature equal to ($T_{boiling}$-20°C), by analogy with those of the Rainbow, Lucky Strike and Menez Gwen sites (see Table 1), and a salinity in the range 24-34 psu. For reasonable plume heights between 50 m and 200 m, the plume model gives a heat output in the range 20 - 2000 MW (Fig. 11). Hence, the north AFZ site could be either comparable to the three other studied sites (with an unknow number of vents) or a vent complex with vents close enough to each other as to integrate individual sources during plume rise, like the TAG site (26°N) where the plume model gives a heat output in the range 500 - 940 MW (Rudnicki and Elderfield, 1992).

7. Conclusions

The main results of the present helium isotope survey are the following :

- In addition to the known hydrothermal sites of Rainbow, Lucky Strike and Menez Gwen, whose plumes produce sharp ^3He anomalies in the water column, three ^3He plumes were detected at 35.89°N, 38.98°N and ~40°N along the MAR. These plumes, which also show substantial CH_4 enrichments, likely correspond to active hydrothermal sites yet to be discovered.

- The $CH_4/^3He$ ratio of the largest plume (the north AFZ plume at 38.98°N) is typical of a pure basaltic system releasing mantle ^3He and juvenile carbon species. The two other sites, which show higher $CH_4/^3He$ values, are in an intermediate position between basaltic and ultramafic-hosted systems.

- Based on the observed number of ^{3}He anomalies over the total length of the surveyed segments, the distribution of hydrothermal sites corresponds to a site frequency which is in good agreement with the global vent field statistics of Baker and German (2004).

- The application of the plume model of Speer and Rona (1989) to the Rainbow, Lucky Strike and Menez Gwen plumes confirms that the heat output computed by such models is only an estimation of the heat released by the focused part of the flow imputable to one single vent. Hence, as a general rule, unless the individual vents belong to a highly focused system where they are close enough as to coalesce at an early stage into a larger plume, the plume model is inadequate to estimate the thermal budget of any particular venting site.

- Along the Terceira Rift, the present study also points to substantial ^{3}He inputs in the deep nodal basins. These ^{3}He anomalies may correspond to direct volcanic degassing since no corresponding methane anomaly could be detected.

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Site	Site Depth*	Site Area*	Nb of Vents*	Plume Height	$T_{boiling}$	T_{Hy}*	S_{Hy}	Plume model Heat flux	Total Heat flux**	Heat flux by vent
	(m)	(km^2)		(m)	(°C)	(°C)	psu	(MW)	(MW)	(MW/vent)
Rainbow	2300	0.020	10	150	381	365	34	43	1320±600	132±60
Lucky Strike	1700	0.608	21	60	357	325	26	9	3800±1200	181±57
Menez Gwen	870	0.023	4	50	306	280	24	22	600±300	150±75
NFFZ	*< 1200*	-	-	*50 - 200*	*320 - 325*	*295 - 305*	*24 - 34*	*20 - 2000*	-	-

* Site and vent fluids data are from Douville (1999) and Charlou et al. (2000).
** Total heat fluxes are from Jean-Baptiste et al.,1998; 2004 (heat flux for Menez Gwen was inferred by scaling it to those of Rainbow and Lucky Strike according to the respective number of vents and temperature of the sites).

Table 1

Figure captions

Fig. 1 : Location map of the MAR and of the Azores Archipelago. The open black circles represent the oceanographic stations occupied during the present survey. The red squares and dots are the "background" stations from the TTO/NATS section (1981) at 36.25°N and from the WOCE/A24 cruise (1997) respectively.

Fig. 2 : Time-evolution of the δ^3He background in the Azores domain between 1981 and 1997. The 1981 data belong to the 36.25°N TTO/NATS section across the MAR, from 9.40 W to 42.83°W. The stations belonging to the Azores domain are shown in red (see Fig.1) while the stations outside are shown in black. The selected 1997 data (in green) correspond to the three southermost stations of the WOCE/A24 cruise (fig.1). Also shown (in blue) are the δ^3He profiles at two off-axis stations, Flame1/31 and Flores/8 occupied in 1997.

Fig. 3 : δ^3He vertical profiles over the Menez Gwen, Lucky Strike and Famous segments. The green profile (WOCE/A24 - station 3) represents the regional δ^3He background.

Fig. 4 : δ^3He vertical profiles over the Amar segment, which hosts the Rainbow site. The red profiles are within 6 km of the venting site. The green profile (WOCE/A24 - station 3) represents the regional δ^3He background.

Fig. 5 : δ^3He vertical profiles over the Amar Minor and South Amar segments. The red profile with the ^{3}He peak at 2075 m corresponds to station Flame2-17 (35.89°N) located in the Amar Minor segment. The second red profile with the small anomaly is the adjacent station Flame2-15 (35.99°N). Note that the δ^3He background at 36°N is logically below that defined by the WOCE/A24 station 3 (in green) located at 39.38°N due to the decreasing influence of the tritiumgenic ^{3}He component at lower latitudes. Inset : CH_4 vertical profile at station Flame2-17.

Fig. 6 : (a) δ^3He vertical profiles immediately north of the Açor F.Z. (stations CD97-05/CD97-06/CD97-07 in red) and between the North Azores and Kurchatov fracture zones (in black). The green profile (WOCE/A24 - station 3) represents the regional δ^3He background. (b) Methane vertical profiles at station CD97-07, north of the Açor Fracture

Zone (in red) and at stations CD97-09, CD97-12 and CD97-13 between the North Azores and Kurchatov Fracture Zones (in black).

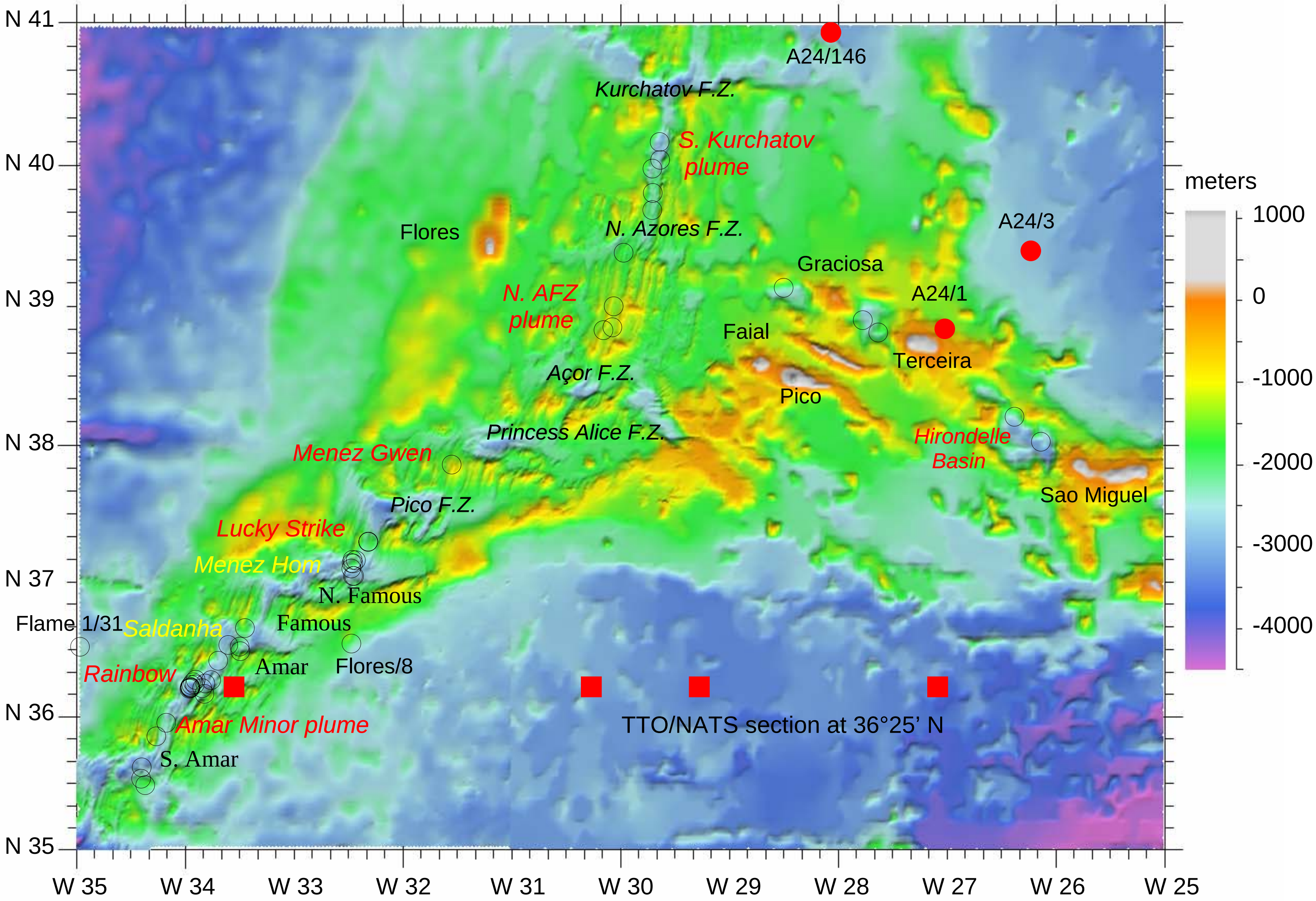
Fig. 7 : Detailed bathymetry of the area beneath the ^{3}He plume detected north of the Açor Fracture Zone (Sigma cruise, 1991 - by courtesy of Alain Normand, IFREMER).

Fig. 8 : δ^{3}He vertical profiles in the Hirondelle basin (in red) and the East and West Graciosa basins (in blue and black respectively). The green profile (WOCE/A24 - station 3) represents the regional δ^{3}He background.

Fig. 9 : δ^{3}He section along the MAR from 35.5°N to 40.2°N (the sites yet to be discovered are in indicated in red).

Fig. 10 : Rainbow site : Relationship between the heat output deduced from the plume model and the power 4 of plume height for three different entrainment constants (0.075, 0.1 and 0.125 respectively).

Fig. 11 : Heat ouput versus plume height calculated by the plume model for the north AFZ plume.



N 41
N 40
N 39
N 38
N 37
N 36
N 35
W 35
W 34
W 33
W 32
W 31
W 30
W 29
W 28
W 27
W 26
W 25
meters
1000
0
-1000
-2000
-3000
-4000
A24/146
Kurchatov F.Z.
S. Kurchatov plume
Flores
N. Azores F.Z.
A24/3
Graciosa
A24/1
N. AFZ plume
Faial
Terceira
Açor F.Z.
Pico
Princess Alice F.Z.
Menez Gwen
Hirondelle Basin
Sao Miguel
Pico F.Z.
Lucky Strike
Menez Hom
N. Famous
Flame 1/31
Saldanha
Famous
Rainbow
Amar
Flores/8
Amar Minor plume
TTO/NATS section at 36°25' N
S. Amar

Fig. 1

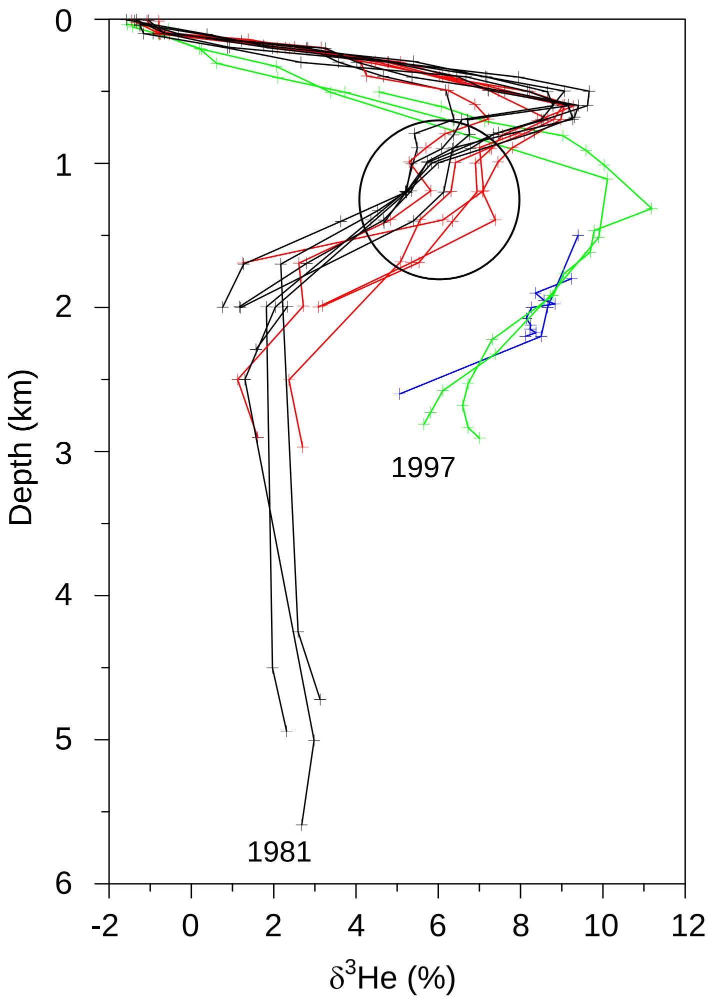
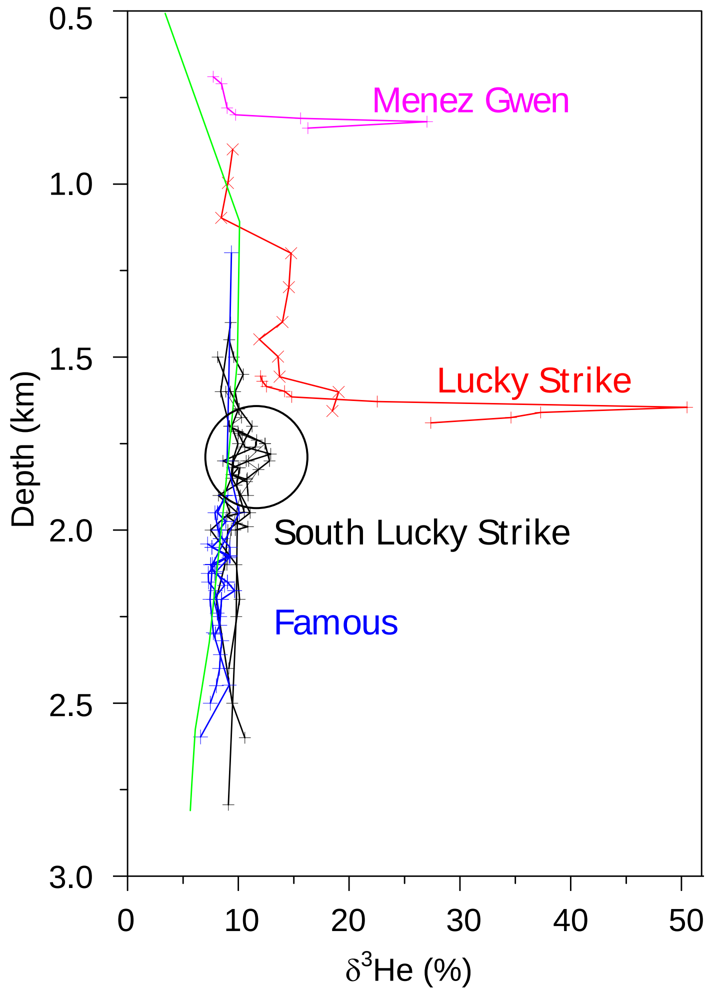


Fig. 2



0.5
1.0
1.5
2.0
2.5
3.0
Depth (km)
0
10
20
30
40
50
δ^3He (%)
Menez Gwen
Lucky Strike
South Lucky Strike
Famous

Fig. 3

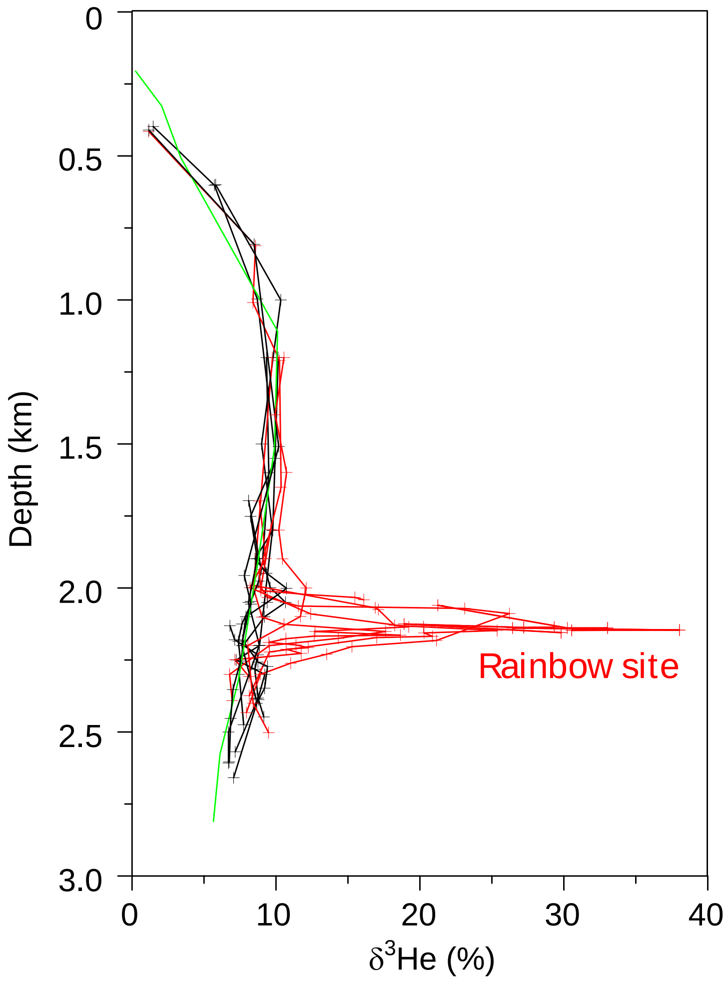
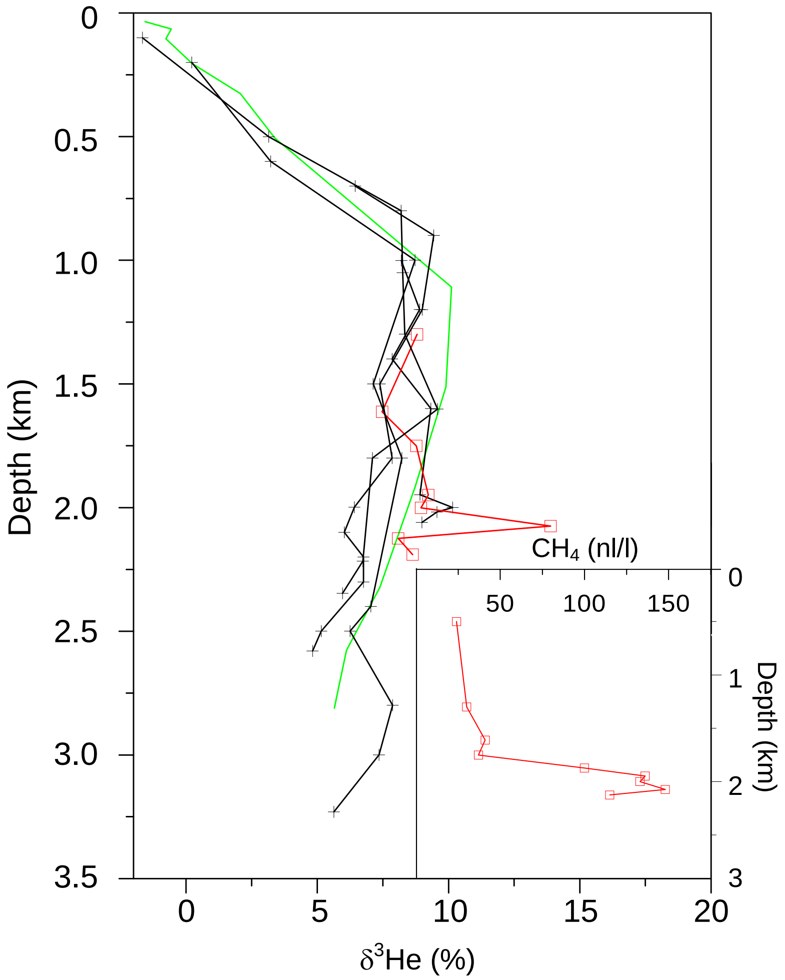
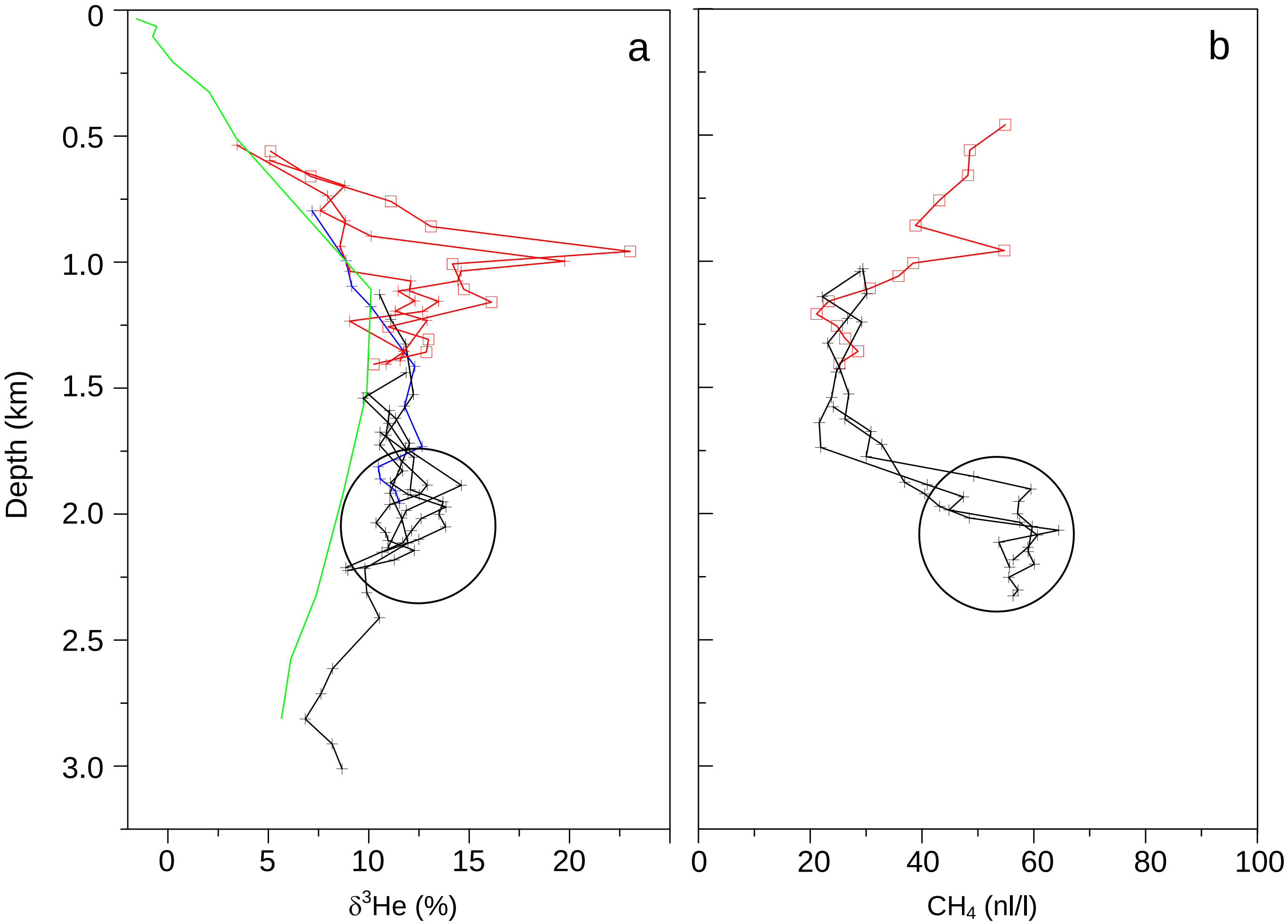


Fig. 4



Depth (km)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
5
10
15
20
δ^3He (%)
CH_4 (nl/l)
50
100
150
0
1
2
3
Depth (km)

Fig. 5



a
b
Depth (km)
0
0.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
δ^3He (%)
0
20
40
60
80
100
CH_4 (nl/l)

Fig. 6

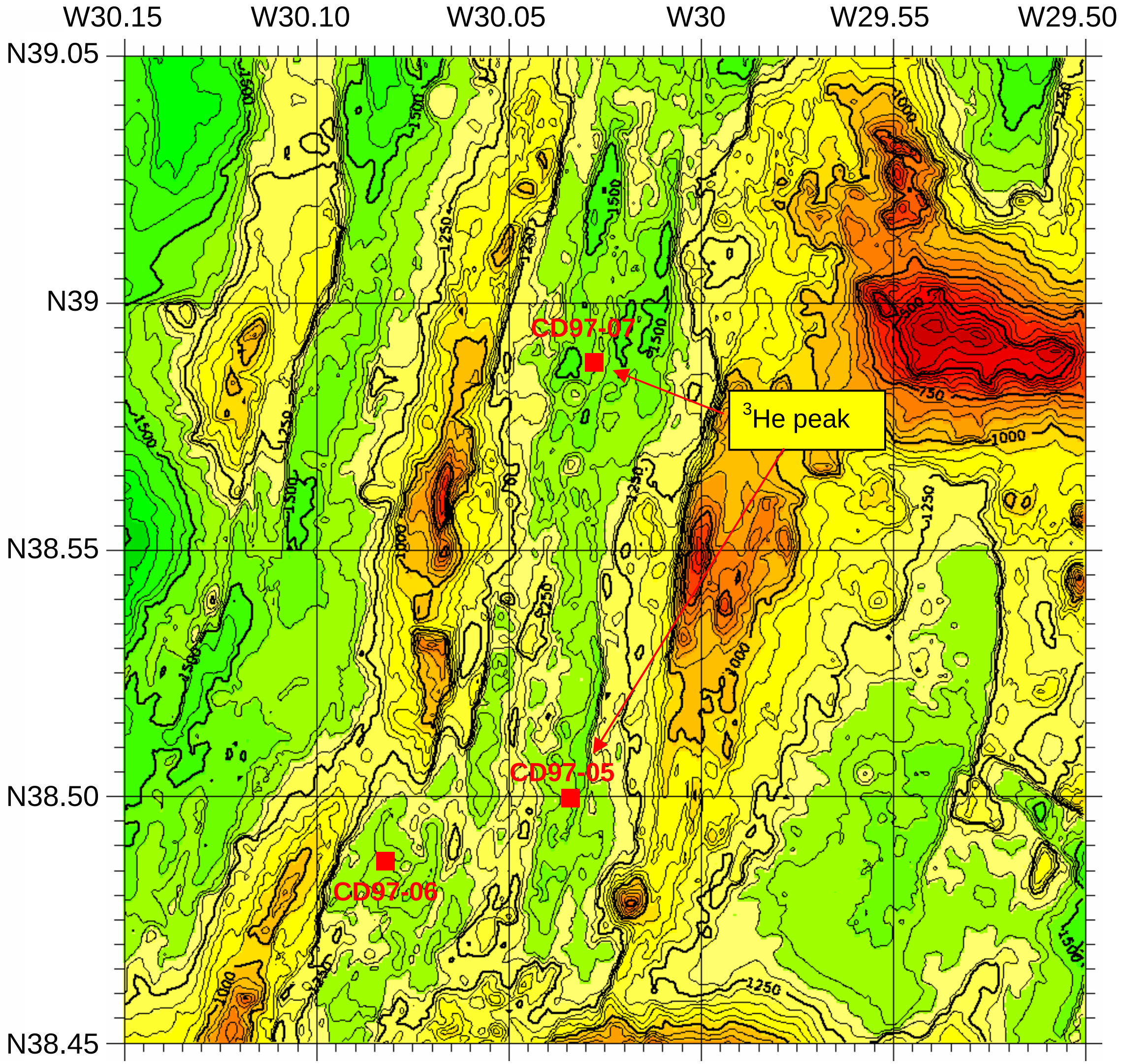
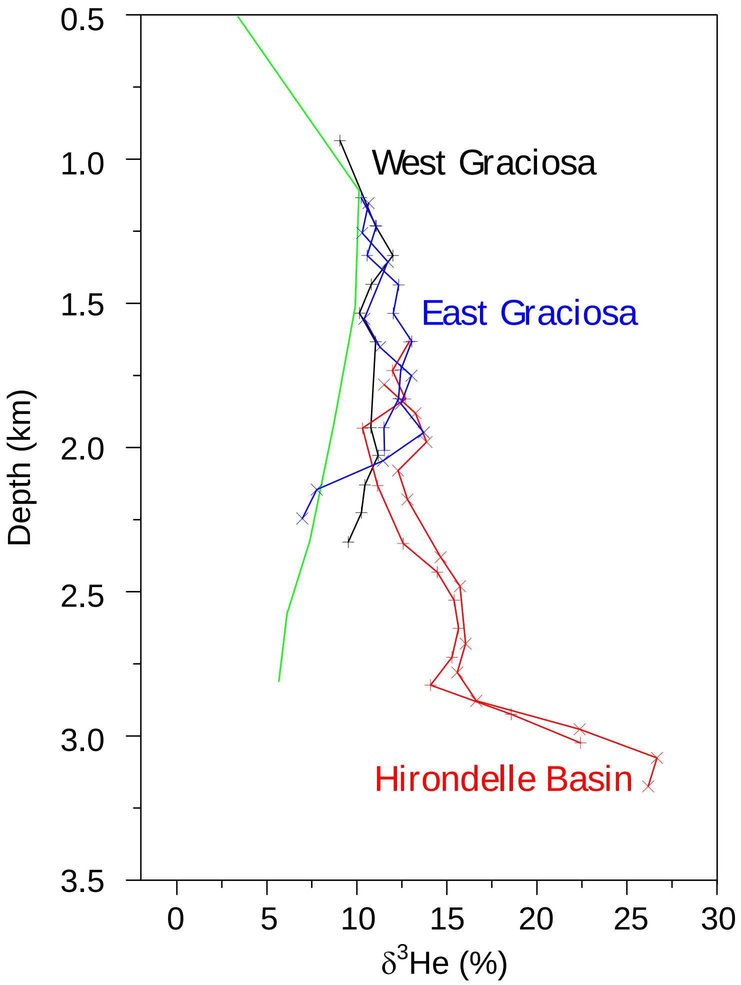
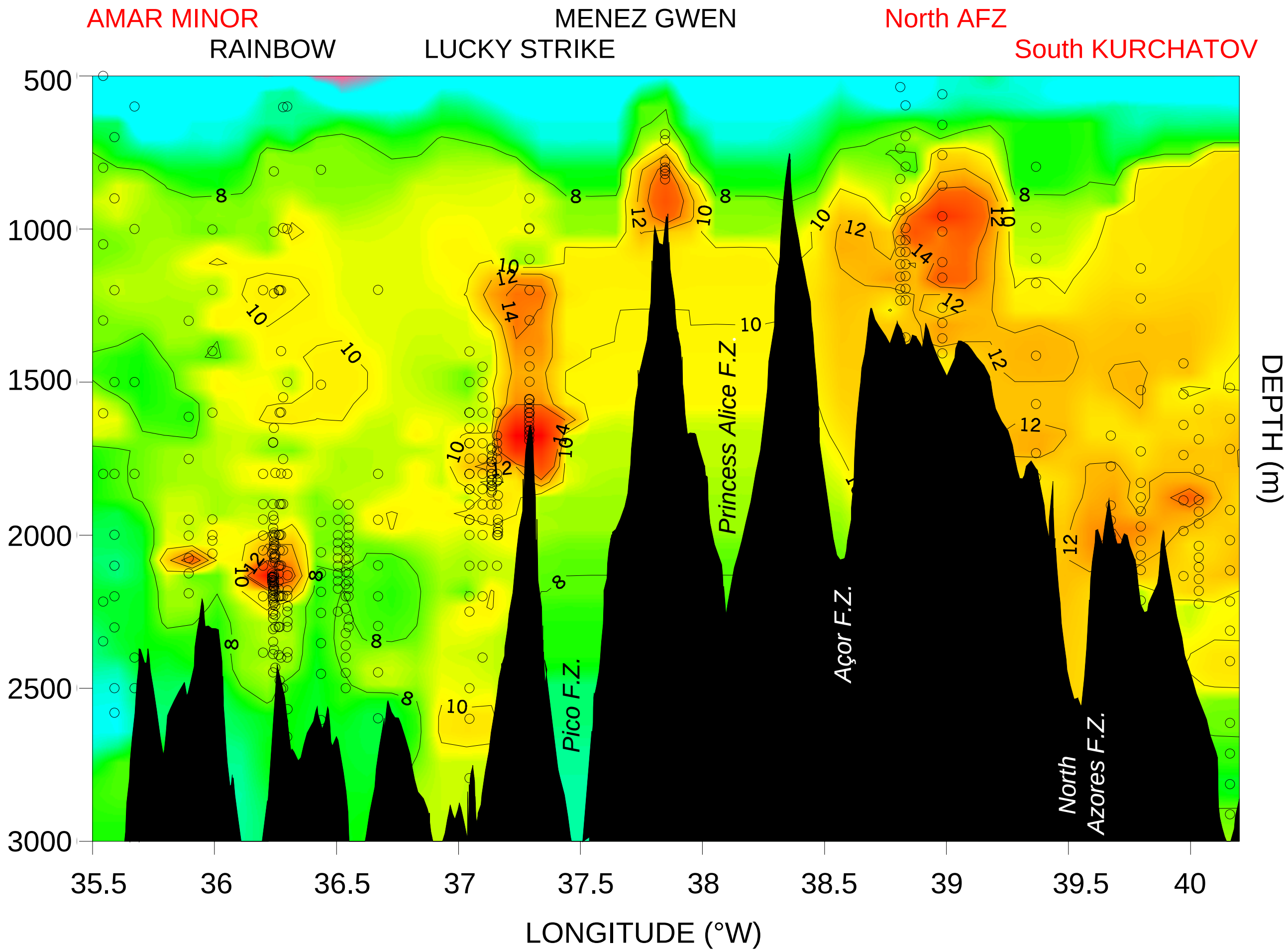

W30.15
W30.10
W30.05
W30
W29.55
W29.50
N39.05
N39
N38.55
N38.50
N38.45
CD97-07
CD97-05
CD97-06
³He peak

Fig. 7



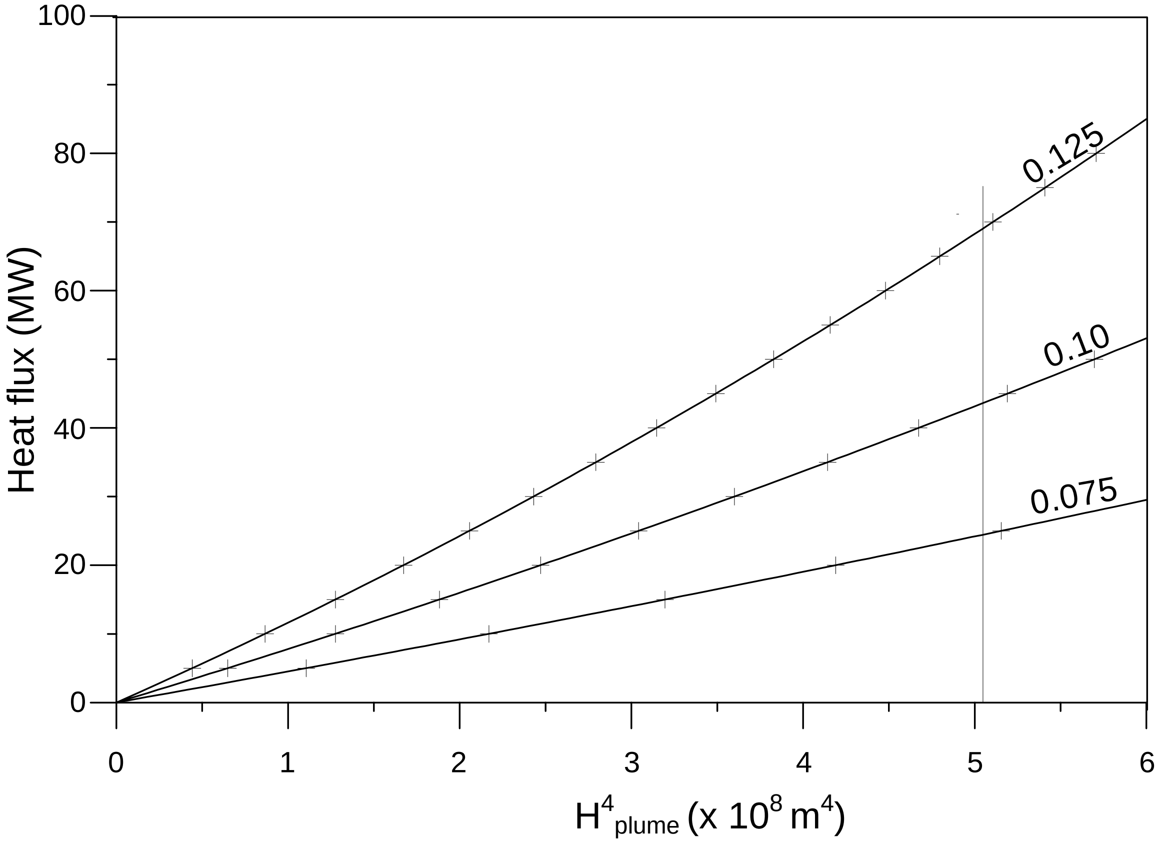
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Depth (km)
0
5
10
15
20
25
30
δ3He (%)
West Graciosa
East Graciosa
Hirondelle Basin

Fig. 8



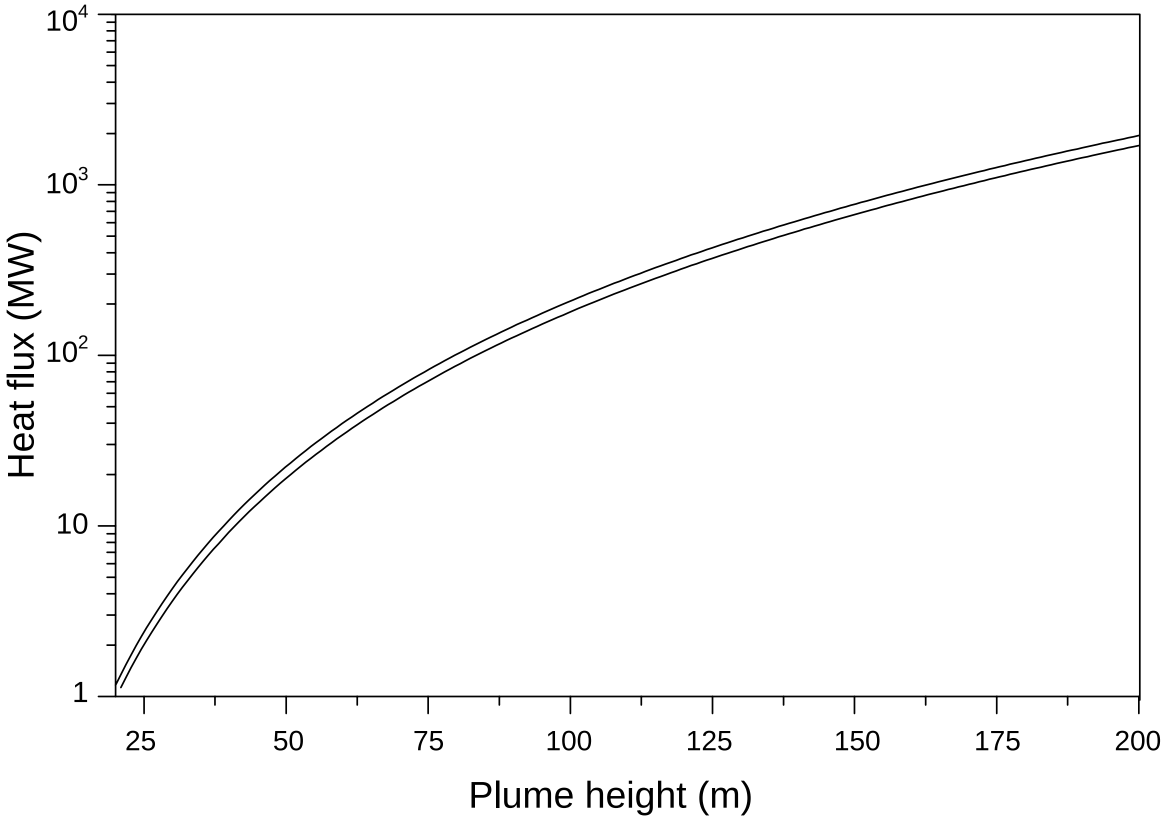
AMAR MINOR
RAINBOW
LUCKY STRIKE
MENEZ GWEN
North AFZ
South KURCHATOV
DEPTH (m)
LONGITUDE (°W)
Pico F.Z.
Princess Alice F.Z
Açor F.Z.
North Azores F.Z.

Fig. 9



100
80
60
40
20
0
Heat flux (MW)
0
1
2
3
4
5
6
H4plume (x 108 m4)
0.125
0.10
0.075

Fig. 10



10^4
10^3
10^2
10
1
Heat flux (MW)
25
50
75
100
125
150
175
200
Plume height (m)

Fig. 11