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44. MEASUREMENTS OF RADIOGENIC HEAT PRODUCTION ON BASEMENT SAMPLES FROM SITES 897 AND 900[1]

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ABSTRACT

Concentrations of radionuclides were measured on six samples each from Sites 897 and 900 of Leg 149 in the Iberia Basin and four samples each from three dredge sites located off Galicia Bank. They are used to calculate radiogenic heat production for rocks located in a rifted, nonvolcanic continental margin setting. Results can be separated into three distinct groups: Galicia dredge samples, primarily from granodiorites (A_{av} = 1.67 ± 0.31 µW/m^3); Site 900 samples, primarily from metamorphosed gabbros (A_{av} = 0.21 + 0.19 µW/m^3); and Site 897 samples of serpentinized peridotites (A_{av} < 0.01 µW/m^3). Values for the Galicia Bank granodiorites are lower than typical granitic values observed in Brittany. Values for Site 900 metamorphosed gabbros are higher than typical values for tholeiitic basalts and similar to values for the lower continental crust. Some reduction is probably caused by radionuclide mobility during weathering. However, it is not possible to distinguish these rocks as lower continental crust, rather than lower oceanic crust, based solely on these values. The low values for the serpentinite samples from Site 897 are consistent with low concentrations in mantle peridotites and additional reduction during hydration.

For simple models, heat flow across older rifted margins such as Iberia and Galicia Banks should increase from ocean to continent, in proportion to the increased volume of radionuclides in the continental rocks. These results, therefore, suggest that heat-flow observations over the thinned continental crust of the Galicia Bank Margin should be elevated with respect to measurements on the thinned continental (or oceanic) crust of the Iberia Basin. However, a preliminary comparison between seafloor measurements off Galicia Bank and deeper Leg 149 measurements from Sites 897, 898, and 900 indicate just the reverse. Comparable values for both locations are observed in the oceanic/serpentinite ridge domain, but landward values on transitional crust at Site 900 in the Iberia Basin are 16-23 mW/m^2 higher than values landward of the serpentinite ridge on Galicia Bank.

INTRODUCTION

The expected variation in conductive heat flow at the seafloor across passive continental margins depends primarily on two normally competing factors: (1) an increase in lithospheric thickness from thinner lithosphere beneath the younger ocean basins to thicker lithosphere beneath the older continents; and (2) an increase in radiogenic heat production from low values for basaltic oceanic crust to higher values for granitic continent crust. For young margins, the lithospheric factor dominates and heat flow generally increases toward the ocean. The amount of this increase can be used to help constrain models of lithospheric thinning (e.g., Burrus et al., 1987). For older margins, the contribution of crustal heat production dominates and heat flow decreases toward the ocean. The amount of this decrease is expected to be larger for margins adjacent to continents with a high concentration of radiogenic elements in the upper crust. In this case, the variation in heat flow across the margin can be used to help constrain models for crustal thinning (e.g., Louden et al., 1991).

One difficulty with using heat flow measurements across old margins to help constrain the mechanism of crustal thinning lies with uncertainties in values of radiogenic heat production. These uncertainties result from the scatter in measurements on samples from continental boreholes, as well as from the lack of observations adjacent to many passive margins. This problem is particularly relevant to the margins adjacent to the Iberian Peninsula, where no measurements of radiogenic heat production have been reported.

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The main purpose of this paper is to present the first measurements of radiogenic heat production for the Iberia Margin. We use samples from Sites 897 and 900 of Leg 149 in the Iberia Basin and compare these to measurements on dredged samples from Galicia Bank. Measured values of heat production will be applied in simple models to interpret the heat flow in these two adjacent regions.

MEASUREMENT OF RADIOGENIC HEAT PRODUCTION

Sample Location

The location and generalized values for marine and land heat flow are shown in Figure 1 for the regions adjacent to the Leg 149 sites. This region has the largest number of heat flow measurements relevant to the study of passive margins, with numerous values on land (Lucazeau and Vasseur, 1989) and three detailed transects at sea across Goban Spur, Galicia Bank, and the Amorican Margins (Foucher and Sibuet, 1980; Louden et al., 1991). Values of radiogenic heat production in the Paleozoic metamorphosed cratons that border these margins are generally high (e.g., Richardson and Oxburgh, 1978; Jolivet et al., 1989), and there is a clear decrease from higher continental values (often >90 mW/m^2) to lower oceanic values (generally <60 mW/m^2). However, continental heat flow and radiogenic heat production measurements are lacking within the Paleozoic section of northwestern Spain, immediately adjacent to the Leg 149 drill sites and to previous drill sites off Galicia Bank.

The location of the Leg 149 sites in the Iberia Basin and dredge sample locations adjacent to Galicia Bank are shown in Figure 2. Also shown are the location of three seismic profiles (*Lusigal* 12, *Resolution* 3, and *Sonne* 16) that have been used to construct a seismic transect along the drill sites (Shipboard Scientific Party, 1993). Six samples each from Sites 897 and 900 were analyzed for the concentration of radiogenic heat-producing elements; four samples were

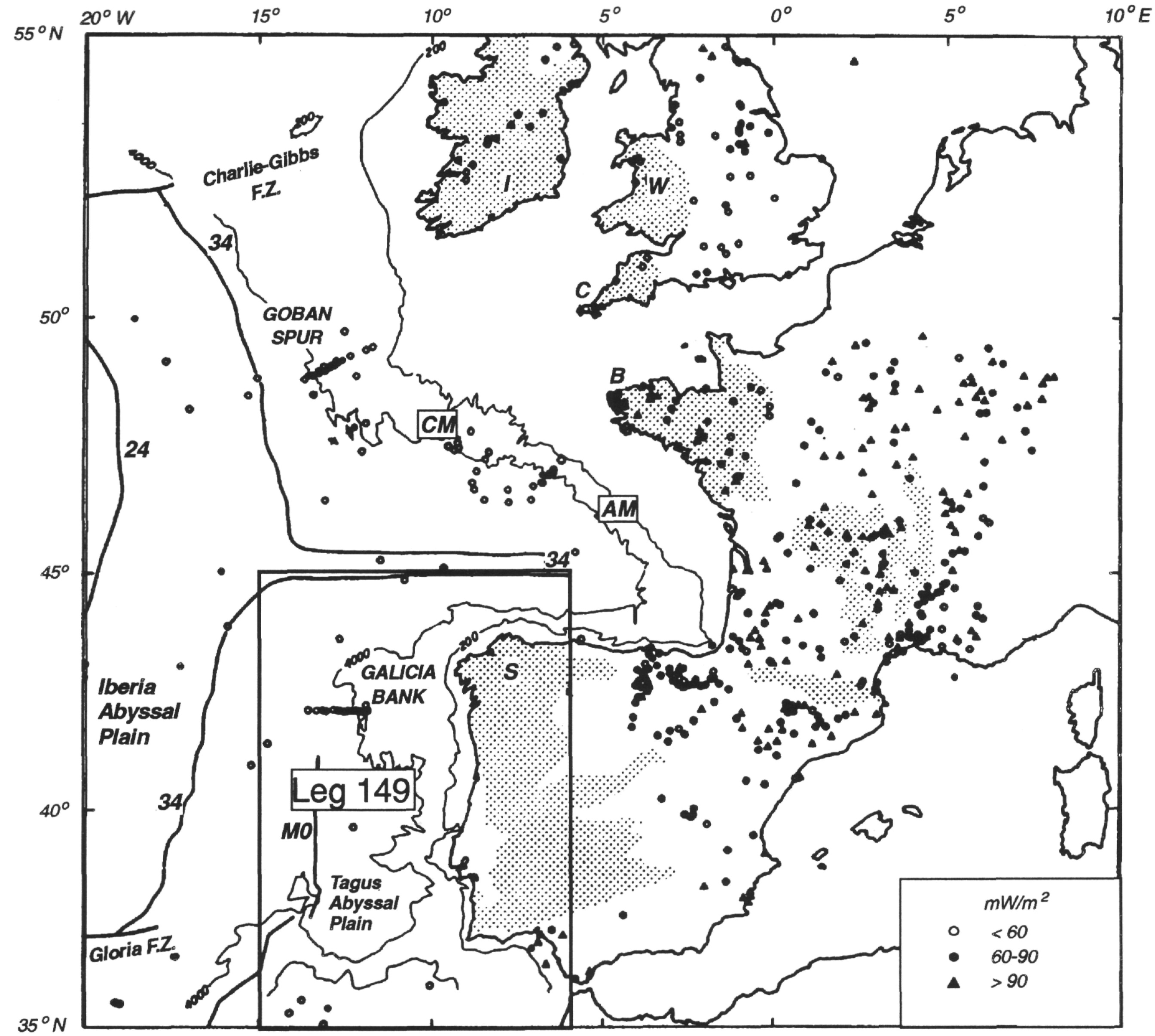

Figure 1. Generalized, uncorrected heat-flow values, selected magnetic isochrons, and bathymetry from the northwestern Atlantic Ocean and adjacent regions of western Europe (after Louden et al., 1991). Letters (I = Ireland, W = Wales, C = Cornwall, B = Brittany, and S = Spain) and shaded areas denote general regions of Paleozoic basement adjacent to the Mesozoic margins (after Montadert et al., 1979). Inset shows location of Figure 2 and general location of Leg 149 sites. CM = Celtic Margin, AM = Amorican Margin, FZ = fracture zone.

analyzed from each of the dredge sites GAL 02,07/08, and 11. A general description of the sampled rock types and the location of each sample are given in Table 1.

Technique

The technique used for measuring the concentrations of radioelements in rocks is described by Mareschal et al. (1989). Samples were crushed to a fine powder and neutron activated in the "slowpoke" reactor at École Polytechnique (Montréal). The samples were subjected to a flux of 5×10^{11} neutrons/cm^2-s for 2 hr. After irradiation, the concentrations of U, Th, and K were measured by gamma-ray spectrometry, following the semi-absolute method of Bergerioux et al. (1979). Gamma rays were measured with planar low-energy photon scintillometers and coplanar GeLi detectors. For U^{238}, gamma rays at 277 kev from the disintegration of Np^{239} (half life 2.35 days) were counted. For Th^{232}, the gamma rays at 312 kev were produced by disintegration of Pa^{233} (half life 27 days). For K^{41}, gamma rays at 1525 kev from the disintegration of K^{42} (half life 12 hr) were counted. For some samples, the K concentration was also measured with the standard X-ray spectrometry technique (Schroeder et al., 1980). The overall reproducibility was verified by measuring different aliquots of the same sample and was better than 5%.

Results

Concentrations of the radioelements and the resulting radiogenic heat production are given in Table 1. The heat production values are shown as histograms in Figure 3. Except for one lower value of 0.307 μW/m^3 for a dolomite sample from Galicia Bank, values can be separated into three distinct groups: Galicia dredge samples, primarily granodiorites (A_{av} = 1.67 ± 0.31 μW/m^3); Hole 900A samples, prima-

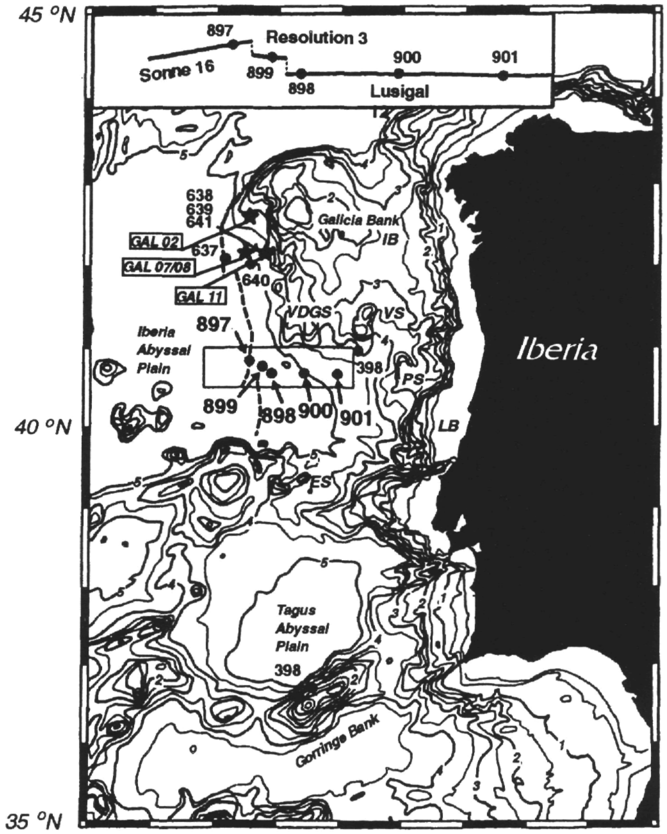

Figure 2. Bathymetry (500-m contour interval with thick annotated lines every 1000 m) of the West Iberian Margin and location of Leg 149 Sites 897-901. Also shown are drill sites from ODP Leg 103 (637-641); labels in boxes denote location of dredged rock samples used for measurement of radiogenic heat production. The bold dashed line is the predicted location of the peridotite ridge (Beslier et al., 1993). The inset map (top) shows the location of seismic profiles (solid lines) used to construct the composite structural section in Figure 3. IB = Galicia Interior Basin, VDGS = Vasco da Gama Seamount, VS = Vigo Seamount, PS = Porto Seamount, LB = Lusitanian Basin, ES = Estremadura Spur. After Shipboard Scientific Party (1993).

rily metamorphosed gabbros (A_{av} = 0.21 ± 0.19 µW/m^3); and serpentinized peridotites from Holes 897C and 897D (A_{av}< 0.01 µW/m^3). The average heat production for the Galicia Bank granodiorites are lower than the average for Paleozoic granites observed in Brittany (3.3 ± 0.6 µW/m^3; Jolivet el al., 1989) and Wales and Cornwall (3.1 ± 2.1 µW/m^3; Richardson and Oxburgh, 1978), as might be expected. Values for Site 900 are higher than typical values of 0.08 µW/m^3 for tholeiitic basalts (Stacey, 1992) and similar to values of 0.4 µW/m^3 for the lower continental crust (Galson, 1983; Ashwal et al., 1987; Fountain et al., 1987; Mareschal et al, 1989). The serpentinite samples from Site 897 have negligible radionuclides. This result is not surprising as typical mantle peridotites have low concentrations, and these concentrations (particularly U^{238}) would be further reduced during hydration. Similar weathering could also have reduced the concentrations of radionuclides at Site 900.

DISCUSSION

The measurements of radiogenic heat production suggest that heat flow over the thinned continental crust of the Galicia Bank Margin should be higher than it is on the thinned continental (or oceanic) crust of the Iberia Basin, given that their lithospheric ages and crustal thicknesses are the same. To test this prediction, heat-flow measurements from Leg 149 (Sawyer, Whitmarsh, Klaus, et al., 1995) are compared with previously published values for Galicia Bank (Louden et al., 1991). The heat flow at Sites 897, 898, and 900 is recalculated from the original data using linear least-squares fits to values of temperature vs. Bullard depth (Fig. 4, Table 2). Bullard depths (R_S) are calculated using the linear least-squares fit to thermal conductivity (k_s) vs. subseafloor depth (z) for all data from Leg 149 (Fig. 5), using the relationship (Louden and Wright, 1989):

$$R_s = \frac{1}{b}\ln\left(\frac{k_o + bz}{k_o}\right);\ \text{where, } k_s = k_o + b \cdot z.$$

As is typical for most such determinations of heat flow, there is a large uncertainty produced by the large variation in k_s and few measurements of temperature.

The resulting heat-flow values for Leg 149 (Table 2) are shown in Figure 6, as a function of distance along the Leg 149 transect. Before comparing these values with measurements across Galicia Bank, we assess the possibility that focusing and dispersal of heat flow through contrasts between the low-conductivity postrift sediment and higher conductivity basement may have disturbed the conductive heat flow measured at the seafloor. This process is modeled in Figure 6 using a finite element method (C. Jaupart, pers. comm., 1989). We assume a constant basal heat flux of 50 mW/m^2 and constant basement conductivity, k_b = 2.5 W/m·K. The conductivity of the sediment is assumed to following the relationship, k_s = 2.25- $e^{-0.43z}$, which gives values of 1.25 W/m·K at the seafloor, 1.48 W/m·K at z = 600 m (consistent with the observed conductivities in Fig. 5), and 1.83 W/m·K at maximum sediment thicknesses of ~2 km (Fig. 6). Sub-bottom topography for the two layers is constrained by the three multichannel profiles shown in Figure 2, using assumed mean sediment (v_s) and water (v_w) velocities of 2.0 and 1.507 km/s, respectively. Mean values of v_s are consistent with core measurements (Sawyer, Whitmarsh, Klaus, et al., 1995), as well as with the measured depths to basement at Sites 897, 898, and 900. The result of this modeling shows that the topographic correction can be large but only very near Site 901, where the basement rises nearly to the seafloor. Seafloor measurements of heat flow at the other sites, therefore, should be representative of local crustal values.

A comparison between observed heat flow across Goban Spur and the Leg 149 sites in the Iberia Basin is given in Figure 7B. This comparison shows that similar values for both margins are observed in the oceanic/serpentinite ridge domain, but landward values on transitional crust at Site 900 are 16-23 mW/m^2 higher than values landward of the serpentinite ridge on Galicia Bank. These variations in heat flow are interpreted in terms of variations in heat production using the pure-shear, depth-independent model of continental extension (McKenzie, 1978). In this model, heat flow and subsidence are parameterized as a function of β, which defines the fractional amount of initial vertical thinning of both lithosphere and crust. Following Voorhoeve and Houseman (1988), the effects of radiogenic heat production are included within the model, by addition of the quantity, $H\,h\,[1 - h/2L]/\beta$, which linearly reduces as a function of β^{-1}, where H = rate of radiogenic heating (uW/m^3), h = thickness of radiogenic crust (km), and L = lithospheric thickness (km).

Theoretical values of heat flow vs. ln β, which result from this model (Louden et al., 1991), are shown in Figure 7A for a variety of ages. These show the competition between the increase in heat flow caused by the thinning of the oceanic lithosphere vs. the reduction in heat flow caused by the thinning of the more radiogenic continental crust. By 130 Ma, an age representative of the Iberia Margin (Shipboard Scientific Party, 1993), the expected variation in heat flow across the margin is controlled primarily by the contribution from

Table 1. Measurements of radiogenic heat production.

Location	ID number	Depth (mbsf)	Lat. (N), Long. (W)	U (ppm)	Th (ppm)	K_2O (%)	A (μW/m^3)	Description
Galicia Bank, dredges	860203	0	42°11.53′, 12°14.44′	0.69	1.52	0.20	(0.307)	Massive dolomite*
	860204	0	42°11.56′, 12°14.38′	4.10	16.61	0.86	2.323	Fine-grained sandstone*
	860205	0	42°11.66′, 12°14.32′	2.55	10.82	1.39	1.563	Fine-grained sandstone*
	860206	0	42°11.71′, 12°14.30′	1.73	8.91	1.31	1.206	Fine-grained sandstone*
	860701	0	42°38.54′, 12°28.45′	0.49	6.85	2.04	0.807	Granodiorite
	860806	0	42°38.23′, 12°27.60′	1.06	6.92	1.30	0.890	Granodiorite
	860807	0	42°38.21′, 12°27.58′	0.79	7.44	3.07	1.028	Granodiorite
	860808	0	42°38.15′, 12°27.51′	0.64	8.43	3.89	1.138	Granodiorite
	861101	0	42°09.63′, 12°34.40′	2.55	19.65	3.35	2.373	Granodiorite*
	861106	0	42°09.65′, 12°34.36′	0.88	21.34	3.89	2.107	Granodiorite*
	861107	0	42°09.65′, 12°34.29′	2.22	26.79	3.45	2.797	Granodiorite*
	861108	0	42°09.62′, 12°34.25′	1.68	18.10	3.98	2.097	Granodiorite*
	Core, section, interval (cm)						1.666 Mean 0.31 σ	
Iberia Basin, Leg 149	149-900A-							
	80R-1, 115–117	750.1	40°40.992′, 11°36.270′	0.22	0	0.6061	0.117	Norite
	82R-1, 37–39	768.17	40°40.992′, 11°36.270′	0.49	0	1.5421	0.278	Amphibolite
	83R-2, 55–58	775.89	40°40.992′, 11°36.270′	0.45	0	0.7928	0.195	Pyroxene amphibolite
	84R-2, 27–30	779.14	40°40.992′, 11°36.270′	1.30	0	0.2866	0.368	Plagioclasite
	84R-4, 36–43	782.15	40°40.992′, 11°36.270′	0.32	0	0.2463	0.108	Amphibolite
	85R-1, 97–100	787.67	40°40.992′, 11°36.270′	0.07	0	0.3677	(0.054)	Amphibolite
							0.213 Mean 0.192 σ	
	149-897C-							
	71R-3, 48–51	719.38	40°50.331′, 12°28.444′	<0.05	<0.05	0.0022	<0.01	Serpentinized peridotite
	72R-1, 54–57	726.14	40°50.331′, 12°28.444′	<0.05	<0.05	0.0014	<0.01	Serpentinized peridotite
	72R-2, 97–101	728.02	40°50.331′, 12°28.444′	<0.05	0.07	0.0013	<0.01	Serpentinized peridotite
	149-897D-							
	23R-5, 35–41	814.88	40°50.331′, 12°28.444′	<0.05	<0.05	0.0014	<0.01	Serpentinized peridotite**
	23R-6, 87–93	816.77	40°50.331′, 12°28.444′	<0.05	<0.05	0.0017	<0.01	Serpentiinzed peridotite**
	24R-2, 41–46	820.08	40°50.331′, 12°28.444′	<0.05	<0.05	0.0021	<0.01	Serpentinized peridotite**

Notes: * = Paleozoic; ** = heterogeneous.

crustal heat production. The residual mantle effect of <5 mW/m^2 is not very sensitive to reasonable uncertainties in its rifting age.

In Figure 7B, we show the effect of changes in radiogenic heating in the models at an age of 130 Ma. Values of $\beta = 5$ are assumed for the Leg 149 sites, which is consistent with observed crustal thicknesses of ~6 km (Whitmarsh et al, 1990). It is clear that the higher heat flow at Site 900 can be explained only by high values of radiogenic heat production (3-6 μW/m^3) and certainly not the low value of 0.21 μW/m^3 as measured, even if one increases the assumed thickness of the radiogenic layer *(h)*. Larger topographic effects produced by off-profile variations in the basement are not consistent with site survey reflection profiles. Although the Leg 149 heat-flow measurements are not conclusive because of their large uncertainties, surface measurements of heat flow along the profile (Sibuet et al., 1994) are consistent with a region of elevated heat flow at this site. Other possibilities are that the measured heat production at Site 900 is not representative of the complete crustal section or that some other process has disturbed the surface flux. Both these possibilities require further study.

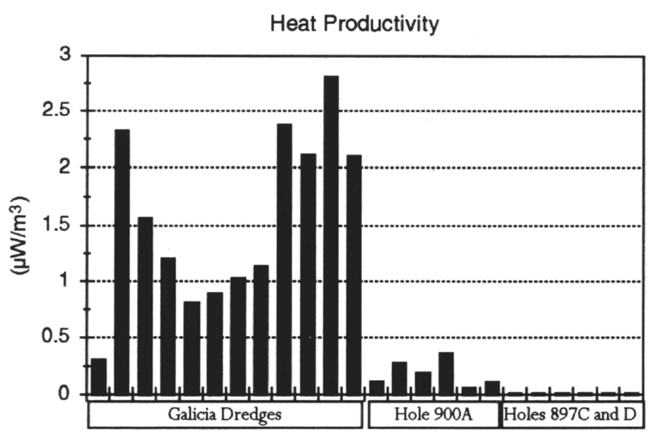

Figure 3. Histograms of radiogenic heat production measured on ODP samples from Holes 897C, 897D, and 900A and dredged samples from the Galicia Bank as located in Figure 2.

SUMMARY

Measurements of radionuclide concentrations on samples from Sites 897 and 900 of Leg 149 in the Iberia Basin and from three dredge site locations off Galicia Bank yield values of radiogenic heat production which can be separated into three distinct groups: Galicia dredge samples, primarily granodiorites (A_{av}= 1.67 ± 0.31 μW/m^3); Site 900 samples, primarily metamorphosed gabbros (A_{av} = 0.21 ± 0.19 μW/m^3); and Site 897 serpentinized peridotites (A_{av} < 0.01 μW/m^3). Values for the Galicia Bank granodiorites are lower than typical granitic values observed in Brittany and Cornwall. Values for Site 900 are higher than typical values for tholeiitic basalts and similar to values for the lower continental crust. Some reduction is probably caused by radionuclide mobility during weathering. However, it is probably premature to distinguish these rocks as lower continental crust, rather than lower oceanic crust, based solely on these values. The low values for the serpentinite samples from Site 897 are consistent with low concentrations typical for mantle peridotites and additional reduction during hydration.

These results suggest that heat flow observations over the thinned continental crust of the Galicia Bank Margin should be elevated with respect to measurements on the thinned continental (or oceanic) crust of the Iberia Basin. A preliminary comparison between previous shallow-marine measurements off Galicia Bank and deeper measurements from Sites 897, 898, and 900 of Leg 149 in the Iberia Basin indicate just the reverse. Comparable values for both margins are observed in the oceanic/serpentinite ridge domain, but landward values on transitional crust at Site 900 in the Iberia Basin are 16-23 mW/m^2 higher than values landward of the serpentinite ridge on Galicia Bank. The large uncertainties in heat flow for the Leg 149 sites and the limited number of determinations of radiogenic heat production, however, means that this inconsistency requires further confirmation from additional measurements of radiogenic heat production in basement landward of Site 900 and additional heat flow stations in its vicinity.

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Table 2. Leg 149 heat flow.

Site	Lat. (N), Long. (W)	T (°C)	Depth (mbsf)	R_s ($m^2 \cdot K/W$)	σ_R	Q (mW/m^2)	σ_Q
897	40°50.33′, 12°28.44′	2.4	0.0	0.0	0.0	55.7	7.3
		6.1	55.2	43.3	5.8		
		11.9	214.4	164.4	21.9		
898	40°41.10′, 12°07.43′	2.4	0.0	0.0	0.0	49.9	6.5
		6.8	113.7	88.6	11.8		
		9.2	176.4	136.1	18.1		
900	40°40.99′, 11°36.27′	2.4	0.0	0.0	0.0	63.3	8.3
		8.8	122.4	95.2	12.7		
		10.8	170.6	131.7	17.6		
		13.0	218.8	167.7	22.3		

Notes: T (temperatures) for Sites 897 and 900 have been offset by -1.2° and -1.4°C, respectively. R_s ($\pm\sigma_R$) = $(1/b)\ln\{(k_o + bz) / k_o\}$, where k_o = 1.26 (±0.17) W/m·K; b = 0.00041 (±0.00005) W/m^2·K. Q (heat flow) ($\pm\sigma_Q$) is determined from linear fit to T vs . R_s ($\pm\sigma_R$).

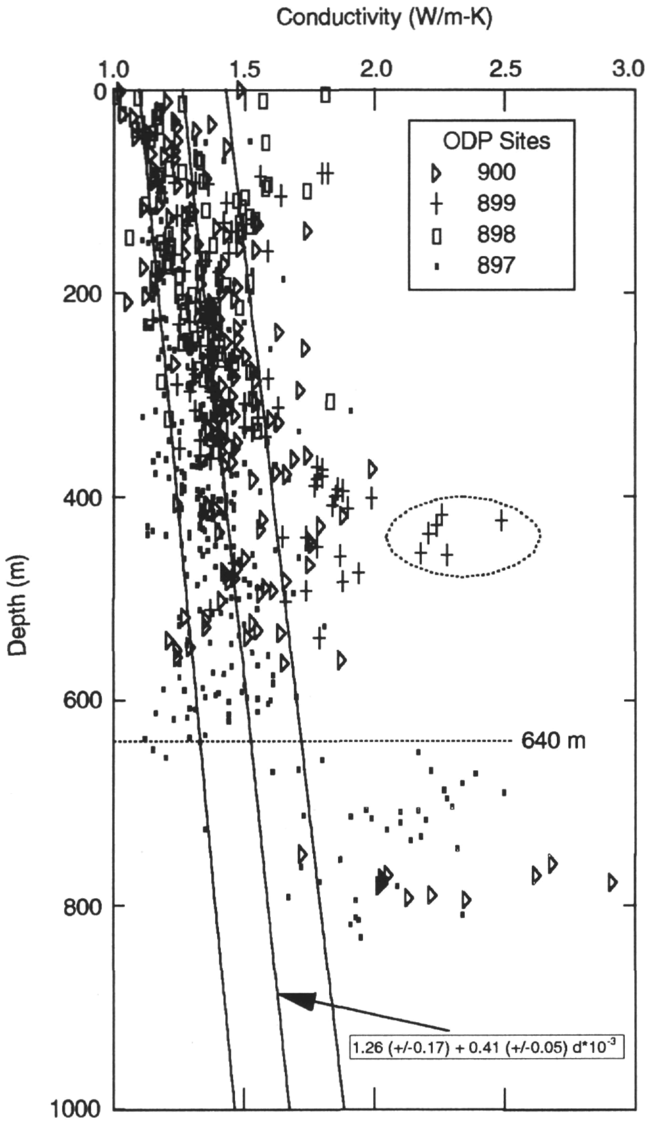

Figure 4. Temperature vs. Bullard depth and lines of least-squares regression for Sites 897, 898, and 900. Values are given in Table 2. Temperatures at each site (from Sawyer, Whitmarsh, Klaus, et al., 1995) have been uniformly adjusted to produce a constant seafloor temperature of 2.4°C. Bullard depths (±lσ) are calculated (see text and Table 2) from the known depths of the temperature probe using the mean linear conductivity function (±lσ) of Figure 5.

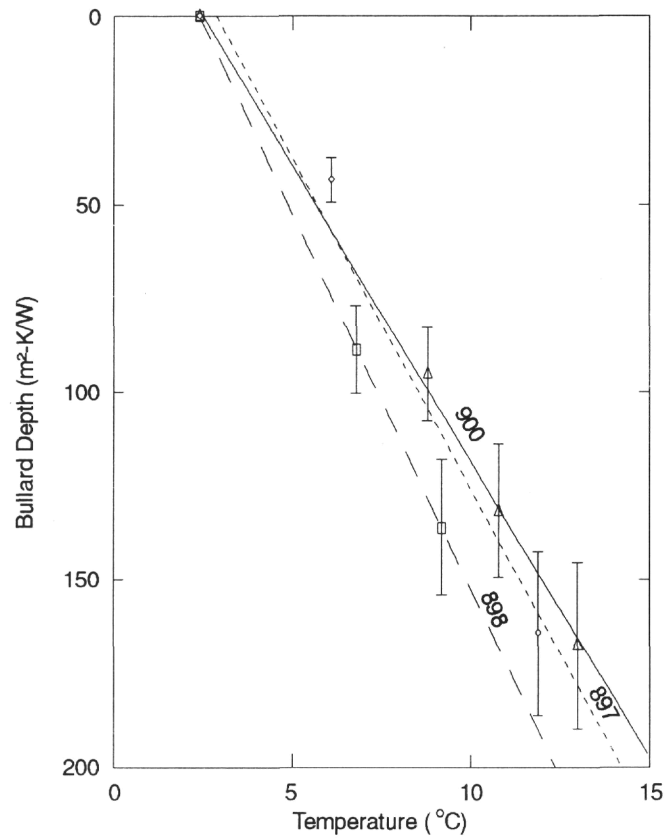

Figure 5. Measurements of thermal conductivity on sediment samples as indicated from Sites 897, 898, 899, and 900 (Sawyer, Whitmarsh, Klaus, et al., 1995). Linear least-squares regression (±1σ) lines are shown for fits to the data, where z < 640 m, excluding the anomalously high values enclosed by the dotted line.

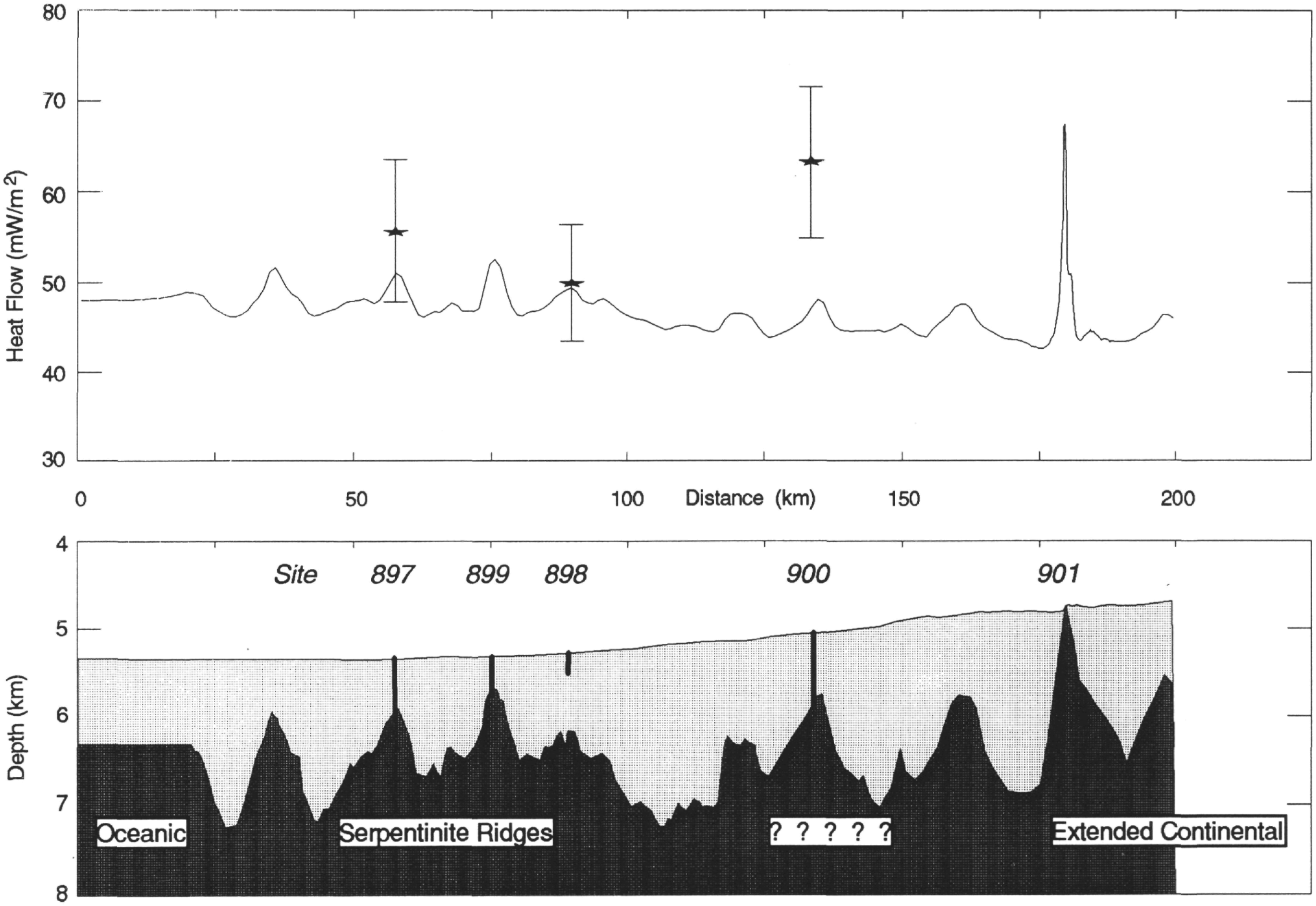

Figure 6. Locations of observed heat flow (±1σ) for Sites 897, 898, and 900 along the composite seismic section, assembled from parts of the three seismic sections located in Figure 1. Conversion from two-way traveltime to depth assumes v_w = 1.5 and v_s = 2.0 km/s. Generalized interpretation of basement type follows Shipboard Scientific Party (1993); question marks indicate basement of uncertain origin. Predicted heat flow along profile (solid line) is calculated as described in the text.

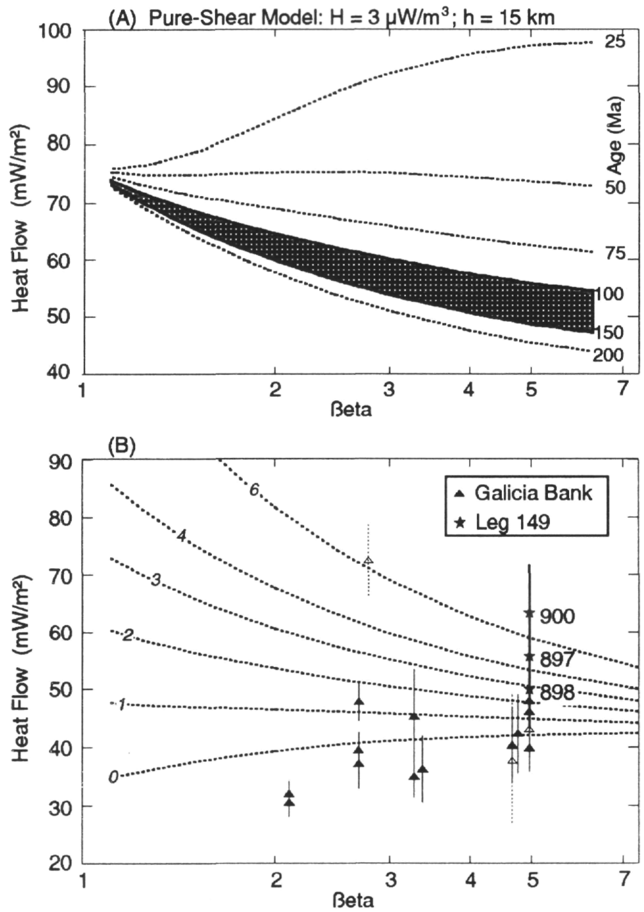

Figure 7. **A**. Variations in heat flow with stretching factor (β) for a pure-shear model (McKenzie, 1978) including the effects of radiogenic heating (Voorhoeve and Houseman, 1988). Separate curves are for separate lithospheric ages as indicated (in Ma), with expected values for the 130-Ma Iberia Margin falling within the shaded region. Assumed values of radiogenic heat production (*H*) and thickness *(h)* are 3 μW/m^3 and 15 km, respectively. After Louden et al. (1991). **B**. Values of corrected heat flow (±lσ) across Galicia Bank and for Iberia Basin sites as a function of stretching factor (β), compared to pure-shear models with various amount of radiogenic heat production *(H* in μW/m^3), as indicated. Lithospheric age is 130 Ma; other parameters in the model are the same as used in (A). Open symbols and dotted error bars indicate values with significant nonlinearities in temperature gradient for Galicia Bank.