36. DATA REPORT: GEOCHEMICAL LOGGING RESULTS FROM VANUATU: SITES 829, 830, 831, AND 8331

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ABSTRACT

Geochemical well logs were obtained in the igneous and sedimentary sequences drilled at Sites 829, 830, 831, and 833 of Ocean Drilling Program Leg 134. Corrections have been applied to the logs to account for variations in borehole size, borehole fluid composition, downhole temperature, and logging speed. Concentrations of the elements Th, U, and Gd, and the dry weight percentages of the oxides of Si, Ca, Al, Fe, Ti, and K have been derived. In each of the logged holes the log-derived geochemistry agrees well with shipboard carbonate-derived CaO and X-ray fluorescence core measurements.

INTRODUCTION

The New Hebrides Island Arc lies in the southwest Pacific Ocean (Fig. 1), marking the subduction zone of the Australia-India plate, which moves eastward beneath the North Fiji Basin and the Pacific plate. The primary objectives of Ocean Drilling Program (ODP) Leg 134 were to investigate the complex tectonic and magmatic evolution of this arc and the processes involved in the evolution of an intra-arc basin. Seven sites were drilled, and four holes were logged with the geochemical tool string: Holes 829A and 830C, situated on the forearc slope of the New Hebrides Island Arc; Hole 831B, on the summit platform of the Bougainville Guyot; and Hole 833B, east of the island arc on the lower east flank of the North Aoba Basin.

Geochemical logs provide continuous, in-situ measurements of the major rock-forming elements in the formation at 0.1524 m (6 in.) intervals. They provide a large database of geochemical information unaffected by problems such as incomplete or preferential core recovery and core disturbance, which afflict core-based studies.

This report describes the hole conditions and logging operations for each hole logged with the geochemical tool string, discusses the function of each tool on the string, explains the data processing techniques, and qualitatively compares the processed elemental and oxide data from the logs with lithostratigraphic descriptions and core measurements.

DATA ACQUISITION

Site 829

Site 829 lies within the collision zone of the d'Entrecasteaux Zone along the forearc slope of the New Hebrides Island Arc. Hole 829A penetrated 590.3 m of sedimentary and igneous rocks with 33.4% recovery. Hole 829B was drilled through sediments to 19.5 mbsf with 80% recovery; Hole 829C was drilled through sediments to 58.4 mbsf with 90.2% recovery.

To prepare Hole 829A for logging, a wiper trip was made between 580 and 91 mbsf, where the pipe was set for logging operations. Five logging runs were made in all, and hole conditions were generally good. The quad-combination tool string, consisting of the natural gamma-ray spectrometry tool (NGT), the long-spacing sonic tool (SDT), the lithodensity tool (HLDT), and the dual induction tool (DITE), was the first to be run, from 475 to 50 meters below seafloor (mbsf). The formation microscanner tool string, consisting of the NGT, the general purpose inclinometer, and the formation microscanner (FMS) tools, was run from 473 to 49 mbsf. The geochemical logging tool string (GLT), consisting of the NGT, the aluminum activation clay tool (AACT), and the gamma-ray spectrometry tool (GST), was run third to record data from 476 to 155 mbsf. The digital borehole televiewer (BHTV) was run from 429 to 155 mbsf. The final logging run was made with a new magnetic susceptibility tool (Shipboard Scientific Party, 1992a).

Site 830

Site 830 is located on the forearc slope in the collision zone between the Bougainville Guyot and the central New Hebrides Island Arc. The site was chosen to penetrate a thrust slice in the forearc, where thin superficial sedimentary rocks appear to overlie a strongly reflective acoustic basement. Three holes were drilled at this site: Hole 830A, drilled to 96.9 mbsf with 55.5% recovery; Hole 830B, washed to 48.5 mbsf, then cored to 281.7 mbsf, with 20.9% recovery; and Hole 830C, washed to 235.0 mbsf, then cored to 350.6 mbsf, with 16.8% recovery.

Pipe was set at 51.6 mbsf in Hole 830C, and two logging runs were completed. The first run was made with the quad-combination tool string, which logged data from 272 to 11 mbsf. The second run was made with the geochemical tool string, which logged data from 247 to 40 mbsf, over two logging passes. Hole conditions were generally poor with increasing fill during logging operations; indeed, a very large borehole diameter precluded the use of the FMS at this hole (Shipboard Scientific Party, 1992b).

Site 831

Site 831 is located on the summit platform of the Bougainville Guyot, just west of the New Hebrides Island Arc subduction zone. The main objectives at this site were to determine if the carbonate cover was suitable as a sea-level indicator and to ascertain the age of the basement. Hole 831A was drilled to 116.5 mbsf with 22.4% recovery. After washing to 102.4 mbsf in Hole 831B, drilling penetrated to 852.0 mbsf with only 11.6% recovery; volcanics were reached beneath the carbonate cover.

Pipe was set at 101 mbsf in Hole 831B for the quad-combination tool string, which logged data from 818 to 62 mbsf. Pipe was raised to 82 mbsf, and the FMS tool string was run from 755 to 83 mbsf. Two runs of the geochemical combination recorded data from 755 mbsf to the seafloor. The susceptibility, magnetometer, and BHTV tools were also run. Logging conditions were generally good at this hole (Shipboard Scientific Party, 1992c).

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Figure 1. Location of Leg 134 drill sites, Vanuatu, southwest Pacific Ocean. Bathymetry in kilometers.

Site 833

Site 833 is located on the lower east-central flank of the North Aoba Basin. Two holes were drilled at this site: Hole 883A penetrated 199.5 mbsf with 49.0% recovery; Hole 833B was drilled to 1001.1 mbsf with 56.2% recovery.

Drill pipe was set relatively deep in Hole 833B at 250 mbsf to avoid the poor hole conditions found in the shallower part of the hole. The quad-combination tool string, run first, recorded data from 887 mbsf to the end of pipe at 250 mbsf. Due to hole problems, a full wiper trip was made, and the pipe was re-set at 540 mbsf. The FMS tool string was then run from 934 to 557 mbsf. The third tool string, the geochemical, was run from 885 to 557 mbsf; a short section was recorded through pipe from 450 to 408 mbsf. The final logging run of the magnetometer tool was made from 866 to 540 mbsf, but the data were badly affected by the adverse hole conditions (Shipboard Scientific Party, 1992d).

GEOCHEMICAL LOGGING TOOL

Nuclear geochemical logging uses three separate modes of gammaray spectroscopy to obtain a comprehensive elemental analysis of the formation. The GLT deployed in ODP operations consists of four tool components (Fig. 2). At the top of the string an NGT measures the spectrum of natural gamma radiation of the formation with a sodium iodide scintillation detector, from which the concentrations of K, Th, and U are derived (Lock and Hoyer, 1971). The NGT precedes the other tools as it ascends the borehole, measuring the natural gamma-ray activity of the formation before the nuclear sources of the tools below irradiate the formation. The second tool on the string, an AACT, takes measurements from which the concentration of Al in the formation is derived (Scott and Smith, 1973). The AACT measures the gamma rays produced by delayed neutron activation induced by a ²⁵²californium (Cf) source, which the CNT-G above the AACT carries. The GST, at the bottom of the tool string, consists of a "minitron" tritium source of pulsed 14 MeV neutrons and a gamma-ray scintillation detector. Incident neutrons lose energy through scattering interactions and, on reaching thermal energies, are captured by elemental nuclei, causing the emission of gamma rays. The spectrum of gamma rays detected can be used in conjunction with data from the NGT and AACT to derive the weight percentages of the elements Si, Fe, Ca, S, Ti, and Gd. The GST also measures the contribution of Cl and H, from both the borehole and the formation, to the detected spectrum.

The only major elements in the formation not measured by the geochemical tool string are magnesium (Mg) and sodium (Na). Neither of these elements has a sufficiently large capture cross section relative to its typical abundance to be detected by the GST (Hertzog et al., 1989). An estimate of their concentrations can be derived from the photoelectric factor (PEF) of the lithodensity tool. The recorded PEF log is compared to a computed PEF derived from a summation of the photoelectric contributions from the GLT-measured elements. Any difference is attributed to unmeasured elements in the formation

(i.e., Mg and Na). This calculation, however, requires very high quality data from both the lithodensity tool and the GLT, in addition to a reasonable abundance of these elements in the formation. These criteria were not met in any of the logged holes described, and the calculation was, therefore, not performed.

DATA REDUCTION

During logging operations aboard *JOIDES Resolution* the data are transmitted electronically up the conductive logging cable and recorded digitally in the Schlumberger Cyber Service Unit (CSU). Some preliminary processing of the data occurs at this time to produce field logs, which are immediately available to the shipboard scientific party for initial interpretation. Subsequent post-cruise processing on shore allows for more comprehensive environmental corrections for borehole size, logging speeds, borehole-fluid salinity, temperature, and pipe effects. Processing of the GST spectrometry data is required to trans-



Figure 2. Schematic drawing of the geochemical logging tool string.

form them into elemental-oxide weight fractions. The processing is performed using a series of programs written by Schlumberger, described below. The processing flow is summarized in Figure 3.

Reconstruction of the Relative Elemental Yields from the Recorded Spectra

The first step of processing determines from the measured spectra of the GST the relative contribution of each element (yield) to the total recorded spectrum. The basic model of this program assumes that each downhole spectrum can be represented as a linear combination of a set of "standards," or basis spectra. These standards approximate the spectrum of each element and are combined with the recorded spectrum in a weighted, least-squares inversion at each depth level to determine the relative elemental yields.

Shipboard CSU processing has a standard six-element inversion that solves for Si, Ca, Cl, H, S, and Fe only. These six elements provide a useful framework for initial shipboard interpretation. Post-cruise processing typically utilizes the additional spectra of Ti, Gd, and K, which have been shown substantially to improve the fit of the elements to the recorded spectra (Grau and Schweitzer, 1989).

It is possible to remove and substitute other standards (elements) at this stage of the fitting process. In some environments logged by ODP certain elements are below the detection resolution of the tool (Bristow and deMenocal, 1992; Jarrard and Lyle, 1991). This is more often the case in high-porosity environments, where most of the detected gamma-ray spectrum is derived from Cl and H in the formation and borehole, rather than from the rock matrix. S and K were found by experimentation to be below the resolution of the GST in Holes 829A and 830C. These unresolved elements were found to introduce instability into the inversion, inducing significant noise in the remaining elements; they were, therefore, omitted from the calculation of the elemental yields. In Holes 831B and 833B the full set of nine elemental standards were used. Simple arithmetic averaging, using a 7-point (3.5 ft), moving window, was applied to the output yields of all of the holes to reduce noise in the data.

Depth Shifting

Geochemical processing involves the integration of data from different tool strings. Consequently, it is important that all the data are depth correlated to one reference logging run. This is done using the natural gamma-ray curve from the NGT, which is run on each tool string. The reference run is selected after considering the nature of the cable tension, which indicates the degree of tool sticking, and the logging speed. Faster logging runs are less susceptible to data degradation caused by the ship's vertical motion (heave), which is not completely neutralized by ODP's wireline heave motion compensator (Goldberg, 1990). Data were referenced (according to depth) to the geochemical string run for Holes 829A and 830C and to the quadcombination string run for Holes 831B and 833B.

Calculation of K, Th, and U from NGT Data

This routine calculates the concentrations of K, Th, and U from the natural gamma-ray spectrum detected by the NGT (Lock and Hoyer, 1971). The recorded spectrum is divided into five discrete energy windows, with the three windows at the high-energy end covering a char- acteristic peak of the three radioactive series. There are relatively few counts in the high-energy range where peak discrimination is best; thus, a contribution from the high count rate, low-energy part of the spectrum is included to improve the count statistics. The counts from the five energy windows are inverted at each depth level to give the concentrations of K, Th, and U. This procedure is done at sea, but is improved on shore by the inclusion of caliper and temperature logs in the calculation. The onshore calculation also corrects for K present in

the borehole fluid when KCl is added to inhibit clay swelling. A 7-point (3.5 ft) filtering window was applied to the raw input data to reduce noise in the logs. The outputs of this program are K (wet weight percent), Th (ppm), and U (ppm), as well as a total gamma-ray curve and a computed gamma-ray curve (Th + K). Although the NGT is run on all of the tool strings, the data shown for each of the logged holes (Figs. 4, 6, 8, and 10) are taken from the geochemical tool run, as this is performed at the lowest logging speed and hence provides the best count statistics.

Calculation of Aluminum Concentration

The fourth processing routine calculates the concentration of Al in the formation using the data recorded by the AACT. This procedure performs corrections on the raw data for borehole fluid, formation capture cross section, formation slowing-down length, formation density, and borehole size. Count rates of gamma rays from the AACT are combined with those from the NGT to subtract out background radiation; the concentration of Al is derived from the residual. The measurement is highly dependent on the ²⁵²Cf neutron source strength. The source is calibrated by a routine that automatically accounts for source decay.

After the calculation of the wet weight percentage of Al, density and porosity logs are used to convert both Al and K from the previous routine to dry weight percentages. The porosity is derived from one of the following: the neutron porosity tool, the induction logs, applying Archie's law (Archie, 1942), or from the density logs, using the following equation:

$$\phi = (\rho M a - \rho) / (\rho M a - \rho F l), \tag{1}$$

where: ϕ = porosity, ρMa = matrix density, obtained from core measurements in g/cm³, ρb = bulk density from the log in g/cm³, and ρFl = fluid density (~1.05 g/cm³).

The best porosity log is determined from comparison with shipboard core porosity measurements. For Holes 829A, 831B, and 833B the porosity curve was derived from the lithodensity tool, as shown above, and from the induction log for Hole 830C.

Finally, a correction is made for Al produced by fast neutron interactions with Si, which occur when Si becomes activated by the ²⁵²Cf, causing a reaction that produces the ²⁸Al isotope. The AACT data are combined with the elemental yields from the GST and the K from the NGT to determine the background Si interference, which is subtracted from the Al log. The program outputs Al and K, which are used in the following closure model.

Conversion of Elemental Yields to Elemental Weight Fractions (Hertzog et al., 1989)

Relative concentrations of the GST-derived elemental yields can be determined by dividing each elemental yield by a relative spectral sensitivity factor, S_i . This factor is principally related to the thermal neutron capture cross sections of the various elements. The relative elemental concentrations are related to the desired absolute concentrations by a depth-dependent normalization factor, F, as defined by the relationship:

$$Wt_i = FY_i / S_i \tag{2}$$

where Wt_i = absolute elemental concentration, F = normalization factor, Y_i = relative elemental yield, and S_i = spectral sensitivity factor.

The normalization factor is calculated based on the assumption that the sum of all the elemental weight fractions is 100%. The closure model accounts for C and O, which are not measured by this tool string, by approximating their amounts in combination with each of the measurable elements as a single oxide or carbonate. The dry weight percentages of Al and K are normalized with the reconstructed elemental yields to determine F at each depth interval from the following equation:

$$F\left[\sum X_{i}Y_{i}/S_{i}\right] + X_{K}Wt_{K} + X_{AI}Wt_{AI} = 1.0$$
(3)

where X_i = weight of oxide or carbonate/weight of element *i*, and the subscripts K and Al refer to the potassium and aluminum components.

Since the closure relationship by nature only involves elements in the rock matrix, no contribution from the borehole or pore fluids needs to be taken into consideration. The model compensates for tool standoff and washouts by automatically increasing the normalization factor.

Calculation of Oxide Percentages

The final routine converts the elemental weight percentages into oxide percentages by multiplying each element by its associated oxide factor (Table 1). To overcome the problem of variable Ca oxide factor in the clay and carbonate intervals, Ca is calculated as CaO (as opposed to CaCO₃) for Leg 134 data, and shipboard core-based carbonate measurements have been converted to CaO for comparison.

COMPARISON OF GEOCHEMICAL LOGS TO CORE Site 829

The processed natural gamma-ray logs from Hole 829A are displayed in Figure 4. The main variations in lithostratigraphic Units I to VI are described in terms of varying chalk and clay components. Clayrich Unit III is defined by sharp increases in K, U, and Th values. All of the gamma-ray logs peak sharply in the middle of Unit IV; this bed was not recovered, but it is probably a thin, clay-rich unit within the chalk breccia. Unit VII, a volcanic breccia, shows higher K values relative to Th and U. Below Unit VII several thin units with alternating silty clay and chalk components are reflected in the gamma-ray signals.

The oxide weight fractions are shown in Figure 5 with the calculated statistical uncertainties of each element, based on the equations of Grau et al. (1990). This error estimate is closely related to the normalization factor (Eq. 3), which is calculated at each depth interval and is displayed on the right-hand side of the figure. A lower normalization factor indicates better counting statistics—more signal from the formation—and, hence, higher quality data. The large spikes in the normalization factor around 400 mbsf are due to a large borehole diameter in the volcanic breccia and result in a large statistical error for the calculated oxides. Overall, the oxides agree well with the core-based lithostratigraphic classification (Shipboard Scientific Party, 1992a). CaO values from the geochemical logs show an excellent cor- relation with CaO derived from shipboard core carbonate measurements.

Site 830

The processed natural gamma-ray curves and oxide weight fractions for Hole 830C are shown in Figures 6 and 7, respectively. The core recovery column represents Holes 830A and 830B, whose water depths were 9.5 m deeper than that of Hole 830C, which was logged but not cored at the depths shown. This difference makes exact depth correlation of unit boundaries difficult.

Hole 830C is subdivided into two main lithostratigraphic units, based primarily on the recovered core from other holes at the site. Unit I is predominantly a clay-rich volcanic siltstone and extends from the seafloor to 175 mbsf. The logs show small-scale variability but no definite trends within this unit, in which recovery was poor. The boundary with underlying Unit II is characterized by an increase in Si, Fe, and Ti oxides and a corresponding decrease in Al and K oxides. This is a reflection of the change from the clay-rich Unit I into the more silicic and coarse Unit II. This boundary appears at a higher level (~167 Table 1. Oxide factors for closure normalization.

Element	Oxide	Conversion factor
Si	SiO ₂	2.139
Ca	CaO	1.399
Fe	FeO (total Fe)	1.358
K	K ₂ O	1.205
Ti	TiO	1.668
Al	Al ₂ Ő ₃	1.899

m) on the logs than is suggested by the recovered core. The more coarse and porous nature of Unit II, coupled with a larger hole diameter, leads to a greater statistical uncertainty in the oxide data, which is clearly illustrated by the uncertainty estimates in Figure 7.

CaO values from the geochemical logs resemble the mean of those derived from shipboard core measurements. Poor core recovery, leading to depth uncertainty in the core measurements, precludes comparison of the small-scale variability.

Site 831

In Hole 831B the geochemical logs span Units I–III, a thick sequence of almost pure carbonates with very little lithostratigraphic variation. These units overlie a brecciated andesitic basement that was not fully reached by the geochemical tool string because of hole fill. The natural gamma-ray curves from the geochemical string at Hole 831B are displayed in Figure 8. Figure 9 shows the oxide weight fractions with calculated uncertainties.

The total gamma-ray curve shows a fair degree of variation in lithostratigraphic Unit II. This variation mainly is caused by uranium (U) variations in the formation. Uranium is associated with organic matter in coral-rich zones. The correlation between high uranium levels and recovered coral is high (Shipboard Scientific Party, 1992c). The logs exhibit virtually no variation in the major element chemistry of dominant CaO. This log agrees with the few core measurements (CaCO₃-derived CaO), with the exception of four measurements taken between 670 and 730 mbsf, where unrepresentative sampling of small heterogeneities within the core material cause discrepancies. Major elements other than Ca are probably all at or below the resolution levels of the geochemical tool. Small-scale variation primarily is caused by statistical noise.

Site 833

The processed natural gamma-ray curves over the interval of 875 to 555 mbsf are displayed in Figure 10. These open-hole logs cover the bottom portion of lithostratigraphic Units III, IV, and the upper part of Unit V. The individual and total gamma-ray curves show fairly low concentrations of K, Th, and U in Units III and IV, which consist of calcareous volcanic silt and sandstone. A few thin, more clay-rich zones are identified by spikes in all of the gamma-ray curves. Unit V, which consists of thick basaltic sills interbedded with thin calcareous volcanic siltstones, is characterized by a sharp increase in total gamma-ray count, attributable mainly to an increase in K and Th contents.

The oxide weight fractions are shown in Figure 11 with their respective calculated statistical uncertainties. The low and constant value of the normalization factor is an indication that the data are of good quality. The oxides exhibit only small-scale variability in Units III and IV. Core- and log-derived CaO values correlate well throughout the hole. The basaltic sills of lithostratigraphic Unit V, defined by the oxide logs, show an increase in Fe, Si, K, and Ti oxides and trace elements Gd and Th, and a corresponding decrease in CaO, at the upper boundary of Unit V. Results of X-ray fluorescence (XRF) on eleven core samples within the basaltic sills show a good correlation with log-derived oxides.

SUMMARY

The reprocessing of natural gamma-ray logs improves the measurements obtained in the field by incorporating the environmental corrections described. Geochemical logs, converted from relative elemental yields to elemental and oxide weight fractions, generally compare very well with the available shipboard carbonate and XRF measurements, thus augmenting the results obtained from studies of recovered core.

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^{*} Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).



Figure 3. Flow diagram summarizing the post-cruise processing of the geochemical logging data. Schlumberger logging tool acronyms: FMS = formation microscanner tool, CNT = compensated neutron tool, LDT = lithodensity tool, DITE = dual induction tool, SDT = digital sonic tool, NGT = natural gamma-ray spectrometry tool, AACT = aluminum activation clay tool, <math>GST = gamma-ray spectrometry tool. CALI = caliper, RHOB = bulk density, PHIT = porosity. Elements with prefix C refer to the relative elemental yields; elements with the prefix W refer to the dry-weight percentages of the respective elements. Processing routine names are in bold italics.



Figure 4. Processed natural gamma-ray data from the NGT for Hole 829A.



Figure 4 (continued).

633



Figure 5. Estimates of major oxide weight fractions derived from the geochemical logging tool for Hole 829A. Solid circles represent CaO values derived from shipboard carbonate measurements of core. Solid diamonds represent core XRF measurements of major oxides. See Figure 4 for key to lithology.



Figure 5 (continued).



Figure 6. Processed natural gamma-ray data from the NGT for Hole 830C. See Figure 4 for key to lithology.



Figure 7. Estimates of major oxide weight fractions derived from the geochemical logging tool for Hole 830C. Solid circles represent CaO values derived from shipboard carbonate measurements of core. See Figure 4 for key to lithology.



Figure 8. Processed natural gamma-ray data from the NGT for Hole 831B. See Figure 4 for key to lithology.



Figure 8 (continued).



Figure 9. Estimates of major oxide weight fractions derived from the geochemical logging tool for Hole 831B. Solid circles represent CaO values derived from shipboard carbonate measurements of core. See Figure 4 for key to lithology.

	CORE RECOVERY	ТІТНОГОВУ ЛИПТ	DEPTH BELOW SEA FLOOR (m)	SiO2 0 % 50	CaO 0 % 199	FeO*	Al ₂ O ₃ 0 % 5	K ₂ O	TiO ₂ 1 0 % 5	Gd 0 ppm 1	S 0 0 % 1	Normalization Factor 5 0 1500	DEPTH BELOW SEA FLOOR (m)
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Figure 9 (continued).

DATA REPORT



Figure 10. Processed natural gamma-ray data from the NGT for Hole 833B. See Figure 4 for key to lithology.

CORE RECOVERY LITHOLOGY /JNIT	DEPTH BELOW SEA FLOOR (m)	SIO ₂ 0 % 100 0	CaO FeO* % 100 0 %	Al ₂ O ₃ 20 0 % 30	K2O	TiO2	Gd 5 0 ppm 30	Normalization Factor 0 1500	DEPTH BELOW SEA FLOOR (m)
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Figure 11. Estimates of major oxide weight fractions derived from the geochemical logging tool for Hole 830C. Solid circles represent CaO values derived from shipboard carbonate measurements of core. See Figure 4 for key to lithology.

DATA REPORT