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30. NEUTRON ABSORPTION CROSS SECTION (Σ) OF BASALTIC BASEMENT SAMPLES FROM HOLE 896A, COSTA RICA RIFT[1]

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ABSTRACT

The neutron absorption cross section (Σ) of a sample is a measure of the moderating power of the sample in response to its bombardment by neutrons. This physical property is measured automatically by the Geochemical Logging Tool (GLT), and is required for the subsequent land-based data processing of the GLT logs. This contribution reports part of a project to measure accurately the Σ of lithologies commonly drilled in the Ocean Drilling Program (ODP) for both lithological characterization and the calibration of the GLT measurements. From Hole 896A 10 samples of basaltic basement were selected for Σ measurements. For these samples Σ shows only a small range of variation in response to the nearly constant chemistry of the basement, with an average of 0.00599 cm^2/g, and standard deviation of 0.00027 cm^2/g. Over the depth interval from which the core samples were taken (195–355 mbsf) the increase in Σ observed with depth is a direct result of increasing iron and titanium in the basalts.

INTRODUCTION

The neutron absorption cross section (Σ) of a sample is a measure of the moderating power of the sample in response to bombardment by neutrons. In pulsed nuclear logging tools, such as the Geochemical Logging Tool (GLT), which is employed regularly in the Ocean Drilling Program (ODP) (Brewer et al., 1992), Σ is measured routinely for making environmental corrections during the subsequent land-based data processing. Σ is a direct function of the chemical composition of a sample; in principle it is a simple summation of the weight fraction of each element multiplied by the corresponding elemental cross section. In practice, the measurements of Σ made downhole at each depth interval contain (chemical) contributions from the borehole fluid, the rocks themselves (Kerr et al., 1992), and fluids in the formation. As hydrogen and chlorine are important components of the fluids and strongly affect Σ, the downhole measurement is particularly sensitive to total porosity and the composition of the fluid (Ellis, 1987). This sensitivity is utilized in the hydrocarbon industry where measurements of sigma on the rocks themselves enable the wireline-measured Σ values to be partitioned more effectively between the rocks and their associated formation fluid (Ellis, 1987). Typically, oil field lithologies are generally different from those recovered in ocean drilling. For this reason it is necessary to measure Σ directly on some of the more common ocean floor lithologies to enable calibration, validation, and interpretation of the wireline measured Σ (with the Geochemical Logging Tool; GLT), and, in addition, to provide more complete characterization of the same lithologies.

This contribution is part of a project being jointly undertaken by Leicester University Borehole Research (LUBR) and AEA Technology of which a primary objective is to improve the quality of geochemical logs. To this end, Σ has been accurately measured on several core samples from Legs 126, 148, and 149. Measurements on 10 samples of basaltic basement from Hole 896A, which was drilled during Leg 148 (Alt, Kinoshita, Stokking, et al., 1993), are described here.

Located approximately 200 km to the south of the Costa Rica Rift spreading center are ODP Holes 504B and 896A (Dick, Erzinger, Stokking, et al., 1992; Alt, Kinoshita, Stokking, et al., 1993). Hole 896A was drilled 1 km south of Hole 504B on a bathymetric high overlying a basement topographic high (Alt, Kinoshita, Stokking, et al., 1993) and penetrates crust approximately 28,000 yr older than the 5.9 Ma crust drilled in Hole 504B (Alt, Kinoshita, Stokking, et al., 1993). Basement was drilled at 179 mbsf; however, because the hole was cased, cored material was recovered only between 195.1 and 469 m below seafloor (mbsf) (Alt, Kinoshita, Stokking, et al., 1993). In the drilled section, core recovery averaged 26.9%, with pillow lavas (57%) and massive flows (38%) accounting for the majority of the lithostratigraphy (Alt, Kinoshita, Stokking, et al., 1993). The recovered basalts are sparsely to highly phyric plagioclase and olivine tholeiites, although in an approximately 40 m section (353.1–391.1 mbsf) clinopyroxene is present as a phenocryst phase (Alt, Kinoshita, Stokking, et al., 1993). With the exception of glassy pillow rims the majority of the rocks are slightly altered (<10%; Alt, Kinoshita, Stokking, et al., 1993) and variably veined.

SAMPLE SELECTION

Samples were crushed in an agate tema mill, to yield 60 to 80 g of fine powder. Some 10 g of this material was subsampled for major and trace element analysis, the remainder was used for the Σ analysis. Glass fusion beads were used for the major element analysis and the trace elements were determined on pressed powder pellets, and the major and trace elements were determined by X-ray fluorescence (XRF) spectrometry (Table 1) at Nottingham University, using identical procedures to those described in Alt, Kinoshita, Stokking, et al. (1993).

CALCULATION OF Σ

Each element has a characteristic thermal neutron absorption cross section. For a given sample, the value of Σ is the sum of the weight fraction of each element multiplied by its corresponding elemental cross section (Ellis, 1987). For measurements made down-

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Table 1. Major and trace element chemistry of Σ measurements for Hole 896A samples.

Sample:	1	2	3	4	5	6	7	8	9	10
Depth (mbsf):	195.4	201.2	287.0	289.2	317.7	325.2	325.5	348.4	349.0	354.5
Major elements:										
SiO_2	49.42	49.40	49.20	48.99	48.66	49.04	49.23	49.98	49.63	49.42
Al_2O_3	17.68	17.53	17.24	15.92	16.62	17.03	17.44	15.92	16.24	15.81
TiO_2	0.71	0.70	0.74	0.80	0.73	0.76	0.78	0.85	0.88	0.89
Fe_2O_3	8.33	8.58	9.40	9.93	9.48	9.43	8.99	9.95	9.80	9.98
MgO	7.21	7.19	7.17	8.07	7.69	7.24	7.05	7.93	7.38	8.60
CaO	13.40	13.57	13.29	13.04	13.04	13.39	13.19	12.82	12.98	12.41
Na_2O	2.06	2.01	1.88	1.91	1.90	1.91	1.95	1.84	2.06	1.88
K_2O	0.07	0.07	0.05	0.08	0.07	0.07	0.05	0.23	0.17	0.10
MnO	0.16	0.16	0.17	0.18	0.19	0.18	0.18	0.18	0.18	0.19
P_2O_5	0.05	0.06	0.05	0.06	0.05	0.05	0.05	0.07	0.07	0.08
LOI	1.06	0.93	1.03	0.93	1.19	0.91	1.01	0.28	0.58	0.70
Total	100.15	100.20	100.22	99.91	99.62	100.01	99.92	100.05	99.97	100.06
Trace elements:										
Ba	<8	13	11	10	13	12	<8	25	29	27
Ce	20	39	29	17	24	39	24	12	19	27
Co	54	46	47	46	41	41	43	35	39	42
Cr	395	379	361	343	332	328	362	283	282	328
Cu	81	87	80	78	62	79	78	61	48	49
Ga	15	14	15	17	15	15	16	15	17	16
Nb	1	<1	<1	2	<1	<1	<1	<1	<1	<1
Ni	189	170	155	136	148	147	149	103	105	100
Rb	2	1	2	3	2	2	2	5	4	3
S	1931	1672	1568	166	309	1185	1988	433	110	1500
Sc	45	41	41	36	40	42	46	46	46	47
Sr	70	68	70	61	65	64	66	56	61	57
Th	1	1	2	<1	<1	<1	<1	<1	<1	2
U	2	<1	<1	2	<1	<1	2	<1	1	<1
V	227	215	226	235	221	222	243	254	256	259
Y	23	22	21	24	23	22	26	27	27	28
Zn	55	55	55	49	52	51	63	58	60	57
Zr	41	41	46	42	39	42	43	45	50	48

Notes: Major elements measured in weight percent (wt%), and trace elements in parts per million (ppm). LOI = loss on ignition.

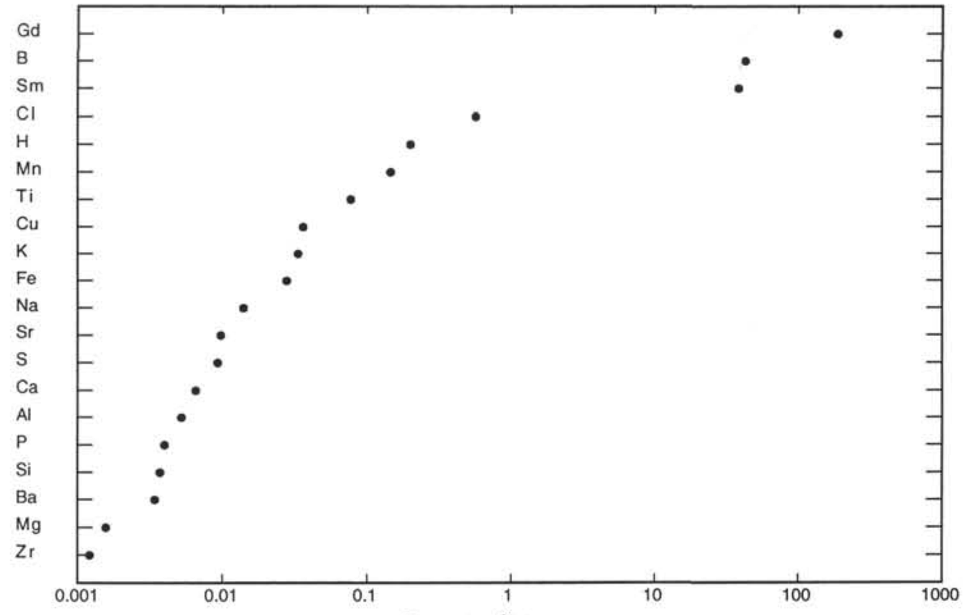

Figure 1. Variation in elemental cross section for several geochemically common elements, together with Gd, B, and Sm, which have the strongest neutron absorption.

hole, that sample will include, in addition to the rocks themselves, the fluids in the formation, and a contribution from the borehole fluid. In the exercise reported here we are concerned only with the Σ value of the rock.

The value of Σ is strongly influenced by the extreme range and variation in elemental cross section; thus some elements may occur at levels of only a few parts per million but can have a significant effect on the nuclear absorption properties of the rock. To illustrate this, the elemental cross sections for several elements (high absorbers and those that are geochemically dominant) are ordered and plotted in Figure 1.

It can be seen that the elemental cross sections vary over several orders of magnitude with Gd, B, and Sm having by far the highest nuclear absorptions. Even the presence of a few parts per million of

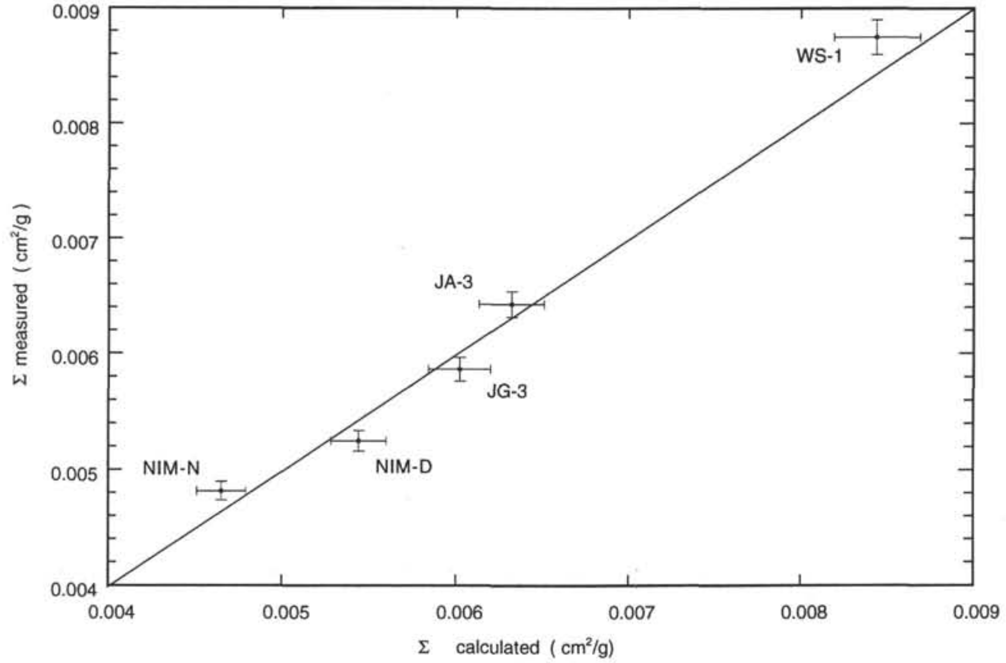

Figure 2. Comparison of calculated and measured values of Σ for five geochemical reference materials that were run together with the Hole 896A samples. Error bars are estimated one sigma errors.

these elements can have a significant effect on the total sample absorption. Of more systematic significance are Cl and H, which come next in order and are an expression of the contribution that the fluids (borehole and/or formation) make to the wireline-measured S.

Given the complete chemistry of a sample, Σ can easily be calculated. The errors present in such a calculation can arise from the uncertainty in the chemical analysis, particularly of those elements with a large cross section, and uncertainty about the elemental cross section values (Ellis, 1987; Hertzog et al., 1989). The particular problem elements (Gd, B, Sm, H, and Cl) are difficult to determine and are frequently not measured. In the interpretation of nuclear logs in the Ocean Drilling Program, H and Cl are so overwhelmingly part of the borehole fluid that they can be regarded as absent in the formation; that is, it is virtually impossible to separate out the formation signal for these two elements. In this way, a simple plot of measured Σ against calculated Σ, which should be near to a 1:1 line, generally shows the calculated values to be lower. To a great extent it is the difference between the calculated and measured values that is important as it is essentially an expression of the chemistry which has not been taken into account in the calculation.

Table 2. Core location, and measured and calculated Σ values for 10 basalt samples from Hole 896A.

Sample	Depth (mbsf)	Core, section, interval (cm)	Piece	M	C	Inc REE
1	195.4	1R-1, 29–36	7	0.00576	0.00472	0.00555
2	201.2	2R-1, 30–32	7	0.00566	0.00472	0.00556
3	287.0	11R-1, 98–109	8B	0.00593	0.00489	0.00572
4	289.2	11R-3, 30–35	5	0.00610	0.00496	0.00579
5	317.7	14R-3, 21–24	4	0.00591	0.00491	0.00575
6	325.2	15R-1, 94–97	14	0.00583	0.00488	0.00572
7	325.5	15R-1, 122–126	18	0.00587	0.00485	0.00568
8	348.4	17R-4, 53–58	3B	0.00660	0.00488	0.00571
9	349.0	17R-4, 113–116	11	0.00619	0.00494	0.00578
10	354.5	18R-1, 142–145	12B	0.00609	0.00497	0.00580
Arithmetic mean:				0.00599	0.00487	0.00571
Standard deviation:				0.00027	0.00009	0.00009
Minimum:				0.00566	0.00472	0.00555
Maximum:				0.00660	0.00497	0.00580

Notes: M = measured Σ, C = calculated Σ, and Inc REE = calculated Σ, including the rare-earth elements.

MEASUREMENT OF Σ

The direct measurements of Σ (the thermal neutron absorption cross section) were made using the NESSUS facility at the center of the NESTOR reactor at Winfrith in Dorset, U.K. (Butler et al., 1986). NESTOR contains a ring of enriched uranium fuel elements in an annulus of light water that acts as both coolant and neutron moderator. In the center of the reactor is a 2-ft-diameter graphite internal thermal column through which passes a vertical channel to form the NESSUS facility. Coarse- and fine-control shutters are located just outside the ring of fuel elements.

The insertion of a sample into the reactor results in an increased absorption of neutrons so that a control shutter has to be closed slightly to compensate and to enable the reactor to continue to operate at a steady power. The amount by which this calibrated shutter has to be closed is a measure of the neutron absorption of the sample (Butler et al., 1986).

Prior to measurement the samples were dried for 4 days at 80°C, and then loaded into 50-cm³ PTFE bottles for entry into the reactor. The method is nondestructive. In addition to the Hole 896A samples, five igneous rock geochemical reference materials (GRMs), were also measured to monitor the accuracy of the measurement technique, whereas, the calibration and precision of the facility was maintained by the use of two established NESSUS standard samples of pure copper and Ottawa Sand. A full error analysis of each measurement, including variation in the reactivity and mass of the sample and PTFE bottle, sample density and a moderation correction, gives a consistent range of about 2.0%. Figure 2 shows the level of agreement between the measured and calculated values of Σ for the five igneous GRMs. All standards adhere closely to the 1:1. The greatest discrepancy, with a slightly lower calculated value, is the dolerite

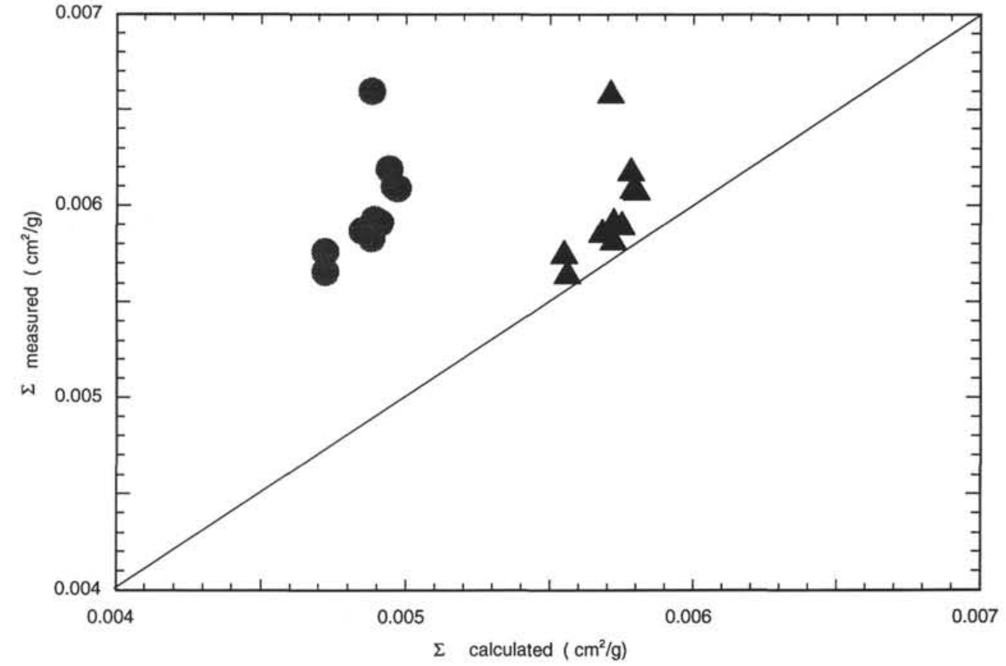

Figure 3. Comparison between measured and calculated values of Σ for the Hole 896A basalts. The solid circles are for values calculated from the major and trace element analysis without the inclusion of any rare earth elements except Ce and Y. The solid triangles are calculated from the same data together with the inclusion of average rare earth data for Dy, Er, Eu, Gd, and Sm derived from a data base of basalt analyses from nearby Hole 504B (Emmermann, 1985; Kempton et al., 1985; Tual et al., 1985).

WS-1. This is probably the least well characterized GRM of the five measured.

Table 3. Average composition (major and trace element) for Hole 896A basalt samples, together with the contribution made to the average Σ by each element.

	%/ppm	Σ contribution	% of Σ total
Major elements:			
SiO_2	49.3	0.000853	15.12
Al_2O_3	16.74	0.000461	8.17
TiO_2	0.78	0.000361	6.40
Fe_2O_3	9.39	0.001812	32.12
MgO	7.55	0.000073	1.29
CaO	13.11	0.000609	10.80
Na_2O	1.95	0.000199	3.53
K_2o	0.10	0.000026	0.46
MnO	0.18	0.000199	3.53
P_2O_5	0.06	0.000001	0.02
$H_2O + CO_2$	0.09	0.000191	3.39
Trace elements:			
B	0.34	0.000015	0.26
Co	43	0.000016	0.28
Cr	339	0.000012	0.21
Cu	70	0.000003	0.05
Gd	3.60	0.00067	11.93
Ni	140	0.000007	0.12
S	1086	0.000010	0.18
Sc	43	0.000015	0.27
Sm	2.22	0.000085	1.51
Sr	64	0.000001	0.02
B	236	0.000014	0.25
Y	24	0.000003	0.05
Zn	56	0.000001	0.01
Zr	44	0.000001	0.01
	Sum		
	Major element contribution:	84.83%	
	Trace element contribution:	15.17%	

Σ IN BASALTIC BASEMENT OF HOLE 896A

Details of the location downhole and measured and calculated values of Σ for the 10 basalt samples are given in Table 2. The samples are arranged in order of increasing depth below seafloor. The measured values of Σ vary over a narrow range (0.00566–0.00660 cm²/g) with a mean of 0.00599 cm²/g. Calculated values of Σ were obtained from the normal geochemical analyses of these samples which, for the record, are tabulated in Table 2. The calculated values are, on average, 18% lower than the measured values, a difference due mainly to the absence of rare earth element (REE) and boron data on these samples. In an attempt to verify this effect average values for boron and those rare earths that are particularly strong neutron absorbers (Dy, Er, Eu, Gd, and Sm) were obtained from a compilation of analyses of basalts from nearby Hole 504B (Emmermann, 1985; Kempton et al., 1985; Tual et al., 1985), because both B and REE data for the Hole 896A rocks are not yet available. The calculated values together with this assumed rare earth component are also given in Table 2, and the measured and calculated data sets are all displayed in Figure 3. The contribution of individual elements to the Σ value in the basalts from Hole 896A is illustrated in Table 3. In Table 3, the Σ contribution was calculated using the average of the 10 Hole 896A basalts (Table 2) and the average Gd, Sm and B values from the Hole 504B basalts (Emmermann, 1985; Kempton et al., 1985; Tual et al., 1985; Ishikawa and Nakamura, 1992). The major elements contribute a significant proportion to Σ, and, in particular Fe and Si, whereas, the trace element contribution is strongly influenced by Gd. Although B has a large capture cross section area, its very low concentrations in the relatively "fresh" basalts (Ishikawa and Nakamura 1992) limit its overall contribution to S. However, in 504B, B is strongly enriched in low-temperature alteration zones (Ishikawa and Nakamura 1992),

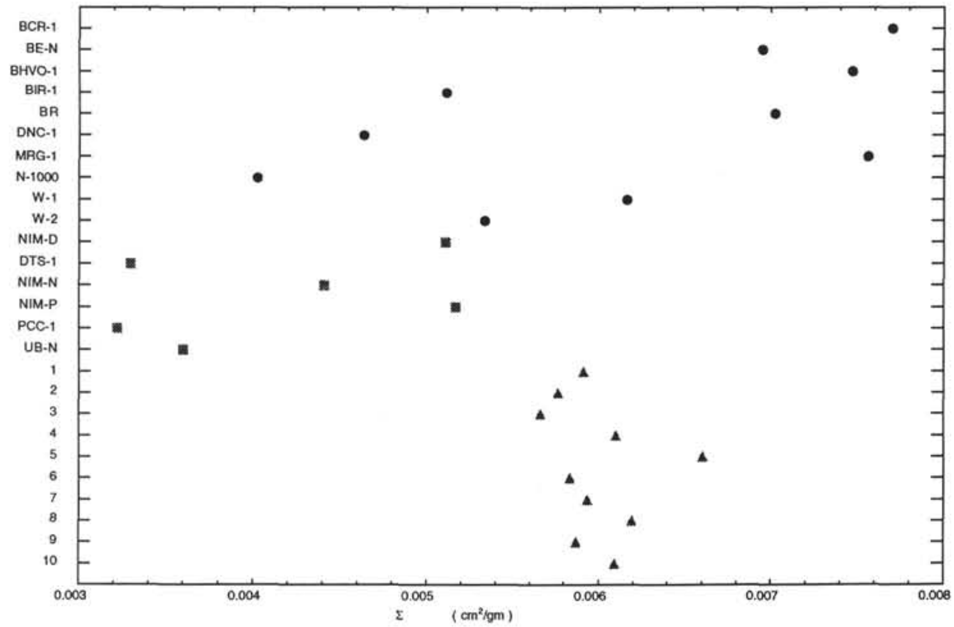

Figure 4. Comparison of measured and calculated Σ values for several well-characterized geochemical reference materials and basalts recovered from Hole 896A. Circles = basaltic/gabbroic reference materials; squares = ultrabasic/serpentinitic reference materials; triangles = basalts from Hole 896A.

where it may contribute significantly at such values to the overall Σ value.

Probably the most significant feature of the measured Σ values from Hole 896A is the near constant value. This is demonstrated further by comparison with several other basic and ultrabasic geochemical reference materials. The latter have to be chosen for this purpose because no other basic/basic rock analyses are available which even approach the level of characterization available in well-established geochemical standards. The comparison with the Hole 896A samples is shown in Figure 4. The lithologies and sources of the GRMs used for this exercise are given in Table 4. The "accepted" values used in the calculations were taken from the geostandards compilation (Govidaraju, 1989). From the limited number of samples available Σ is seen to vary between about 0.003 and 0.008 cm²/g for basalts with values of less than 0.005 cm²/g for basic rocks, a reflection essentially of the higher Mg/Fe ratio in the latter. The Hole 896A basalts are seen to be constrained to a very limited range of S. This reflects the constancy of composition seen in the chemical analyses, but also points to the lack of significant variation in the key elements, such as the rare earths and boron, that have very high elemental cross sections.

Despite the relative consistency of Σ within Hole 896A there is a suggestion of an increase in this parameter over the depth interval 195 to 355 mbsf from which the measured samples were taken (Fig. 5). This reflects a real change in the geochemistry with increasing iron downhole over this interval, and a sharp increase in TiO_2 at 340 mbsf. The spatial variation in basalt chemistry is discussed elsewhere.

CONCLUSIONS

Σ has been measured on 10 samples of basalts from Hole 896A. The measured Σ shows only a small range of variation in response to the nearly constant chemistry of the basalts, with an average of 0.00599 cm²/g, and standard deviation of 0.00027 cm²/g. Over the depth interval from which the core samples were taken (195–355 mbsf), the increase in Σ correlates with an observed increase in iron and titanium in the basalts with depth. This new data for Σ can now be used to constrain the processing of GLT data in basaltic basement.

Table 4. Source of Geochemical Reference Materials used for comparison with Hole 896A basalt samples, together with values of Σ calculated from their currently "accepted" chemical compositions.

Sample	Lithology	Source	Σ (cm²/g)
BCR-1	Basalt	USGS	0.00770
BE-N	Basalt	GIT-IWT	0.00695
BHVO-1	Basalt	USGS	0.00747
BIR-1	Basalt	USGS	0.00511
BR	Basalt	CRPG	0.00702
DNC-1	Basalt	USGS	0.00464
MRG-1	Gabbro	CCRMP	0.00756
N-1000	Gabbro	LU	0.00402
W-1	Diabase	USGS	0.00616
W-2	Diabase	USGS	0.00534
NIM-D	Dunite	SABS	0.00511
DTS-1	Dunite	USGS	0.00329
NIM-N	Norite	SABS	0.00441
NIM-P	Peridotite	SABS	0.00517
PCC-1	Peridotite	USGS	0.00322
UB-N	Serpentinite	ANRT	0.00360

Note: Currently "accepted" chemical compositions from Govidaruju (1989). Sources for standards as follows: USGS = United States Geological Survey, Reston, VA; GIT-IWT = Groupe International de Travail-International Working Group; CRPG = Centre de Recherches Petrographiques et Geochimiques; CCRMP = Canadian Certified Reference Materials Project; LU = Leicester University; MINTEK = Council for Mineral Technology, South Africa; and ANRT = Association Nationale de la Recherche Technique, Paris.

The Σ measurements obtained by the GLT in the ocean drilling program are derived from Σ component of seawater in the borehole, in open fractures and in pore space in addition to the contribution from the rock mass. With the extremely low porosity and, hence pore space encountered in many oceanic basalts, the Σ contribution from this source is minimal. It may hence be possible to determine the difference between the measured Σ and that assumed for the rock (actually measurements on core) to give an estimation of the open fracture network. Furthermore such discrepancies between the measured and calculated Σ may provide evidence of highly altered basalts in zones of low recovery, where the alteration is dominated by low-temperature minerals containing high boron concentrations.

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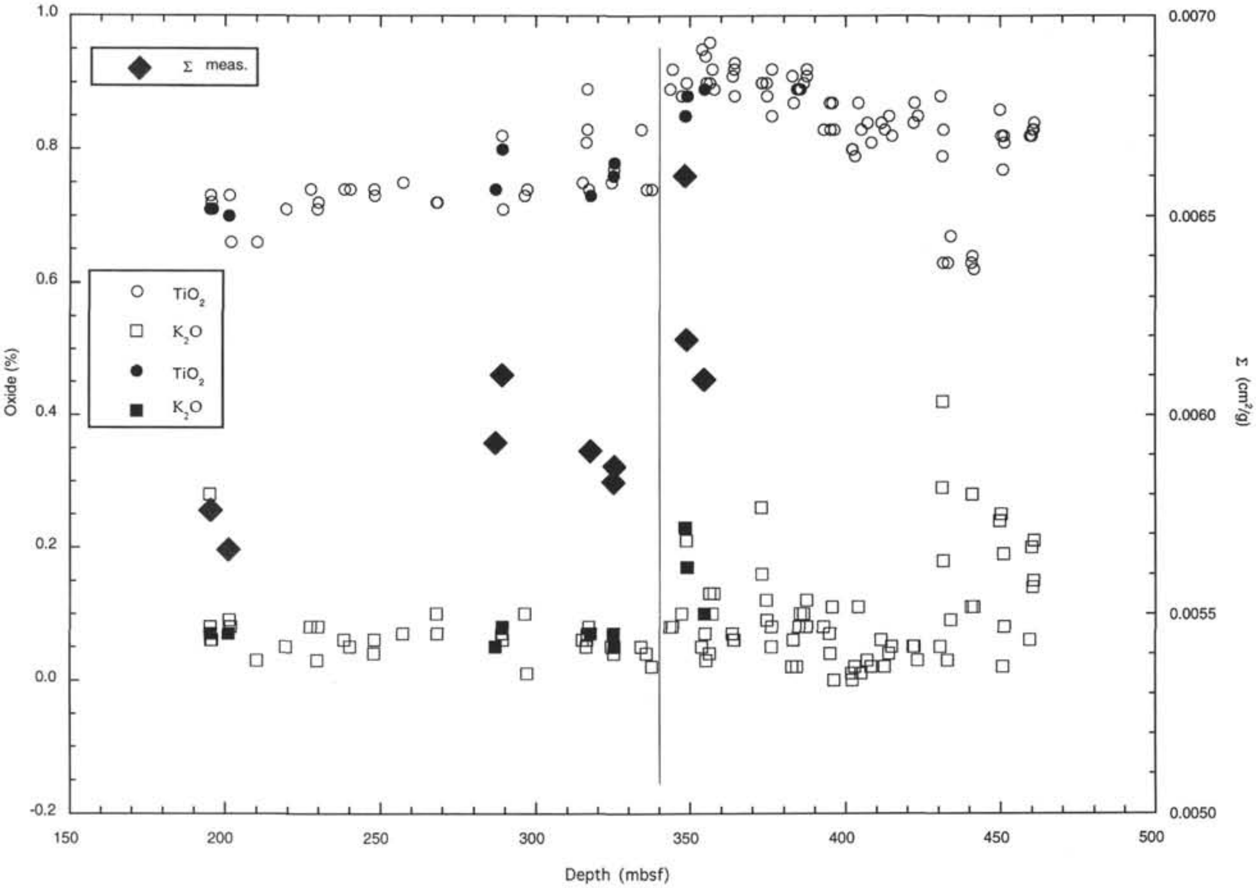

Figure 5. Variation of Σ with depth in Hole 896A. Also shown is the variation in TiO_2 and K_2O as measured on core samples. Solid squares and circles indicate the samples used for Σ determination, open squares and circles indicate other core samples.