

37. RELATIONSHIP BETWEEN LITHOLOGY AND THE NEUTRON ABSORPTION CROSS SECTION (Σ) OF SAMPLES FROM LEG 149¹

J.C. Lofts,² P.K. Harvey,³ M.A. Lovell,³ and J. Locke⁴

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 used in the subsequent land-based processing of the GLT log data. This contribution reports part of a project to measure accurately the Σ of lithologies commonly drilled in the Ocean Drilling Program for both lithological characterization and the calibration and modeling of the nuclear measurements. Σ was measured on 13 samples obtained during Leg 149. These samples, from Holes 897C, 899B, and 900A, were chosen to include a range of both sediment and basement lithologies. Measurements of Σ on two altered basalts from Hole 900A gave an average of 0.00688 ± 0.00014 cm²/g. These figures are higher than, but still generally similar to, values obtained on basalts from Hole 896A (Leg 148) in the East Equatorial Pacific, which suggests that oceanic basalts could be characterized by a reasonably consistent range of Σ (0.0055 ± 0.00011 to 0.0075 ± 0.00015 cm²/g). Three serpentinized peridotites and eight sediment samples measured gave higher values of Σ , averaging 0.01217 ± 0.00025 and 0.01478 ± 0.00030 cm²/g, respectively. Comparison of the measured values of Σ with estimates calculated from the routine chemical analyses of the samples confirms that the use of calculated Σ values is unreliable unless the chemical analysis is particularly complete.

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 Schlumberger's geochemical logging tool (GLT), which is employed regularly by the Ocean Drilling Program (ODP), Σ is measured routinely and is used for environmental corrections during the subsequent land-based data processing of chemical logs. In addition, the lithologic sensitivity of the GLT makes it useful as a log in its own right for the geological characterization of formations. 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, 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. This sensitivity is utilized in the hydrocarbon industry in which measurements of Σ on the rocks themselves enable the wireline-measured Σ values to be more effectively partitioned between the rocks and their associated formation fluid. Typically, oil field lithologies are different from those found 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 modeling of wireline-measured Σ , and in addition to provide more complete characterization of the same lithologies.

This contribution is part of a project jointly undertaken by Leicester University Borehole Research (LUBR) and AEA Technology, the trading name of the United Kingdom Atomic Energy Authority. The project's primary objective is to improve the quality of geochemical logs. To this end Σ has been accurately measured on a number of core samples from Legs 126, 148, and 149. Measurements on 13 samples of sediments and basement rocks from Holes 897C, 899B, and 900A, which were drilled during Leg 149, are described here. The results obtained for the Leg 148 samples are reported in Brewer et al. (in press).

The rocks drilled on Leg 149 are particularly suitable for this investigation of Σ because of the wide range of lithologies. One of the primary objectives of the leg was to investigate the ocean/continent transition where it occurs on the eastern edge on the Iberia Abyssal Plain by drilling through the sedimentary cover into basement. As a result, a range of pelagic and turbiditic sediments, together with altered basement peridotites and basalts, was available for sampling. Details of the samples chosen are given in Table 1. Eight samples were chosen from Hole 897C, together representing a traverse "downhole." Three samples were taken from petrographic Unit I (samples 1, 2, and 3), four from Unit II (Unit IIA, sample 4; Unit IIB, sample 5; Unit IIC, samples 6 and 7). Sample 10 came from the peridotite basement. Two serpentinized peridotites (samples 15 and 16) were sampled from Hole 899B, and two altered basalts (samples 19 and 21) and one sediment (sample 18) were sampled from Hole 900A (Table 1).

SAMPLE PREPARATION AND MEASUREMENT PROCESS

The selected samples were crushed in an agate grinding mill to yield 65 to 80 g of fine powder, which was used for the Σ measurements. Some 10 g of this material was subsequently used for routine geochemical analysis. This chemical analysis was conducted by X-ray fluorescence spectrometry at the University of Leicester, with the major elements determined on glass fusion beads and the trace elements on pressed powder pellets. The resulting analyses for the 13 Leg 149 samples are given in Table 2.

¹Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), 1996. *Proc. ODP, Sci. Results*, 149: College Station, TX (Ocean Drilling Program).

²GeoQuest, Schlumberger House, Gatwick, West Sussex, RH6 0NZ, United Kingdom. phk@le.ac.uk

³Borehole Research, Department of Geology, Leicester University, LE1 7RH, United Kingdom.

⁴AEA Technology, Reactor Services, Winfrith, Dorchester, Dorset, DT2 8DH, United Kingdom.

Table 1. Core location, measured and calculated Σ values, and lithology of the 13 samples from Hole 897C used in this study.

Sample	Core, section, interval (cm)	Depth (mbsf)	Σ (cm ² /g)				Lithology
			Measured	Error (M)	Calculated	Error (C)	
1	8R-2, 2-14	119.42	0.01546	0.00032	0.00520	0.00010	Pelagic ooze
2	21R-1, 90-103	244.3	0.01600	0.00034	0.00599	0.00012	Pelagic ooze
3	23R-1, 37-51	263.07	0.01398	0.00029	0.00503	0.00010	Fine-grained sandstone/turbidite
4	26R-2, 37-51	293.37	0.01462	0.00031	0.00495	0.00010	Carbonate ooze
5	31R-4, 1-13	344.41	0.01243	0.00026	0.00444	0.00009	Carbonate ooze
6	38R-6, 49-57	415.39	0.01519	0.00032	0.00571	0.00011	Gray pelagic clay
7	47R-6, 53-70	502.23	0.01573	0.00033	0.00605	0.00012	Brown pelagic clay
8	66R-4, 41-46	681.16	0.01302	0.00027	0.00599	0.00012	Serpentinized peridotite
9	21R-3, 120-125	420.68	0.01127	0.00024	0.00526	0.00011	Serpentinized peridotite
10	23R-2, 44-49	437.45	0.01221	0.00026	0.00416	0.00008	Serpentinized peridotite
11	52R-1, 104-111	480.24	0.01483	0.00031	0.00583	0.00012	Brown hemipelagic clay
12	83R-2, 85-89	776.17	0.00599	0.00013	0.00490	0.00010	Altered basalt
13	85R-3, 38-44	789.52	0.00776	0.00016	0.00569	0.00011	Altered basalt

Notes: Measured = directly measured Σ value; error (M) = estimated error in the measured value; calculated = Σ value calculated from the geochemical analyses given in Table 2; error (C) = estimated error in the calculated value.

Table 2. Major and trace element chemistry of the 13 Leg 149 samples used for Σ measurements.

Sample:	1	2	3	4	5	6	7	10	15	16	18	19	21
Hole:	897C	897C	897C	897C	897C	897C	897C	897C	899B	899B	900A	900A	900A
Depth (mbsf):	119.4	244.3	263.1	293.4	344.4	415.4	502.2	681.2	420.7	437.5	480.2	776.2	789.5
Major oxides (wt%)													
SiO ₂	50.98	55.85	59.60	37.08	37.27	61.13	59.09	38.49	37.70	43.43	56.98	47.41	44.44
Al ₂ O ₃	14.97	19.14	13.02	12.96	10.59	17.84	18.63	2.55	2.36	1.02	19.08	18.25	18.76
TiO ₂	0.76	0.80	0.57	0.45	0.35	0.82	0.83	0.07	0.14	0.01	0.77	0.28	0.15
Fe ₂ O ₃	4.80	6.01	4.55	4.54	3.00	6.35	7.28	8.05	6.63	8.54	6.72	7.74	9.46
MgO	1.97	2.00	1.46	1.85	1.92	2.36	2.37	37.86	33.36	43.31	1.97	10.00	11.70
CaO	9.13	2.13	6.53	19.42	22.87	0.74	0.70	0.03	5.48	0.58	1.28	11.24	6.58
Na ₂ O	1.32	1.16	1.25	1.23	1.28	1.33	1.24	0.00	0.00	0.00	1.42	1.59	1.42
K ₂ O	2.44	3.73	2.84	1.59	1.35	3.55	3.75	0.01	0.02	0.01	4.06	0.56	1.05
MnO	0.05	0.05	0.04	0.14	0.13	0.10	0.15	0.11	0.08	0.11	0.10	0.11	0.09
P ₂ O ₅	0.13	0.11	0.12	0.15	0.18	0.15	0.22	0.01	0.03	0.01	0.12	0.03	0.03
LOI	12.93	8.90	10.49	20.55	22.34	6.10	6.34	13.30	14.85	4.46	6.26	3.75	6.73
Total	99.48	99.89	100.47	99.96	101.30	100.47	100.60	100.49	100.64	101.48	98.77	100.94	100.40
Trace elements (ppm)													
As	11	13	11	3	2	3	17	1	<1	<1	15	1	<1
Ba	287	394	354	291	655	506	341	<8	<8	<8	546	117	43
Ce	55	69	56	59	43	82	102	<7	<7	<7	77	<7	<7
Co	14	14	11	14	13	19	29	79	65	86	23	48	60
Cr	66	86	69	72	57	94	93	2234	1947	2943	79	456	124
Cu	24	27	22	29	35	29	56	<1	7	10	24	3	4
Ga	18	25	18	16	15	25	26	3	2	1	29	15	14
La	29	33	30	34	31	35	45	4	5	5	41	4	5
Mo	1	2	1	1	1	1	1	<1	<1	<1	1	<1	<1
Nb	18	17	13	11	10	18	19	1	2	<1	20	1	1
Nd	20	27	22	28	22	32	42	<1	1	<1	31	1	<1
Ni	27	31	23	45	39	55	86	2074	1738	2326	60	174	290
Pb	24	28	23	15	13	18	23	1	2	1	24	<1	1
Rb	135	190	156	117	119	187	193	4	4	4	255	8	14
Sc	11	11	13	13	13	12	14	10	10	9	12	28	11
Sn	6	7	5	4	5	7	9	1	1	2	9	2	1
Sr	300	130	275	723	795	125	139	3	24	2	190	243	255
Th	12	16	11	10	8	14	17	<1	<1	1	19	<1	<1
Tl	<1	1	1	1	<1	1	1	<1	<1	<1	1	<1	<1
U	4	5	4	1	2	3	3	1	<1	<1	3	<1	<1
V	94	112	89	101	72	116	110	48	50	45	101	115	46
W	1	3	1	2	<1	2	3	<1	<1	<1	4	<1	<1
Y	26	30	23	27	23	38	45	2	4	1	29	6	3
Zn	72	83	64	69	98	113	135	37	34	42	123	31	40
Zr	171	173	159	100	89	201	206	<3	13	<3	213	5	<3

Note: LOI = the % loss on ignition at 1050°C.

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. For measurements made downhole, a 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 of a number of geochemically important elements are ordered and plotted in Figure 1. It will be seen that the elemental cross sections vary over several orders of magnitude with many of the rare-earth elements, together with boron and lithium, having by far the highest nuclear absorptions. Even the presence of a few parts per million of these elements can have a significant effect on the total sample absorption. Of those elements that can typically occur in significant concentrations in the rock and its associated fluids ("major elements"), Cl and H have the largest cross sections. C

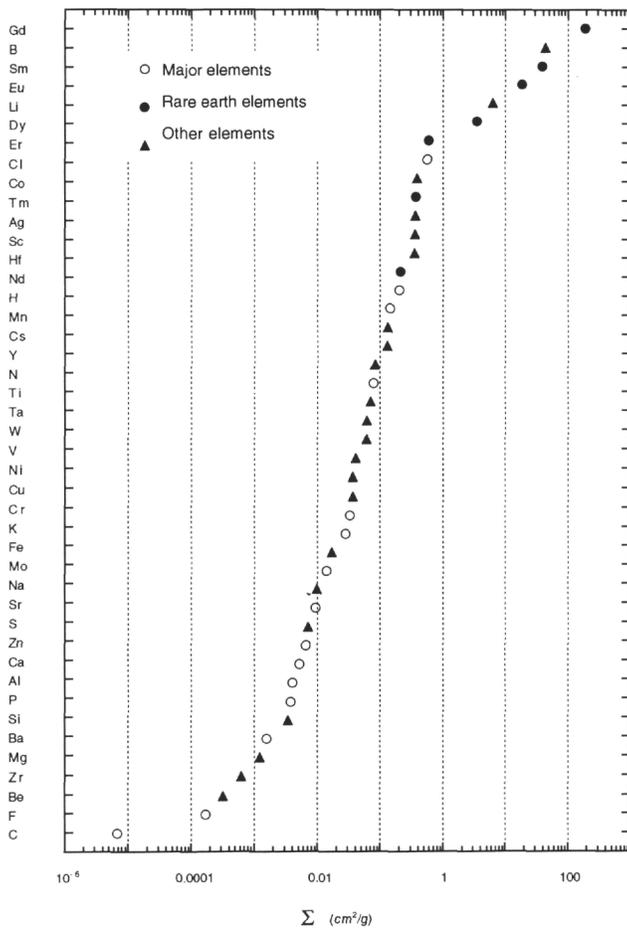
MEASUREMENT OF Σ 

Figure 1. Variation in elemental cross section for a number of geochemically common elements, emphasizing the importance of several of the rare-earth elements (particularly Gd), together with boron and lithium, as strong neutron absorbers.

sequently, in boreholes drilled by the ODP, with seawater typically as the borehole fluid, a significant part of the wireline-measured Σ results from these two elements.

Given the complete chemistry of a sample, Σ is readily calculated. The errors present in such a calculation arise from uncertainty in the chemical analysis, particularly of those elements with a large cross section, and uncertainty about the values of the elemental cross sections. Lack of detailed information about the latter, in particular, prevents rigorous calculation of the error for an individual calculated value; typical uncertainties, however, have been shown in related studies to be of the order of 2%. This value has been assumed to apply here. The particular problem elements (Gd, B, Sm, H, and Cl) are difficult to determine and are usually not measured during routine geochemical analysis. In the interpretation of ODP nuclear logs, 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 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, usually 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 that has not been taken into account in the calculation.

Direct measurements of Σ were made using the NESSUS facility at the center of the NESTOR reactor at Winfrith in Dorset, United Kingdom. NESTOR contains a ring of enriched uranium fuel elements in an annulus of light water, which acts as both a 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.

Prior to measurement the samples were dried for 4 days at 80°C, and then loaded into 50 cm³ poly-tetra-fluoro ethylene (PTFE) bottles for entry into the reactor. The method is nondestructive. In addition to the Leg 149 samples, 10 geochemical reference materials (GRMs) also were measured to monitor the accuracy of the measurement technique, while 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 2.1%. This value has been used to estimate the errors given in Table 1.

For the GRMs, Σ values were calculated using the compositions tabulated in a recent compilation (Govindaraju, 1994) and comparison was made with the measured values (Table 3). Figure 2 shows the level of agreement between these measured and calculated results. All standards adhere closely to the 1:1 line; the greatest discrepancies, with slightly lower calculated values, are for the Japanese andesite (JA-3), dolomite (JD0-1), and lake sediment (JLk-1).

LITHOLOGICAL VARIATION IN Σ

The 13 samples used for these measurements came from three of the holes drilled on Leg 149 (Holes 897C, 899B, and 900A) and were chosen to provide a good range of the lithologies found. The resulting sample set comprises eight sediment samples (including two carbonate oozes and one fine sandstone, together with pelagic clays and oozes), three serpentinized peridotites, and two altered basalts.

The two basalts, from Hole 900A ($\Sigma = 0.00599 \pm 0.00013$ and 0.00776 ± 0.00016 cm²/g, average = 0.00688 ± 0.00014 cm²/g), have similar, comparatively low measured values of Σ , which are only slightly higher than their calculated values (Fig. 3), showing that most of the variation in Σ can be accounted for by elements that can be determined during routine chemical analysis. In comparison, measurements of Σ on 10 basaltic basement samples from Hole 896A in the East Equatorial Pacific (Brewer, et al., in press) gave an average of 0.00599 cm²/g, with a standard deviation of 0.00027 cm²/g, which is altogether similar but lower by about three standard deviations. The very limited evidence available (nine samples at two sites) suggests moderate ($0.0055 - 0.0075$ cm²/g) and reasonably consistent values for Σ in oceanic basalts.

The serpentinized peridotites show a similar degree of variation in their measured values ($\Sigma = 0.01127 \pm 0.00024$ to 0.01302 ± 0.00027 cm²/g, average = 0.01217 ± 0.00025 cm²/g), but have calculated values that are significantly less than the measurements (between 34% and 47% of the measured values). Most of the major and trace elements most likely to be important, both geochemically and with respect to their neutron absorption, were determined (Table 2) and taken into account in the calculations; it is therefore a real problem to account for these much higher observed values. Ultrabasic rocks,

Table 3. Source of geochemical reference materials used for validating the calibration of the Leg 149 samples, together with the values of Σ calculated from their currently "accepted" chemical compositions*.

Geochemical reference number	Lithology	Source	Σ (cm ² /g)			
			Calculated	Error (C)	Measured	Error (M)
JDo-1	Dolomite	GSJ	0.00187	0.00007	0.00226	0.00008
JLs-1	Limestone	GSJ	0.00263	0.00008	0.00267	0.00008
NIM-N	Norite	MINTEK	0.00467	0.00014	0.00482	0.00008
NIM-D	Dunite	MINTEK	0.00545	0.00016	0.00525	0.00009
JG-2	Granite	GSJ	0.00589	0.00018	0.00587	0.00010
JA-3	Andesite	GSJ	0.00614	0.00019	0.00643	0.00011
JSd-2	Stream sediment	GSJ	0.00777	0.00018	0.00808	0.00014
SO-1	Soil	CCRMP	0.00870	0.00026	0.00862	0.00016
SO-2	Soil	CCRMP	0.00884	0.00024	0.00881	0.00017
JLk-1	Lake sediment	GSJ	0.00973	0.00025	0.01022	0.00021

Notes: * Govindaraju, 1994. GSJ = Geological Survey of Japan; MINTEK = Council for Mineral Technology; CCRMP = Canadian Certified Reference Materials Project; calculated = Σ value calculated from the geochemical analyses given in Table 2; error (C) = estimated error in the calculated value; measured = directly measured Σ value; error (M) = estimated error in the measured value.

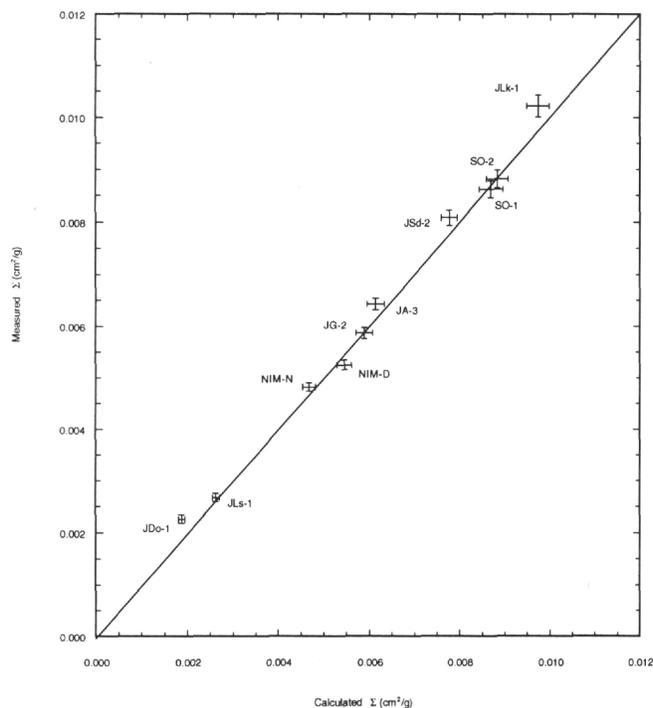


Figure 2. Comparison of measured and calculated values of Σ for 10 geochemical reference materials run with the Leg 149 samples. (See Table 3 for lithology and source of the GRMs).

including their serpentinized products, typically have Σ values between about 0.003 and 0.006 cm²/g; examples among the GRM data presented in Figure 2 include the Norite (NIM-N) and dunite (NIM-D).

The eight sediments measured show generally higher values of Σ than the altered igneous basement samples ($\Sigma = 0.01243 \pm 0.00025$ to 0.01600 ± 0.00034 cm²/g, average = 0.01478 ± 0.00030 cm²/g) and like the serpentinized peridotites, fall significantly below the 1:1 calculated:measured line in Figure 3. Such discrepancies are likely in marine sediments for which only a limited range of trace elements are determined. In particular, the missing rare-earth element abundances and boron should account for most of the difference between the calculated and measured values. The important point here is that without complete chemical characterization calculated values of Σ are likely to be distinctly lower than the "true" (measured) values.

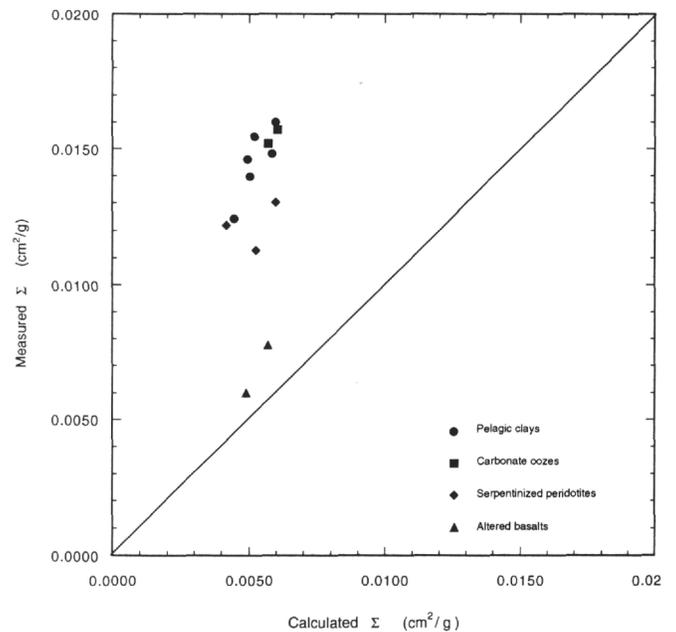


Figure 3. Comparison between measured and calculated values of Σ for the Leg 149 samples. The error bars for both sets of measurements (error estimates given in Table 1) include approximately the area covered by the plotted symbols.

CONCLUSIONS

Measurements of the neutron absorption cross section on two altered basalts from Hole 900A gave an average of 0.00688 ± 0.00014 cm²/g; corresponding calculated values are only slightly lower in absolute terms. The measurements obtained are higher than, but still generally similar to, values obtained on basalts from Hole 896A (Leg 148) in the East Equatorial Pacific, suggesting that oceanic basalts might be characterized by a reasonably consistent range of Σ (0.0055 ± 0.00011 - 0.0075 ± 0.00015 cm²/g). Although the available data are limited at present the possibility of reasonably constant values of Σ for the basaltic basement is potentially valuable for modeling the nuclear properties of such rocks.

Both the serpentinized peridotites and sediments measured had higher values of Σ , averaging 0.01217 ± 0.00025 and 0.01478 ± 0.00030 cm²/g, respectively, but calculated values that in all cases accounted for less than half the measured value. It is not immediately

clear why this should be for the altered ultrabasic rocks, although in the case of the sediments the absence of many of the strong neutron-absorbing elements from the analysis is to blame. These data provide some accurate and valuable information for the nuclear modeling of these lithologies, and they demonstrate that the use of values of Σ calculated from a chemical analysis may be misleading unless the analysis is particularly complete.

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