16. PETROLOGY AND GEOCHEMISTRY OF VOLCANIC ROCKS FROM THE NEW HEBRIDES FOREARC REGION, SITES 827, 829, AND 830¹

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ABSTRACT

Igneous rocks recovered from Ocean Drilling Program (ODP) Leg 134 Sites 827, 829, and 830 at the toe of the forearc slope of New Hebrides Island Arc were investigated, using petrography, mineral chemistry, major and trace element, and Sr, Nd, and Pb isotopic analyses.

Basaltic and andesitic clasts, together with detrital crystals of plagioclase, pyroxenes, and amphiboles embedded in sed-lithic conglomerate or volcanic siltstone and sandstone of Pleistocene age, were recovered from Sites 827 and 830. Petrological features of these lava clasts suggest a provenance from the Western Belt of New Hebrides Island Arc; igneous constituents were incorporated into breccias and sandstones, which were in turn reworked into a second generation breccia.

Drilling at Site 829 recovered a variety of igneous rocks including basalts and probably comagmatic dolerites and gabbros, plus rare ultramafic rocks. Geochemical features, including Pb isotopic ratios, of the mafic rocks are intermediate between midocean ridge basalts and island arc tholeiites, and these rocks are interpreted to be backarc basin basalts. No correlates of these mafic rocks are known from Espiritu Santo and Malakula islands, nor do they occur in the Pleistocene volcanic breccias at Sites 827 and 830. However, basalts with very similar trace element and isotopic compositions have been recovered from the northern flank of North d'Entrecasteaux Ridge at Site 828. It is proposed that igneous rocks drilled at Site 829 represent material from the North d'Entrecasteaux Ridge accreted onto the over-riding Pacific Plate during collision.

An original depleted mantle harzburgitic composition is inferred for a serpentinite clast recovered at 407 meters below seafloor (mbsf) in Hole 829A. Its provenance is a matter of speculation. It could have been brought up along a deep thrust fault affecting the Pacific Plate at the colliding margin, or analogous to the Site 829 basaltic lavas, it may represent material accreted from the North d'Entrecasteaux Ridge.

INTRODUCTION

One of the most controversial aspects of plate tectonics is the mode of interaction between plates at convergent margins. Definition of the mass balance between material added to the over-riding plate and that carried down into the mantle by subduction has attracted the interest of many Earth scientists.

Where convergent compressional tectonics operate, accretion is active and formation of an accretionary wedge occurs with consequent seaward migration of the trench (Karig and Sharman, 1975). In contrast, arc erosion and sediment subduction, with consequent arcward migration of the trench occur at extensional convergent plate boundary settings (Scholl et al., 1980; Aubouin, 1989). Interaction between the converging plates is more complicated where a structural high, such as a continuous ridge (Kyushu-Palau Ridge in the Nankai Trough, Yamazaki and Okamura, 1989; Lousville Ridge in the Tonga Trench, Ballance et al., 1989) or a seamount (Daiichi Kashima seamount in the Japan Trench, Lallemand et al., 1989; Kobayashi et al., 1987; Yamazaki and Okamura, 1989), collides with an arc and begins to be subducted. In this case, a major question concerns whether the topographic high will be accreted or subducted.

The collision and subduction of the d'Entrecasteaux Zone (DEZ) with the Western Belt islands (Espiritu Santo and Malakula) of the New Hebrides Island Arc (Fig. 1) provides an excellent opportunity to study a ridge/seamount collision with an arc (Collot and Fisher,

1988; Fisher et al., 1991). The northern continuous ridge (North d'Entrecasteaux Ridge [NDR]) and a parallel southern chain of seamounts (Southern d'Entrecasteaux Chain [SDC]), which constitute the two parts of the DEZ, caused different styles of collisional deformation of the forearc slope. The collision of the SDC resulted in large anticlines, faults, and thrust faults, dipping gently eastward, together with an arc-slope indentation of about 10 km. In contrast, the collision of the NDR with the western slope of Espiritu Santo Island created a broad shallow protrusion, Wousi Bank, on the forearc region, almost reaching sea level (Collot et al., 1992, this volume; Greene et al., this volume).

Reconstruction of the stratigraphic sequences in the drilled sites on the arc slope, and comparison with rocks drilled on the NDR (Site 828; Coltorti et al., this volume) and Bougainville Guyot (Site 831; Baker et al., this volume) allow definition of the deformation style of these two regions and the accretionary processes transferring material from the Australia-India Plate to the Pacific Plate.

Petrography, mineral chemistry, major and trace element analyses, and Sr, Nd, and Pb isotopic determinations on igneous clasts recovered from Sites 827, 829, and 830 are used to distinguish between the material derived from the arc and that scraped off the DEZ by ridge/ seamount collision and subduction. This information will contribute to a better understanding of the structural evolution of this forearc region.

SITE LOCATION AND STRATIGRAPHY

Three sites (Sites 827, 829, and 830) on the forearc slope were chosen to investigate the geological and tectonic effects of ridge/ seamount collision with the New Hebrides Island Arc (Fig. 1).

Site 827 (15°17.75'S, 166°21.11'E) is located on a flat terrace-like feature along the northern flank of Wousi Bank at a depth of 2803.4 mbsl; it is just in front of the NDR, 4 km east of the trace of the trench, and about 35 km west of the western shore of Espiritu Santo Island. Holes 827A and 827B were drilled at this site, coring 110.6 and 400.4 m, respectively. Four lithostratigraphic units were recognized.

¹ Greene, H.G., Collot, J.-Y., Stokking, L.B., et al., 1994. Proc. ODP, Sci. Results, 134: College Station, TX (Ocean Drilling Program).

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Figure 1. Location of Leg 134 sites. NDR = North d'Entrecasteaux Ridge; SDC = South d'Entrecasteaux Chain; NAB = North Aoba Basin; SAB = South Aoba Basin; NFB = North Fiji Basin. Bold line with teeth indicates plate boundary; teeth are on upper plate. Bathymetry in meters.

Units I and II are a sequence of upper Pliocene to Pleistocene volcanic silt and siltstone with variable clay and sand components. Unit III contains upper Pliocene to middle Pleistocene highly bioturbated calcareous volcanic siltstone with intervals of sed-lithic conglomerate. Lithostratigraphic Unit IV (252.6–400.4 mbsf) is little understood because of poor recovery, and its age is unknown because samples were barren of fossils. This unit mainly consists of sed-lithic conglomerate, very well-lithified volcanic siltstone, and sandstone containing mainly igneous rock fragments and crystals. Clasts, ranging in size from pebbles to the maximum diameter that can fit in the core barrel, are very angular to rounded and poorly sorted. Igneous fragments are mainly represented by volcanic breccia, andesites, and less commonly, dacites; detrital crystals include plagioclases, pyroxenes, and amphiboles.

Site 829 (15°18.97'S, 166°20.70'E) is located within the collision zone of DEZ along the forearc slope of the New Hebrides Island Arc, where the NDR impinges upon the arc slope, about 3 km south of Site 827. Holes 829A, B, and C were drilled at this site; 590 m were cored in the first hole, whereas the other two recovered undisturbed sediments from the first 100 m of the sequence. The lithostratigraphy of Site 829 is complicated by frequent repetitions of the sequence caused by thrust-faults. 21 lithostratigraphic units were distinguished and divided into four composite units. A large variety of effusive, intrusive, and subvolcanic igneous rocks was found. These rocks mainly occur as clasts in volcanic breccia or sed-lithic breccia, and poor recovery often made it difficult to determine whether gabbros were derived from a homogeneous body or from a volcanic breccia. Igneous rocks were encountered at two levels in the stratigraphic sequence. The first, overlying middle Oligocene calcareous chalk, is found between 397.7 and 416.6 mbsf (Cores 134-829A-43R and -44R, Unit VII) for a total recovery of 7 m. The second, underlying Pliocene-Pleistocene sandy volcanic siltstone, is between 513.5 mbsf and the bottom of the hole (581.2 mbsf, Unit XVI), with a recovery of about 14 m (for a complete stratigraphic report, see Meschede and Pelletier, this volume, and Reid et al., this volume). K/Ar age determinations on Samples 134-829A-

59R-1, 81–96 cm, and -61R-1, 36–38 cm, give ages of 9.8 ± 3 Ma and 26.7 ± 2 Ma, respectively (Rex, this volume).

Site 830 (15°57.00'S, 166°46.79'E) is located on the forearc slope in the collision zone between Bougainville Guyot and the Central New Hebrides Island Arc, about 6.5 km east of the plate boundary and about 30 km south of the southern coast of Espiritu Santo Island. Holes 830A, B, and C were drilled at this site for a total penetration depth of 350.6 m and 122.05 m of recovery. Two major lithostratigraphic units were described. Unit I consists of Pleistocene volcanic silt and siltstone with variable amounts of sand and clay and lies unconformably upon lithostratigraphic Unit II, which is a sequence of altered, very coarse volcaniclastic sandstone, partially lithified and poorly sorted, with a matrix of sandy silt. Clasts and isolated pebbles of volcanic breccias and lavas were encountered only in Unit II. They were found at various levels: from 174.9 to 184.6 mbsf (Core 134-830B-14R) and from 252.4 to 262.2 mbsf (Core 134-830B-22R) in Hole 830B, and from 235.0 to 263.7 mbsf (Cores 134-830C-1R, -2R, and -3R) in Hole 830C. All samples from lithostratigraphic Unit II were unfossiliferous.

ANALYTICAL METHODS

X-ray fluorescence (XRF) major and trace element analyses (excluding rare earth elements [REE]) were conducted aboard the *JOIDES Resolution*, at the Institute of Mineralogy, Ferrara University (Italy), and at the Institute of Mineralogy, Petrology and Economic Geology, Tohoku University (Japan).

Analyses aboard ship were performed on glass discs for major elements and on powder pellets for trace elements, using a Compton scattering technique for matrix absorbing corrections (Reynolds, 1967). Major element data are considered accurate between 1% and 5%, whereas accuracy for trace elements varies from 2% to 10%, except for Ba and Ce, which exceed 10% (see "Explanatory Notes," Collot, Greene, Stokking, et al., 1992).

Analyses from Ferrara University were performed on powder pellets using a wavelength-dispersive automated Philips PW 1400 spectrometer. Major elements were determined by a full matrix correction procedure (Franzini et al., 1975), whereas for trace elements, experimentally determined correction coefficients were used (Leoni and Saitta, 1976). Accuracy and precision for major elements are estimated better than 3% for Si, Ti, Fe, Ca, and K and 7% for Mg, Na, Al, Mn, and P; for trace elements (above 10 ppm) they are better than 7% for Rb, Nb, Y, Sr, V, and 15% for Zr, La, Ce, Ba, Ni, Co, and Cr. Analyses of reference standards AGV 1 and BR are reported in Table 1 for comparison. Loss on ignition (LOI) was determined by a gravimetric method.

REE and Y were determined at the Centre de Recherches Pétrographiques et Géochimiques, Nancy (France), by inductively coupled plasma (ICP) emission spectrometry with an accuracy of 15% for Yb and Lu and better than 8% for the other REE (see analyses of reference standards from Roelandts and Michel, 1986). Analytical methods for analyses performed at Tohoku University (including REE) are described in Hasenaka et al. (this volume). In order to facilitate comparison between analyses from different laboratories, Fe2O3 was calculated as 0.15 FeO, and analyses were recalculated to 100% on an anhydrous basis. Analyses carried out in the different laboratories display reasonable agreement. Some discrepancies can be observed in the SiO2 and CaO contents and are probably related to variable degrees of alteration, even in samples very close together in the core (most of them as clasts). Trace elements, particularly those considered unaffected by secondary remobilization, show good agreement, except Y by ICP, which is systematically lower (about 15%) than that by XRF. Isotopic analyses were carried out at the Laboratoire de Géochimique Isotopique, Université de Montpellier, after leaching using 2N HF + 0.5N HBr mixture and cold 2.5N HCl (see the analytical methods section in Briqueu et al., this volume). Minerals were analyzed at the University of Leeds (UK) using a CAMECA SX-50 electron-probe microanalyzer fitted with three wavelength-dispersive spectrometers and a LINK 10/558 energy-dispersive system, at an accelerating voltage of 15 kV, and specimen current of 15 nA. Natural silicates and oxides standards were used, and the raw data were corrected using CAMECA proprietary software. For more details see the analytical methods section in Baker et al. (this volume).

PETROGRAPHY

Site 827

The majority of clasts encountered in lithostratigraphic Unit IV in Hole 827B are lithified volcanic breccias or coarse sandstones containing a preponderance of igneous rock fragments and crystals. Clasts of andesite are set in a very fine-grained clay-chlorite matrix that possibly represents devitrified glass. The matrix also includes some calcite and sporadic foraminifers. The coarser constituents in the matrix include discrete subhedral crystals of plagioclase, clinopyroxene, amphiboles, and opaques that are similar in type and proportion to the phases in the rock fragments. Andesitic clasts are highly plagioclase-phyric with occasional clinopyroxenes and opaques in a fine-grained groundmass made up of plagioclase in association with secondary minerals including chlorite, carbonate, and clay. One clast has a slightly more evolved composition and is referred to as dacitic breccia. Alkali feldspar is more abundant than in the andesitic breccia and a small proportion of quartz (around 1%) occurs in the groundmass.

Site 829

Clinopyroxene + plagioclase-phyric basalts, pyroxenites, and serpentinites were found in Unit VII between 397.7 and 416.6 mbsf (Cores 134-829A-43R and -44R), and plagioclase-phyric basalts, dolerites, microgabbros, and olivine gabbros were encountered in Unit XVI, between 513.5 and 581.2 mbsf (bottom of Hole 829A). Alteration is moderate, and veins and fractures, as well as vesicles, are relatively scarce. The secondary mineral assemblage is typical of low temperature submarine alteration. Chlorite and actinolite in basalts may be attributed to greenschist facies metamorphism, whereas the occurrence of green hornblende in gabbros probably reflects subsolidus deuteric alteration.

Sparsely Clinopyroxene + Plagioclase-phyric Basalts

These rocks are hypocrystalline, fine-grained, and vary from aphyric to sparsely phyric, containing microphenocrysts of subhedral, weakly zoned clinopyroxene (0.1–0.5 mm) and lath-shaped plagioclase (0.2–0.6 mm); a few olivine phenocrysts were found in only one instance (Sample 134-829A-43R-2, 145–147 cm). Groundmass is dominated by plagioclase microlites with intergranular clinopyroxene, opaques, and variable amounts of glass (intersertal to hyalopilitic textures). Elongate, low-crystallinity patches are constituted by brown, altered, devitrified glass. In this lithotype, vesicles are abundant (20–30 vol%), irregularly distributed and infilled with green- to brown-colored, zonally arranged, mixed-layer clay minerals. Where vesicles are more concentrated, devitrified glass, sometimes with a well-developed spherulitic texture, dominates the groundmass.

Moderately Plagioclase-phyric Basalts

These are non-vesicular, hypocrystalline, and fine-grained rocks with scattered lath-shaped or tabular, weakly zoned, plagioclase microphenocrysts (0.20–0.60 mm). Unidentified mafic phases, totally replaced by chlorite and reddish mixed-layer clay minerals, sporadically occur in the phenocryst assemblage. The groundmass is hyalopilitic with skeletal H-shaped plagioclase, rare acicular clinopyroxenes, and small oxide grains set in an altered, completely devitrified glassy mesostasis. Very thin (0.03–0.06 mm) veins are filled with oxides or zeolites. Rare, secondary actinolitic amphibole also occurs.

Dolerites and Microgabbros

Dolerites are medium-grained (0.5-1 mm) and comprised of plagioclase laths (55%) surrounded by subequant clinopyroxene crystals (40%) in a subophitic texture, which becomes locally ophitic when plagioclase crystals are embedded in large clinopyroxenes. Plagioclase is generally radially arranged and displays strong normal zoning, whereas clinopyroxene is colorless and nearly unzoned. Iron oxides (up to 5%) are also present. Alteration products are chlorite and clay minerals. Green hornblende often rims clinopyroxene.

Microgabbros show an ophitic texture with modal proportions similar to dolerites, the main difference being the increase in grain size (1-3 mm).

Gabbros

These rocks are holocrystalline, medium- to coarse-grained (around 5 mm), with subophitic to ophitic texture. Textural relationships suggest that the order of crystallization is olivine, plagioclase, clinopyroxene, and finally magnetite. The idiomorphic bladed crystals of plagioclase are fresh and strongly zoned. Olivine occurs as markedly zoned subhedral, partially altered crystals; when joined by plagioclase, the two phases show cotectic intergrowth. Clinopyroxene, which is sometimes intergrown with Ti-magnetite, occurs as small grains among plagioclase or as large, poikilitic, strongly-zoned crystals. They are often mantled by green hornblende, a feature which is rather common in gabbros dredged from oceanic settings (Prichard and Cann, 1982). Alteration products are iddingsite, and locally, calcite after olivine, and chlorite after clinopyroxene. Chlorite, calcite, clay minerals, and iron hydroxides fill rare cavities and veins. The presence of tiny flakes of biotite in a few samples is noted. This mineral is very unusual in ocean floor rocks and may indicate a relatively high K content compared to normal mid-ocean ridge basalts (Prichard and Cann, 1982; Spadea et al., 1991).

Ultramafic Rocks

The pyroxenite (Sample 134-829A-43R-1, 133–135 cm) has an allotriomorphic-granular texture and is composed of clinopyroxene (80%), orthopyroxene (15%), and olivine (5%). Clinopyroxene occurs as large anhedral crystals up to 8 mm across; conspicuous exsolution of orthopyroxene lamellae and some alteration to serpentine and iron-oxide minerals occur. Orthopyroxene and olivine crystals are smaller (1–2 mm). Olivine is completely pseudomorphed by serpentine and oxide minerals.

The serpentinite fragment (Sample 134-829A-44R-1, 1–4 cm) is coarse-grained, and is dominated by serpentine (65%) with a subordinate amount of orthopyroxene (up to 4 mm; around 25%), clinopyroxene (up to 2 mm; around 5%) and anhedral Cr-spinel (%), which occupies interstitial spaces. No olivine relics have been preserved. Both pyroxenes contain exsolution lamellae. Some secondary tremolite crystals are also present.

Site 830

Lavas

The lavas, always recovered as clasts, vary in modal composition from moderately olivine + clinopyroxene-phyric basalts to highly plagioclase-phyric basalts, the latter type being the more common. Olivine phenocrysts are rare and always pseudomorphed by serpentine and minor calcite. Unaltered colorless clinopyroxene microphenocrysts (0.2–2 mm) often occur both as phenocryst, glomeroporphyritic aggregates, and in the groundmass. Idiomorphic plagioclase is the most common phase, being widely represented either as phenocryst (up to 2–3 mm in size) or in the groundmass. It is extensively altered to clay minerals, calcite and sericite and often has dark, isotropic melt inclusions 20 to 40 mm sized (up to 10%–15% of the crystal volume),

Hole: Core, section: Interval (cm):	829A 43R-3 94-96	829A 43R-3 9597	829A 43R-3 130-133	829A 44R-1 3-4	829A 59R-1 7-10	829A 59R-1 45-50	829A 59R-1 81-85	829A 59R-1 105-108	829A 59R-1 118-120	829A 59R-1 120-122	829A 59R-1 127-130	829A 60R-1 4-8	829A 61R-1 3-5	829A 61R-1 30-33	829A 61R-1 38-41
Depth (mbsf):	403.1	403.2	403.5	407.4	533.0	533.4	533.7	534.0	534.1	534.1	534.2	542.6	552.3	552.6	552.7
Rock type:	Basalt	Basalt	Basalt	Serpentinite	Dolerite	Microgabbro	Dolerite	Microgabbro	Dolerite	Dolerite	Dolerite	Dolerite	Microgabbro	Microgabbro	Gabbro
	1	F	F	F	F	1	F	1	Т	F	Т	Т	1	Т	F
SiO ₂	50.86	49.83	49.51	45.89	47.21	48.86	47.10	48.04	47.91	47.29	47.95	48.39	48.07	47.63	46.29
TiO ₂	0.86	0.98	0.99	0.04	1.00	0.97	1.04	1.88	1.08	1.09	1.04	0.93	1.15	0.97	0.90
Al ₂ O ₃	17.92	19.01	20.25	1.98	16.90	10.04	10.32	16.63	16.28	16.24	16.18	15.79	16.50	17.36	19.07
FeO	1.59	7.00	7.26	6.32	8.13	8.04	1.58	10.00	1.45	9.33	8.76	8.02	0.26	1.00	8 30
MnO	0.17	0.13	0.11	0.15	0.17	0.18	0.17	0.20	0.19	0.17	0.20	0.33	0.22	0.17	0.15
MgO	7.67	8.08	6.52	42.74	11.45	9.86	12.37	6.29	9.35	11.55	9.83	11.01	7.49	7.19	8.77
CaO	9.15	8.54	10.41	1.61	11.36	11.97	10.86	10.61	12.36	11.48	11.92	8.71	12.94	11.86	12.07
Na ₂ O	2.38	2.98	3.08	0.17	2.21	2.03	2.27	4.25	2.68	2.26	2.52	2.32	2.75	3.04	2.80
K ₂ Õ	1.12	1.02	0.53	0.04	0.08	0.04	0.10	0.13	0.10	0.08	0.08	2.05	0.03	0.12	0.06
P ₂ O ₅	0.15	0.11	0.11	0.00	0.11	0.06	0.11	0.18	0.07	0.11	0.07	0.06	0.05	0.07	0.11
LOI	4.37	12.37	11.46	19.76	1.44	2.68	2.19	3.93	2 	2.32			1.05	1 	1.14
mgv	0.62	0.64	0.62	0.92	0.72	0.69	0.73	0.53	0.66	0.71	0.67	0.69	0.59	0.56	0.65
Ni	43	29	33	2194	145	132	158	145	125	145	130	138	106	147	157
Co		36	34	135	52		55		54	51	55	49		63	48
Cr	78	88	267	3370	358	323	382	154	314	389	298	358	303	217	328
Rb	11	233	207	95 n.d	294 nd	280	303	209	275 nd	512 nd	230	270	200 n d	190	247
Sr	248	232	232	23	69	63	67	124	70	64	68	68	88	104	101
Ba	22	38	29	15	30	30	22	59	25	39	24	37	20	25	35
Zr		34	40	n.d.	44	49	50	96	50	48	48	45	53	49	40
Nb	n.d.	3	n.d.	n.d.	3	2	2	5	2	3	1	2	1	2	3
La		3	2	n.d.	3	1	4			2		-		_	n.d.
Ce	11	8	4	n.d.	8	n.d.	8	n.d.	20	5	4	-	11		3
Ŷ	51	22	25	2	28	27	31	40	30	32	29	26	33	32	29
			Т							N		Т		Т	N
Y			21.1							26.6		21.7		27.3	22.9
La			1.40							1.73		1.00		0.60	0.57
Ce			5.80							4.81		4.10		3.10	3.30
Sm			2.35							2.09		1.85		2.21	2.13
Fu			0.90							0.90		0.69		0.90	0.78
Gd			3.22							3.75		2.86		3.65	2.95
Dy			3.55							4.21		3.71		4.85	3.69
Er			2.28							2.46		2.53		3.19	2.00
Yb			2.18							2.60		2.66		3.12	2.19
Lu			0.33							0.39		0.40		0.46	0.31
Ti/Zr		172	149		136	120	125	117	129	136	130	124	130	119	134
Ba/Nb		12			9	16	9	13	13	11	24	19	20	13	11
Zr/ND		11			13	20	22	20	25	14	48	25	55	25	15

Table 1. Major and trace element compositions of igneous rocks from Sites 829 and 830.

Notes: Analyses conducted aboard the *JOIDES Resolution* (J), at Ferrara University (F), Tohoku University (T), and at CRPG (N [Nancy, France]). Y analyses carried out by ICP are reported withdecimals. mgv = Mg/Mg + Fe²⁺ (mol%); LOI = loss on ignition. — = not determined; n.d. = not detected.

Table 1 (continued).

Hole: Core, section: Interval (cm): Depth (mbsf): Rock type:	829A 61R-1 38-41 552.7 Gabbro	829A 61R-1 56-59 552.9 Microgabbro J	829A 61R-1 71-74 553.0 Gabbro F	829A 61R-1 80–86 553.1 Microgabbro I	829A 62R-1 49–52 562.3 Gabbro F	829A 64R-1 10-13 581.3 Gabbro I	830B 14R-1 13-17 175.0 Basalt F	830B 14R-1 13–17 175.0 Basalt	830B 14R-1 59–64 175.5 Basalt T	830B 22R-1 32-33 252.7 Basalt J	830B 22R-1 34–37 252.7 Basalt F	830B 22R-1 40-44 252.8 Basalt T	830C 2R-1 6-8 244.5 Basalt	830C 3R-1 3-4 254.5 Basalt	AVG 1 Andesite F	BR Basalt F
SiO ₂ TiO ₂ Al ₂ O ₃ FeO MnO MgO CaO Na ₂ O K ₂ O K ₂ O P ₂ O ₅		47.90 0.97 17.52 1.50 9.00 0.22 8.45 12.06 2.29 0.05 0.05	46.71 0.81 18.48 1.38 8.28 0.15 8.88 12.39 2.74 0.07 0.10	47.99 0.92 17.94 1.46 8.79 0.16 8.61 10.61 3.39 0.07 0.06 4.62	47.18 1.03 20.67 1.18 7.08 0.13 6.88 12.52 3.10 0.10 0.12 0.12	49.37 0.74 17.55 1.27 7.59 0.18 6.87 14.00 2.33 0.06 0.03 0.06	47.68 0.78 17.37 1.42 8.50 0.19 10.35 10.01 2.99 0.59 0.13		49.85 0.70 13.94 1.58 9.49 0.31 10.03 10.52 2.16 1.30 0.11 0.11	49.98 1.34 18.48 1.40 8.42 0.21 4.64 11.63 3.03 0.60 0.26	48.48 1.48 18.94 1.45 8.73 0.20 5.13 11.62 3.03 0.66 0.26	50.79 1.38 17.29 1.49 8.92 0.22 4.78 10.55 3.45 0.85 0.28 0.28 0.28	51.27 1.49 18.68 1.36 8.15 0.24 5.24 5.24 9.53 3.35 0.42 0.27	51.45 1.19 16.28 1.44 8.66 0.31 6.76 10.98 2.25 0.45 0.22 0.45	59.13 1.09 17.59 6.64 0.10 1.18 4.87 4.26 2.83 0.48	37.91 2.62 11.48 12.26 0.17 13.57 13.30 3.15 1.39 1.31
LOI		3.21	1.85	4.62	2.85	4.00	3.56		6.12 0.65	4.41	0.51	5.07	3.51	7.07		
Ni Co Cr V Rb Sr Ba Zr Nb La Ce Y		189 189 395 229 1 114 25 51 1 7 30 30 1	191 53 439 223 2 98 25 33 n.d. n.d. 5 27	$202 \\ 336 \\ 205 \\ 1 \\ 126 \\ 22 \\ 49 \\ 1 \\ 3 \\ 28$	212 54 331 235 1 111 28 40 4 3 7 32	177 450 212 n.d. 94 24 41 1 	86 44 290 381 6 499 122 42 1 7 7 17 14		51 45 266 321 16 210 195 37 2 	30 25 281 7 361 184 141 6 25 27	28 31 52 307 9 403 213 98 5 19 38 28	24 31 51 n.d. 14 384 351 92 5 	25 8 238 5 244 274 169 4 17 38	50 113 310 7 347 153 112 3 17 24	14 15 14 120 70 672 1198 225 16 39 70 20	263 54 340 239 50 1382 1200 230 105 90 161 28
Y La Ce Nd Sm Eu Gd Dy Er Yb Lu	T 23.7 0.30 2.60 2.60 1.82 0.80 3.33 4.10 2.68 2.57 0.40						N 12.9 4.74 12.1 7.62 2.29 0.70 2.30 2.35 1.19 1.32 0.19	T 4.30 10.7 6.50 2.09 0.67 2.41 2.37 1.50 1.46 0.24	T 13.2 5.30 11.1 6.60 2.11 0.63 2.29 2.31 1.56 1.54 0.25			T 25.0 11.2 27.2 17.2 5.13 1.41 4.57 4.78 2.82 2.59 0.40				
Ti/Zr Ba/Nb Zr/Nb		113 36 73	147	112 20 45	156 7 9	108 35 58	111 135 47		113 98 19	57 31 24	91 44 20	90 69 18	53 69 42	64 51 37		

rounded or lobate, that are completely replaced by chlorite, and usually oriented along crystallographic directions, or zonally arranged.

The groundmass is hypocrystalline, intergranular to hyalopilitic, with microlites of plagioclase, small grains of subequant clinopyroxene and tiny elongated rods of ilmenite set in an altered, devitrified glassy mesostasis, sometimes with a spherulitic texture. Vesicles, which are filled with chlorite, calcite and zeolites, can amount to as much as 20 vol%.

Volcanic Breccias

These breccias are made up of subangular rock fragments and single crystals set in a microcrystalline to mainly devitrified glassy matrix. The composition and texture of rock fragments are similar to those of the lavas, consisting of variably altered basalts ranging from aphyric to highly plagioclase-phyric. Although the compositional variation of the volcanic clasts is wider than that described for the lavas of the first group, the relative mineral abundances and textural relationships are very similar. Fragments are rounded to subrounded and sometimes show gradual, diffuse transitions into the groundmass. Some fragments are lobate or irregular in shape and partially engulf isolated crystals. Two clasts of fine-grained gabbro were also found in Section 134-830C-3R-1.

Single crystals mainly comprise large idiomorphic, fractured, twinned and strongly zoned clinopyroxenes (up to 3 mm), and plagioclase (up to 1.5 mm), with subordinate olivine, amphibole, and small anhedral oxides. They appear to be similar in composition to phases in the associated lava fragments and in the clasts of the previous group.

MINERAL CHEMISTRY

Site 827

Representative analyses of clinopyroxenes and amphiboles from an andesitic clast are reported in Tables 2 and 3. Clinopyroxene plot in the diopside-augite field of the Wo-En-Fs diagram (Fig. 2B), with mgv (mgv = Mg/[Mg + Fe²⁺] = 0.95–0.80). They have a low Ti content

with respect to Al^{IV}, consistent with clinopyroxene phenocrysts in lavas from intraoceanic volcanic arcs (Fig. 3).

Anorthite content in plagioclase shows a large variation (An_{48-65} in one sample and An_{60-94} in another).

Titanium magnesio-hastingsite is fairly abundant and richer in FeO than clinopyroxene (mgv from 0.64 to 0.66; Table 3).

Site 829

Clinopyroxene

This mineral is less common than plagioclase, but it plays a major role in the chemical identification of the parental magma (Leterrier et al., 1982; Beccaluva et al., 1989). Representative analyses are reported in Table 2, and compositions are plotted in the Di-Hd-En-Fs quadrilateral (Figs. 2A and B, and 4). As for plagioclase, clinopyroxene in the basalts has a narrower compositional range than in the gabbros. In the basalts, they fall in the endiopside-augite fields (with a few points also plotting in the salite field) and vary from Wo35En55Fs10 to Wo47En36Fs17. Clinopyroxene rims in the dolerite (Sample 134-829A-59R-1, 81-86 cm) have the highest iron content, with Wo₄₁En₃₄Fs₂₅. In the gabbros, an almost complete compositional range of clinopyroxenes fractionating from a tholeiitic magma is recorded (Fig. 4). Although the whole rock geochemistry does not show a very high FeO and TiO₂ contents (see Table 1), clinopyroxene rims almost reach pure hedenbergite composition (Sample 134-829A-61R-1, 20-22 cm), passing from augite through ferro-augite. This extreme iron enrichment may indicate crystallization in a nearly-closed system, in which the most evolved interstitial liquid could not be interchanged with fresh, undifferentiated magma. In Figure 4, clinopyroxene compositions from gabbros recovered from mid-ocean ridges and from high-Ti ophiolitic complexes are also drawn (Hebert et al., 1989). As expected, the two fields delimit very similar areas, with clinopyroxenes in ophiolitic gabbros having a higher Fe content. The majority of analyses from Site 829 gabbros plot inside these fields, although some analyses have even higher total FeO contents than those from high-Ti ophiolitic complex. The similarity between clinopyroxene compositions from

Table 2. Representative clinonyroyene	compositions from andesitic	hasaltic gabbroic	and ultramafic rock	s from Sites 827 and 829
rable a Representative ennopyroxene	compositions nom andesitie	, basanic, gabbioic,	and unitalitatic roor	is nom ones our and our

Hole: Core, section: Interval (cm): Rock type:	827B 18R-CC 0-2 Andesite					829A 43R-3 94–95 Basalt				829A 59R-1 3-4 Basalt		829A 44R-1 1-2 Serpentinite					
	A ph c	A ph r	mph	A ph	B ph	C ph	gm	gm	ph	gm	gm	Ac	A r	Bc	Br	С	
$\begin{array}{c} SiO_2\\TiO_2\\AI_2O_3\\FeO_3\\FeO\\MnO\\MgO\\CaO\\Na_2O\\Cr_2O_3\end{array}$	52.77 0.23 2.01 2.49 1.74 0.05 17.00 23.64 0.20 0.29	49.43 1.03 4.36 3.62 6.14 0.45 14.21 20.75 0.33 0.00	52.15 0.37 1.87 2.62 6.48 0.41 15.44 20.96 0.31 0.00	53.74 0.16 1.66 0.00 6.07 0.22 19.84 17.15 0.12 0.24	47.19 1.25 7.47 2.10 7.36 0.23 12.97 20.21 0.20 0.02	51.92 0.41 2.94 0.61 6.91 0.12 15.71 20.74 0.18 0.16	52.91 0.30 2.83 0.00 5.98 0.12 17.22 20.25 0.15 0.21	47.65 1.00 7.56 0.29 8.48 0.24 13.40 18.67 0.29 0.00	48.41 1.42 5.13 2.70 7.78 0.14 12.05 22.09 0.32 0.46	47.28 1.77 6.32 3.05 7.25 0.09 11.55 22.42 0.32 0.24	47.95 1.33 5.71 3.26 6.61 0.28 11.59 22.83 0.37 0.18	52.32 0.13 3.44 0.37 2.15 0.08 16.48 23.24 0.28 1.44	51.98 0.25 3.09 0.73 1.65 0.14 16.59 23.33 0.25 1.35	53.74 0.18 2.67 0.00 2.32 0.14 17.07 23.81 0.22 1.14	53.13 0.24 3.16 0.21 2.42 0.04 17.00 23.15 0.29 1.47	53.30 0.20 2.95 0.00 2.49 0.13 16.82 23.36 0.24 1.21	
Total Si Ti Al ^{µv} Al Fe ³⁺ Fe ²⁺ Mn Mg Ca Na Cr Total	100.13 1.915 0.006 0.085 0.089 0.054 0.002 0.929 0.918 0.015 0.009 4.082	100.32 1.830 0.029 0.170 0.197 0.102 0.192 0.014 0.792 0.822 0.025 0.000 4.173	100.61 1.918 0.010 0.082 0.084 0.074 0.202 0.013 0.855 0.825 0.023 0.000 4.086	98.95 1.963 0.004 0.037 0.071 0.000 0.185 0.007 1.080 0.671 0.009 0.007 4.028	98.99 1.776 0.035 0.224 0.332 0.060 0.232 0.008 0.728 0.815 0.015 0.001 4.223	99.54 1.920 0.011 0.080 0.128 0.017 0.214 0.004 0.866 0.822 0.013 0.005 4.075	99.76 1.934 0.008 0.066 0.122 0.000 0.183 0.004 0.938 0.793 0.011 0.006 4.059	97.59 1.809 0.029 0.191 0.338 0.008 0.269 0.008 0.758 0.760 0.021 0.000 4.191	100.04 1.813 0.040 0.187 0.227 0.076 0.244 0.004 0.673 0.886 0.023 0.014 4.173	100.05 1.775 0.050 0.225 0.280 0.086 0.228 0.003 0.466 0.902 0.023 0.007 4.038	99.92 1.801 0.037 0.199 0.253 0.092 0.208 0.009 0.649 0.919 0.027 0.005 4.194	98.49 1.907 0.004 0.093 0.148 0.010 0.066 0.002 0.895 0.908 0.020 0.041 4.052	98.00 1.906 0.007 0.094 0.134 0.020 0.051 0.004 0.906 0.916 0.017 0.039 4.055	100.15 1.930 0.005 0.070 0.113 0.000 0.070 0.004 0.914 0.916 0.015 0.033 4.037	99.64 1.913 0.007 0.087 0.134 0.006 0.073 0.001 0.912 0.893 0.020 0.042 4.045	99.48 1.926 0.006 0.074 0.126 0.000 0.075 0.004 0.906 0.904 0.017 0.035 4.037	
mgv Wo En Fs	0.95 46.6 47.1 6.3	0.80 42.8 41.2 16.0	0.81 41.9 43.4 14.7	0.85 34.5 55.6 9.9	0.76 44.3 39.5 16.2	0.80 42.7 45.1 12.2	0.84 41.4 48.9 9.7	0.74 42.1 42.0 15.8	0.73 47.1 35.7 17.2	0.67 53.5 27.7 18.8	0.76 49.0 34.6 16.5	0.93 48.3 47.6 4.2	0.95 48.3 47.8 4.0	0.93 48.1 48.0 3.9	0.93 47.4 48.4 4.2	0.92 47.9 47.9 4.2	

Notes: mgv = Mg/Mg Fe² (at%); Wo, En, and Fs indicate wollastonite, enstatite, and ferrosilite percentages. ph = phenocrysts; mph = microphenocryst; gm = groundmass; c = core; r = rim. A, B, and C indicate different crystals.



Figure 2. Clinopyroxene compositions of igneous rocks recovered from Sites 827 and 829 in the Wo-En-Fs diagram. 1, 2, 3, and 4 indicate diopside, endiopside, augite, and salite compositions. A. Clinopyroxenes in serpentinite. B. Clinopyroxenes in andesite (Site 827), basalts, and dolerites (Site 829). Fields of lherzolites, harzburgites, and ultramafic cumulates from major ocean basins (dotted line) and from a high-Ti ophiolitic complex (Northern Apennine; solid line) are from Hebert et al. (1989). Compositions of microphenocrysts and groundmass crystals are indicated as core and rim, respectively.

Table 2 (continued).

Hole: Core, section: Interval (cm): Rock type:		829 591 81- Dole	9A R-1 -86 erite			82 611 1- Gab	9A R-1 -3 obro			829 61F 20- Microg	PA R-1 22 gabbro			82 61 36- Micro	9A R-1 -38 gabbro	
	A ph c	A ph r	B ph c	B ph r	Ac	Ar	Bc	Br	Ac	Ar	Bc	Br	Ac	A r	Bc	Br
SiO ₂	50.48	50.02	50.62	50.23	48.31	47.82	48.77	48.27	50.90	49.36	49.55	49.59	51.41	50.92	50.42	50.56
TiO ₂	0.81	0.98	0.85	0.96	0.16	0.17	0.47	0.17	0.76	0.37	1.25	0.96	0.65	0.87	0.78	0.56
Al ₂ O ₃	4.26	1.98	3.36	2.41	1.28	1.02	1.30	0.96	1.38	1.19	2.96	1.61	3.17	1.46	4.20	1.28
Fe ₂ O ₃	1.21	1.49	2.03	0.82	5.34	5.31	4.28	5.19	1.77	2.35	2.98	2.44	2.26	2.63	2.88	2.72
FeO	6.13	13.41	7.06	13.81	19.35	20.79	18.84	21.22	12.40	18.62	9.50	14.89	5.31	11.54	5.13	13.87
MnO	0.17	0.38	0.29	0.49	0.78	0.83	0.69	0.78	0.49	0.63	0.24	0.48	0.16	0.34	0.12	0.45
MgO	14.58	11.51	14.66	11.42	3.85	2.59	5.20	2.63	11.34	6.31	12.03	8.34	14.89	11.34	14.74	9.84
CaO	21.54	19.43	20.58	19.20	20.75	20.63	20.50	20.80	20.68	20.49	20.94	21.35	22.25	21.24	21.60	20.93
Na ₂ O	0.26	0.32	0.31	0.36	0.93	1.00	0.79	0.98	0.42	0.56	0.51	0.55	0.33	0.51	0.39	0.53
Cr ₂ O ₃	0.52	0.00	0.08	0.00	0.05	0.00	0.00	0.04	0.00	0.00	0.00	0.07	0.27	0.02	0.23	0.00
Total	99.46	99.52	99.76	99.70	100.75	100.16	100.84	101.00	100.14	99.89	99.96	100.29	100.43	100.85	100.25	100.73
Si	1.869	1.918	1.884	1.920	1.920	1.929	1.923	1.931	1.938	1.948	1.875	1.920	1.890	1.924	1.858	1.936
Ti	0.023	0.028	0.024	0.028	0.005	0.005	0.014	0.005	0.022	0.011	0.036	0.028	0.018	0.025	0.022	0.016
Ally	0.131	0.083	0.116	0.080	0.080	0.071	0.077	0.069	0.063	0.052	0.125	0.080	0.110	0.076	0.142	0.064
Al	0.186	0.090	0.147	0.109	0.060	0.049	0.061	0.045	0.062	0.055	0.132	0.074	0.138	0.065	0.183	0.058
Fe ³⁺	0.034	0.043	0.057	0.024	0.160	0.161	0.127	0.156	0.051	0.070	0.085	0.071	0.063	0.075	0.080	0.079
Fe ²⁺	0.190	0.430	0.220	0.441	0.643	0.701	0.621	0.710	0.395	0.615	0.301	0.482	0.163	0.365	0.158	0.438
Mn	0.005	0.012	0.009	0.016	0.026	0.028	0.023	0.026	0.016	0.021	0.008	0.016	0.005	0.011	0.004	0.015
Mg	0.805	0.658	0.814	0.651	0.228	0.156	0.305	0.157	0.643	0.371	0.678	0.481	0.816	0.639	0.810	0.561
Ca	0.855	0.798	0.821	0.786	0.884	0.892	0.866	0.892	0.844	0.866	0.849	0.886	0.876	0.860	0.853	0.859
Na	0.019	0.024	0.022	0.027	0.072	0.078	0.061	0.076	0.031	0.043	0.038	0.042	0.024	0.037	0.028	0.040
Cr	0.015	0.000	0.002	0.000	0.002	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.008	0.001	0.007	0.000
Total	4.116	4.082	4.113	4.080	4.078	4.071	4.077	4.067	4.063	4.052	4.125	4.079	4.102	4.076	4.136	4.065
mgv	0.81	0.60	0.79	0.60	0.26	0.18	0.33	0.18	0.62	0.38	0.69	0.50	0.83	0.64	0.84	0.56
Wo	45.3	41.1	42.7	41.0	45.5	46.0	44.6	45.9	43.3	44.6	44.2	45.8	45.6	44.1	44.8	44.0
En	42.6	33.9	42.4	33.9	11.7	8.0	15.7	8.1	33.0	19.1	35.3	24.8	42.4	32.8	42.5	28.8
Fs	12.1	25.0	14.9	25.1	42.7	46.0	39.7	46.0	23.7	36.3	20.5	29.4	12.0	23.1	12.7	27.2



Figure 3. Ti vs. Al^{IV} contents (at%) in clinopyroxenes from (A) basaltic and (B) gabbroic rocks of Hole 829A. Fields of clinopyroxenes from mid-ocean ridge basalts (MORB), within-oceanic plate basalts (WOPB), island arc tholeiites (IAT), boninites (BON), and basaltic andesites, and andesites (BA-A) from the forearc region are from Beccaluva et al. (1989). Compositions of microphenocrysts and groundmass crystals are indicated as core and rim, respectively.

gabbros of Site 829 and those from oceanic basins is also stressed by the Ti vs. Cr diagram (Fig. 5). However, in the Ti vs. Al^{IV} diagram, in which compositional fields from different tectonic settings are reported (Fig. 3; Beccaluva et al., 1989), analyses of clinopyroxene of basalts and gabbros from Site 829 plot inside the island arc tholeiite (IAT) field, overlapping the lowermost part of MORB field. On average, they show significantly lower Ti contents compared to clinopyroxene from major ocean basin gabbros, with clinopyroxene from effusive rocks having even lower Ti contents than those from the gabbros.

Clinopyroxenes in the serpentinite clast are plotted in Figure 2A. They fall in a very restricted area, well within the field of suboceanic mantle tectonite peridotites, but close to the field for Mg-rich clinopyroxenes from oceanic ultramafic cumulates (Serri et al., 1985; Hebert et al., 1989). Similarly, Ti and Cr contents of these clinopyroxene preclude effective separation between oceanic tectonite peridotites and ultramafic cumulates (Fig. 5; Hebert et al., 1989).

Plagioclase

Plagioclase is the most common mineral, in basalts and gabbros. Representative compositions are reported in Table 4 and are plotted



Figure 4. Clinopyroxene compositions of gabbros and microgabbros from Site 829. Fields of gabbros from major ocean basins and from a high-Ti ophiolitic complex (Northern Apennine) are from Hebert et al. (1989). Composition of microphenocrysts and groundmass crystals are indicated as core and rim, respectively.

on An-Ab-Or diagrams in Figure 6. They range from $An_{78.8}$ to $An_{22.6}$. In basaltic rocks, An contents show a more restricted range ($An_{76.9-62.3}$ in microphenocrysts and phenocryst cores; $An_{54.3}$ in phenocryst rims; Fig. 6) than for plagioclase in the gabbros ($An_{78.0-55.2}$ and down to $An_{22.6}$; Fig. 6), the latter suggesting equilibrium with an evolved interstitial liquid.

Olivine

Olivine has only been analyzed in the gabbros from the base of Hole 829A. It is strongly zoned, from Fo_{82-62} in crystal cores to Fo_{68-30} in rims (Table 3). NiO contents vary between 0.29–0.0 wt%, and 0.11–0.0 wt% in cores and rims respectively. These olivine rim compositions provide further evidence for late stage crystallization from evolved, iron-rich liquid, as recognized also for plagioclase and clinopyroxene.

Oxides

Representative analyses of magnetite, Ti-magnetite, and ilmenite from basalts and gabbros are reported in Table 4. A few Cr-spinels in the serpentinite have also been analyzed.

In basalts and dolerites the TiO₂ contents of the magnetite ranges between 3.09 and 14.02 wt%, with ulvospinel and jacobsite molecules in the range 9.31%-42.81% and 0.84%-2.35%, respectively; magnetite in the gabbros has higher TiO₂ and MnO contents. In fact, TiO₂ contents in gabbros cluster in the range 14.6–21.3 wt% (apart from two analyses with ~ 2 wt%), and MnO is always higher than 0.55 wt%. Acicular ilmenite analyzed in Sample 134-829A-59R-1, 3–4 cm, has an anomalously high MnO content (up to 15 wt%).

The Cr/(Cr + Al) vs. $Mg/(Mg + Fe^{2+})$ values of spinels in the ultramafic clast (Sample 134-829A-44R-1, 3–4 cm) are plotted in Figure 7. Their position in this diagram is consistent with an harzburgitic bulk composition but, as for clinopyroxenes, they also overlap into field for oceanic cumulates.

Table 3. Representative amphibole and olivine compositions from basaltic and gabbroic rocks from Sites 827 and 829.

Hole: Core, section: Interval (cm): Rock type:	827B 18R-CC 0-2 Basalt			83 61 1 Ga	29A R-1 -3 bbro	Hole: Core, section Interval (cm): Rock type:	:	8 6 Ga	29A 1R-1 1-3 1bbro		829A 61R-1 36-38 Microgabbro						
1949.4	amph	amph	amph	amph	amph	(1.385)	A ol c	A ol	r Bol	c Bolr	A ol c	A ol ı	Bolo	Bolr	Colc	C ol r	
SiO ₂ TiO ₂	43.14 3.03	39.98 2.41	42.37	43.97 1.02	36.15 0.22	SiO ₂ TiO ₂	38.35 0.00	33.39 0.05	39.14 0.00	34.80 0.03	39.57 0.02	35.96 0.11	39.06 0.04	35.77 0.03	39.44 0.01	37.31 0.00 0.03	
Fe ₂ O ₃ FeO	0.00	0.00	0.00	0.00	0.00 28.88	FeO MnO MaO	25.56 0.47	50.26 1.08	22.57 0.43	43.09 0.76	19.10 0.29	36.63 0.69	18.97 0.33	37.01 0.72 27.03	17.75	29.68 0.44 33.87	
MgO CaO Na ₂ O	13.84 10.75 2.49	13.22 11.82 2.57	13.50 10.57 2.67	9.83 7.94 4.48	1.96 10.41 3.64	CaO NiO Total	0.42 0.07 102.11	0.56 0.00 101.56	0.43 0.14 102.32	0.55 0.00 101.90	0.38 0.11 101.74	0.49 0.06 100.60	0.36 0.01 100.56	0.57 0.04 101.20	0.44 0.19 100.95	0.39 0.00 101.73	
K ₂ Õ Cr ₂ O ₃ H ₂ O Total	0.26 0.03 2.04 99.84	0.37 0.02 2.04 100.17	0.28 0.08 2.04 100.52	0.00 0.04 	0.00 0.00	Si Ti Al	0.993 0.000 0.001	0.992 0.001 0.001	0.996	0.989 0.001 0.001	0.996 0.000 0.002	1.001 0.002 0.001	0.995 0.001 0.002	0.993 0.001 0.001	0.996 0.000 0.001	0.990 0.000 0.001	
Si Ti	6.354 0.336	5.889 0.267	6.217 0.382	6.735 0.118	5.851 0.026	Fe Mn Mg	0.554 0.010 1.436	1.249 0.027 0.718	0.480 0.009 1.501	0.018 0.018 0.959	0.402 0.006 1.584	0.853 0.016 1.105	0.404 0.007 1.585	0.859 0.017 1.118	0.375 0.008 1.608	0.659 0.010 1.339	
Fe ³⁺ Fe Mn	0.000 1.581 0.044	2.652 0.000 1.514 0.021	0.000 1.646 0.022	1.342 0.000 2.851 0.070	2.672 0.000 3.909 0.122	Ca Ni Total	0.012 0.001 3.01	0.000	0.012	0.000 3.01	0.002 3.00	0.001 0.001 3.00	0.000 3.00	0.001 0.001 3.01	0.004 3.00	0.000 3.01	
Mg Ca Na K	3.037 1.696 0.710 0.049	2.903 1.866 0.735 0.070	2.953 1.661 0.758 0.052	2.244 1.304 1.331 0.000	0.472 1.806 1.142 0.000	Fo Fa	0.72 0.28	0 36 0.64	0.76 0.24	0.48 0.52	0.80 0.20	0.56 0.44	0.80 0.20	0.57 0.43	0.81 0.19	0.67 0.33	
Cr Total	0.000	0.003 15.917	0.009 15.759	0.005 15.994	0.000 16.000												
mgv	0.66	0.66	0.64	0.44	0.11												

Notes: Fo and Fa indicate forsterite and fayalite percentages. amph = amphibole; ol = olivine. --- = not determined. Other abbreviations as in Table 2.

WHOLE ROCK GEOCHEMISTRY

Major, minor, and trace element (including REE) analyses of samples recovered from Sites 829 and 830 are reported in Table 1, and are discussed below with emphasis on determining the magmatic affinities and tectonic setting of eruption of these lavas and associated intrusive igneous rocks.

Site 829

Samples from this site show different degrees of alteration, reflected in variable LOI values (in the range of 1.05–4.62 wt%) and also evident in the frequent appearance of normative nepheline, particularly for the gabbroic rocks (up to 5.4 wt%). Two samples of sparsely clinopyroxene + plagioclase-phyric basalts have a very high LOI contents (11.46–12.37), resulting from the high percentage of filled vesicles in this lithotype. As expected, the ultramafic clast has the highest LOI content (19.8 wt%).

Basaltic rocks from this site are quite primitive (mgv: 0.64-0.62), whereas dolerites and gabbros have a wider range of mgv (0.73-0.53). Enrichment in FeO and TiO2, as indicated by clinopyroxene and olivine compositions, is evident in Sample 134-829A-59R-1, 105-108 cm, which has the lowest MgO coupled with the highest FeO and TiO2 contents. Two basalts from this site have Ti/Zr values of 149 and 172 (Fig. 8), values more typical of IAT than normal MORB. In the MORB-normalized incompatible element diagram, these samples are enriched in low field strength elements (LFSE) (by a factor of three for Sr and seven for Ba, relative to MORB) and slightly depleted in high field strength elements (HFSE), particularly Zr (Fig. 9A). Although significant alteration of Site 829 basaltic rocks may have modified their original LFSE contents, their overall geochemical features are unlike those of MORB, and taken together with the HFSE contents transitional between typical MORB and IAT compositions (Fig. 9A), suggest a weak subduction-related signature for the mantle source of these magmas (Pearce, 1983).



Figure 5. Ti vs. Cr (at $\% \times 1000$) contents in clinopyroxenes from serpentinite (Sample 134-829A-44R-1, 1–2 cm) and gabbros from Hole 829A. Fields of oceanic tectonites, ultramafic cumulates, and gabbros are from Hebert et al. (1989).

Gabbros generally represent cumulate mineral assemblages with variable proportions of intercumulus phases. On the Ti-Zr diagram (Fig. 8) they define a field that broadly overlaps with that of the basalts. Dolerites have Ti/Zr values that vary from 124 to 136 (avg. 130), and for the gabbros and microgabbros, the range is 108–156 (avg. 126); all are slightly higher than average values for normal MORB (103–109;

Table 4. Representative plagioclase and oxide compositions from basaltic, gabbroic, and ultramafic rocks recovered from Site 829.

Hole: Core, section: Interval (cm): Rock type:	829A 43R-3 94–95 Basalt		829A 59R-1 3-4 Basalt		829A 59R-1 81–86 Dolerite		829A 61R-1 1-3 Gabbro		Hole: Core, section Interval (cm) Rock type:	829A a: 44R-1 b: 1-2 Serpentinite		829A 59R-1 81–86 Dolerite		829A 61R-1 1–3 Gabbro		829A 61R-1 36–38 Microgabbro	
*	A pl gm	B pl gm	B pl ph c	B pl ph r	pl c	pl r	pl c	pl r	*	A sp	B sp	A mt	B mt	A mt	B mt	mt	
SiO ₂ Al ₂ O ₃	53.02 28.25	51.30 30.09	51.25 30.36	55.15 27.03	48.43 31.98	62.09 23.54	48.37 32.03	62.13 23.31	SiO ₂ TiO ₂	0.00 0.31	0.00 0.23	0.74 3.09	1.36 13.53	0.08 21.28	0.17 14.58	0.09 19.41	
Fe ₂ O ₃ MgO	1.35 0.00	0.96 0.00	0.70 0.33	1.06 0.17	0.45 0.23	0.61 0.00	0.46 0.00	0.36 0.00	Al ₂ O ₃ Fe ₂ O ₃	28.55 3.02	28.99 2.39	0.25 63.16	0.79 41.81	1.74 26.52	2.06 37.62	2.11 29.90	
CaO Na ₂ O	13.17 4.00	15.09 3.31	15.09 3.15	11.28 5.16	16.43 2.56	5.77 8.76	16.56 2.71	5.10 9.58	FeO MnO	15.76 0.27	16.99 0.18	33.53 0.26	43.37 0.28	49.34 0.80	43.26 0.80	47.02 0.64	
K ₂ O Tot	0.05 99.84	0.04 100.80	0.00 100.88	0.14 99.99	0.02 100.11	0.14 100.92	0.06 100.18	0.13 100.60	MgO CaO	13.39 0.00	12.18 0.00	0.21 0.11	0.03 0.27	0.72 0.00	0.30 0.07	1.22 0.00	
Si	2.417	2.328	2.323	2.501	2.222	2.740	2.220	2.751	Cr ₂ O ₃ NiO	39.20 0.26	36.70	0.05	0.02	0.03	0.00	0.00 0.10 100.48	
Al Fe	1.517	0.033	1.622 0.027	1.445	1.730 0.016	1.225	1.733	0.012	Tot	100.75	97.73	101.47	0.050	100.53	98.89	0.002	
Ca	0.000	0.000	0.023	0.012	0.016	0.000	0.000	0.000	Ti	0.000	0.000	0.028	0.030	0.003	0.415	0.538	
Na K	0.354	0.292	0.277	0.454 0.008	0.228	0.750	0.241	0.823	Fe ³⁺	0.406	0.289	1.782	1.159	0.078	1.071	0.829	
101	4.980	4.998	5.004	5.007	5.020	26.5	5.028	3.050	Mn	0.041	0.028	0.008	0.009	0.025	0.026	0.020	
Ab Or	35.4	28.4	27.4	54.5 44.9	21.9	20.5 72.7	22.8	76.8	Ca	5.505 0.000 5.534	0.000 5 341	0.002	0.002	0.000	0.003	0.000	
01	0.5	0.2	0.0	U.a	0.1	0.0	0.5	0.7	Ni Tot	0.037	0.012	0.002 2.988	0.002 2.978	0.000 2.999	0.001 2.998	0.003 2.999	
									mgv	0.60	0.56						
									Mag Usp Jcb			88.4 8.7 0.8	58.0 37.8 0.9	34.3 59.2 2.5	52.0 41.5 2.6	38.7 53.8 2.0	

Notes: An, Ab, and Or indicate anorthite, albite, and orthoclase percentages. Mag, Usp, and Jcb indicate magnetite, ulvospinel, and jacobsite molecule percentages, respectively; crv = Cr/Cr + Al (at%). *Abbreviations: pl = plagioclase; sp = spinel; mt = magnetite. Other abbreviations as in Table 2.



Figure 6. Plagioclase compositions of basalts, dolerites, and gabbros recovered from Hole 829A. Compositions of microphenocrysts and groundmass crystals are indicated as core and rim, respectively.

Sun et al., 1979; Sun, 1980; Sun and McDonough, 1989). Their MORB-normalized incompatible element patterns show, in some cases, a weak HFSE depletion (Figs. 9B and C). REE patterns for basalts and gabbros display moderate to marked LREE depletion (Fig. 10), (basalts and dolerites, $[La/Yb]_n = 0.46-0.48$; gabbros and microgabbros $[La/Yb]_n = 0.13-0.27$), even more pronounced than for normal MORB.

The few Pb isotopic data available for Site 829 (Table 5) are reported in Figure 11, together with the field of MORB from the Indian, Pacific, and Atlantic oceans and lavas from several island arcs (data from Sun, 1980; White and Dupré, 1986; Wilson, 1989). Site 829 gabbros and basalts plot outside the MORB fields, toward more radiogenic Pb values. They have higher ²⁰⁷Pb/²⁰⁴Pb values than the few data available for volcanics of the Central Chain of the New Hebrides Island Arc (Briqueu et al., this volume). Basaltic rocks from Site 828 (Coltorti et al., this volume) also show a tendency toward more radiogenic Pb values, comparable with those of Site 829 volcanics.

The serpentinite clast (Sample 134-829A-44R-1, 3-4 cm) has high MgO, Ni, and Cr contents, and mgv = 0.92 (Table 1). Although a variation in CaO content due to alteration cannot be ruled out, the

Table 5. Sr, Nd, and Pb isotopic compositions of some igneous rocks from Sites 829 and 830.

Hole:	829A	829A	829A	829A	829A	830B	830B
Core, section:	43R-3	59R-1	59R-1	61R-1	64R-1	14R-1	14R-1
Interval (cm):	130-133	1–3	122-124	41-43	13-16	13–17	47–51
⁸⁷ Sr/ ⁸⁶ Sr	0.70450 (2)	0.70580(1)	0.70320 (7)	0.70325 (4)		0.70379 (4)	0.70331 (13)
143Nd/144Nd				0.51307(1)	0.51317 (2)		
²⁰⁶ Pb/ ²⁰⁴ Pb	18.727 (4)	18.865 (4)	18.602 (4)	18.569 (5)	18.616 (8)	18.696 (3)	18.754 (3)
²⁰⁷ Pb/ ²⁰⁴ Pb	15.550 (4)	15.659 (4)	15.609 (4)	15.601 (5)	15.619 (8)	15.556 (4)	15.575 (4)
²⁰⁸ Pb/ ²⁰⁴ Pb	38.248 (12)	38.862 (12)	38.500 (13)	38.474 (14)	38.547 (22)	38.388 (12)	38.570 (11)

Note: Precision for isotopic data, expressed as 2 sigma, is reported in brackets.



Mg/(Mg + Fe²⁺) x 100

Figure 7. Cr/(Cr + Al) (at% \times 1000) vs. Mg/Mg + Fe²⁺ (\times 100) of spinels from serpentinite from Site 829. Fields of oceanic lherzolites, harzburgites, and mafic and ultramafic cumulates are from Hebert et al. (1989).

CaO/Al₂O₃ value (0.81) approaches estimates for primordial mantle composition (0.88, Jagoutz et al., 1979; 0.79, Hofmann, 1988). Normative minerals calculated for this sample indicate a harzburgitic composition, with clinopyroxene less than 5 wt%; a simple mass balance calculation using rock and mineral chemical analyses, produces a similar result, giving a clinopyroxene content of about 4 wt%. A serpentinized ultramafic clast was also recently found at the toe of the accretionary wedge in front of the Bougainville Guyot during a submersible dive (Collot et al., 1992). It has an overall bulk composition very similar to that recovered at Site 829.

Site 830

Volcanic rocks from Site 830 are moderately to highly hypersthene-normative (5.34-22.05 wt%), and their LOI values range from 3.51 to 7.07 wt%. All samples are basalts, with less than 52 wt% SiO₂ and show a variable degree of fractionation, as reflected in mgv values from 0.68 to 0.49. Samples 134-830B-14R-1, 13–17 cm, and -14R-1, 59–64 cm (the highest in the stratigraphic sequences), are the least fractionated, having the highest mgv values and Ni, Co, and Cr contents. The lack of a Fe-enrichment trend is consistent with early magnetite fractionation.



Figure 8. Ti vs. Zr contents in basalts and dolerites (open squares) and gabbros (open circles) from Site 829. Fields of Site 828 basaltic rocks (hatched areas) are reported for comparison (Coltorti et al., this volume). Fields of island arc tholeiites, ocean ridge basalts, and calc-alkaline basalts are from Pearce and Cann (1973).

Chondrite-normalized REE patterns (Fig. 12A) and MORB-normalized incompatible element diagram (Fig. 12B) consistently show that the more fractionated rocks parallel, at higher values, the trend of the less differentiated samples, suggesting a genetic link among these lavas. All samples show distinct negative Nb anomalies, together with pronounced HFSE depletion (for the least fractionated samples), coupled with LFSE and LREE enrichments.

Lead isotopic ratios for two Site 830 samples (Table 5) plot in the fields for island arc lavas (Fig. 11), and are also very similar to the limited available data for basalts from islands of the New Hebrides Central Chain (Briqueu et al., this volume), although the provenance of Site 830 basaltic rocks is to be sought in the Western Belt islands.

DISCUSSION

Site 827

Rocks recovered at this site are mainly volcaniclastic/epiclastic material occurring below an upper Pliocene to middle Pleistocene volcanic siltstone. Clasts of highly plagioclase-phyric basalts, rare dacite, and volcanic breccias are present in a matrix made up of plagioclase, clinopyroxene, amphibole, opaques, and altered glass.

A thick sequence of late Oligocene to middle Miocene volcanoclastics occurs on Espiritu Santo Island (Santo Volcanic Group; Mallick and Greenbaum, 1977). Its sedimentological and petrographic characteristics are very similar to the deposits found at Site 827. Hornblendebearing andesite is a widely distributed lithotype in the Santo Volcanic Group, followed by highly plagioclase-phyric andesite (up to 30 vol%)



Figure 9. MORB-normalized incompatible element patterns for (A) basalts, (B) dolerites, and (C) gabbros and microgabbros from Hole 829A. Normalizing values from Sun and McDonough (1989). MORB and IAT are representative analyses from Sun (1980).



Figure 10. Chondrite-normalized REE distributions for basalts, dolerites, and gabbros from Hole 829A. Normalizing values from Sun and McDonough (1989).

of phenocrysts), basaltic andesite, basalts, and subordinate dacites. The petrography of these rocks matches very closely the igneous components of the volcanic breccia recovered at Site 827, both as clasts and as crystals dispersed in the matrix. Clinopyroxene compositions and, particularly, the presence of amphibole phenocrysts in one andesitic clast suggest a calc-alkaline magmatic affinity.

These data, together with the proximal nature of the Site 827 deposit (very poorly sorted, with angular to subrounded clasts), suggest that this material most probably originated from the Western Belt of the New Hebrides Island Arc. At this stage, it is not possible to distinguish the relative contribution of primary pyroclastic and autoclastic materials on the one hand, from epiclastic materials on the other. The first generation breccia may have been produced by magmaseawater interaction-induced fragmentation of a single lava flow, because both clasts and matrix show similar parageneses and modal abundances (Jones, 1967). This volcaniclastic material was, in turn, emplaced as a rubble avalanche (Jones, 1967) or as submarine lahars (Mitchell, 1970) along the forearc slope of Espiritu Santo Island.

Site 829

Basalts, dolerites, gabbros, and ultramafic rocks occur at various levels in Site 829. Effusive rocks vary from sparsely clinopyroxene + plagioclase-phyric to moderately-plagioclase-phyric basalts. Clinopyroxene phenocrysts in these basalts have lower Ti contents relative to Al^{IV} than those in MORB and are compositionally similar to clinopyroxenes from Site 828 (Coltorti et al., this volume). Basalts are quite primitive and have Ti contents intermediate between those in N-MORB and island arc basalts. Incompatible element distributions further support this transitional character; and HFSE levels are lower than MORB and higher than the average IAT values (Sun, 1980), whereas the reverse is true for LFSE. The latter elements, however, are unreliable, since they are easily mobilized during alteration (Alt et al., 1986; Bienvenu et al., 1990). The higher Ti/Zr values, generally lower HFSE levels, and steeper LREE-depletion compared with normal MORB all argue for a source peridotite that was rather more refractory than for normal MORB (Woodhead et al., 1993), or alternatively, that they were derived by higher extents of partial melting of MORB-source peridotite than that which yields typical MORB.

Despite a strong leaching procedure, ⁸⁷Sr/⁸⁶Sr isotopic ratios vary from 0.7045 to 0.7058 (Table 5), values significantly higher than for N-MORB (DePaolo, 1988). Furthermore, on a ²⁰⁷Pb/²⁰⁴Pb vs. ²⁰⁶Pb/²⁰⁴Pb diagram, Site 829 basalts plot at the limit or well outside



Figure 11. Lead isotopic ratios of basaltic and gabbroic rocks from Sites 829 (filled squares) and 830 (filled circles). Field of basaltic rocks from Site 828 (NDR) (Coltorti et al., this volume) and Central Chain of New Hebrides islands (Briqueu et al., this volume) are reported for comparison. Fields of basaltic rocks from island arc and mid-ocean ridge settings are from Sun (1980), White and Dupré (1986), and Wilson (1989). NHRL = North Hemisphere Reference Line.

the MORB fields toward more radiogenic values, characteristic of arc basalts.

Dolerites, microgabbros, and gabbros show petrographic and geochemical features similar to those of basalts. The crystallization sequence in these rocks (i.e., plagioclase crystallizing before clinopyroxene) is typical of MORB-type basalts, although some small crystals of biotite found in gabbros suggest a K2O content higher than in normal-MORB (Prichard and Cann, 1982; Spadea et al., 1991). Tholeiitic differentiation trends with strong FeO-enrichment are clearly recorded in the olivine and clinopyroxene geochemistry. Ti vs. Al contents in clinopyroxenes mostly plot in the IAT field. Chondritenormalized minor and trace element distribution vary from nearly flat (except for Rb and Ba) to slightly depleted in HFSE and enriched in LFSE (Fig. 9C). 87Sr/86Sr isotopic ratios are in the MORB range and the single Nd determination plots inside the MORB field. In contrast 207Pb/204Pb vs. 206Pb/204Pb isotopic ratios fall within the field of South Sandwich arc volcanics, and are more radiogenic than normal-MORB. These compositional features taken together suggest that the Site 829 basalts and comagmatic dolerites and gabbros probably represent backarc basin basalt magmatic affinities. Effusive rocks with similar intermediate characteristics between MORB and IAT were drilled in the Sulu Sea, a small intra-oceanic basin behind the Sulu Arc (ODP Leg 124; Spadea et al., 1991) and classified as back-arc basin basalts (BABB), by analogy with basaltic rocks found in the North Fiji Basin (Price et al., 1990) and Mariana Trough (Sinton and Fryer, 1987).

The origin of the serpentinite clast cored at around 407 mbsf at Site 829 is difficult to determine. It was originally harzburgitic. However available mineral chemical data cannot determine whether it formed as a residual tectonite peridotite during extraction of tholeiitic magma from sub-oceanic upper mantle, or whether it was a cumulate from a primitive magma. The latter hypothesis seems unlikely, since the only magmas that crystallize significant amounts of orthopyroxene before clinopyroxene are those with boninitic affinities (Crawford et al., 1989), and boninitic magmatism is unknown and unexpected in the region.

On Espiritu Santo and Malakula islands basalts, basaltic andesites, and andesites occur, either as isolated flows or as clasts in volcaniclastic breccias, together with minor intrusion of quartz diorite, diorites, and gabbro. Hornblende is always a common phase in both the effusive and intrusive rocks (Mallick and Greenbaum, 1977; Macfarlane and Carney, 1987). The few available data from Espiritu Santo (Mallick and Greenbaum, 1977), Malakula (Macfarlane and Carney, 1987), and Torres islands indicate a transitional calc-alkaline/tholeiitic character (Macfarlane et al., 1988), partly resembling the lower-K2O suite of the Central Chain lavas (Crawford et al., 1988). The only two trace element analyses of gabbro and diorite from Malakula (Gorton, 1974) show higher Sr, Rb, K, Ba, La, and Ce and lower Zr, Ti, and Y contents with respect to Site 829 igneous rocks. These two analyses, reported on a MORB-normalized diagram, display a clear Nb negative anomaly (Fig. 12). Clearly petrography and geochemistry of igneous rocks from the Western Belt islands are quite unlike from Site 829. On the other hand, basaltic rocks whose petrological features compare favorably with those drilled on the forearc are found on the NDR (Coltorti et al., this volume; Fig. 13). This strongly suggests that the forearc rocks drilled at Site 829 have been accreted to the over-riding plate during collision of the NDR with the forearc of this central section of the New Hebrides volcanic arc.

Concerning the provenance of the peridotitic clast, the only known outcrop of ultramafic rocks in the Vanuatu Archipelago is on the eastern side of Pentecost Island (Mallick and Neef, 1974). However, if the clast really came from this island, erosion and transport before the uplift of Espiritu Santo and Malakula islands should be considered (Collot et al., 1992). In our opinion, two alternative hypotheses can be put forward: (1) exhumation of mantle material by deep thrust plane, affecting the over-riding Pacific Plate at the convergent margin (Collot et al., 1992); or (2) accretion/obduction of mantle material onto the



Figure 12. Basalts from Hole 830B. A. Chondrite-normalized REE patterns. B. MORB-normalized incompatible element distribution. 657 and 649 are two samples (gabbro and diorite, respectively) from Malakula Island (Gorton, 1974). Normalizing values from Sun and McDonough (1989).



Figure 13. MORB-normalized incompatible element patterns of basaltic rocks from Site 829 compared with basaltic lavas from Site 828 (NDR; Coltorti et al., this volume).

DEZ after the Eocene subduction event (Maillet et al., 1983; Kroenke, 1984), accompanied by subsequent accretion on the forearc region of the New Hebrides Arc.

Site 830

Basalts recovered as clasts at Site 830 are strongly hypersthenenormative, and vary from quite primitive to fairly differentiated magmas (mgv = 0.68-0.49). They are found below Pleistocene volcanic silt/siltstone. Petrography of these clasts (both lavas and breccias), together with type and modal proportion of crystal fragments in the matrix, resemble those found in the volcaniclastic/epiclastic deposit of Site 827. Sedimentary and volcanic structures also suggest similar depositional processes.

Trace element distributions show the following: (1) a remarkable HFSE depletion coupled with evident LFSE enrichment; (2) a pronounced Nb-negative anomaly; and (3) an LREE enrichment coupled with flat unfractionated HREE. In the MORB-normalized diagram of Figure 12, the parallelism with the two samples from Malakula Island (Gorton, 1974) is evident. Lead isotopic data for these samples are similar to those of volcanics from the Central Chain of the New Hebrides Island Arc, indicating a clear island arc magmatic affinity.

The age and nature of the deposit suggest that these lavas are derived from the nearby Western Belt volcanic islands of Vanuatu. As for Site 827, these rocks probably represent reworked material from a volcaniclastic formation. From their locations Site 830 sediments are probably derived from the southern part of Espiritu Santo Island and/or northern Malakula Island. However, it should be noted that, in addition to the close similarity in trace element patterns of the basaltic rocks, hornblende (particularly as crystal fragments in Site 830 igneous rocks), is less abundant than in rocks from Site 827. These findings suggest a greater contribution of material from Malakula Island in the Site 830 deposits with respect to those of Site 827.

On Malakula Island, abundant volcanic breccias petrographically similar to the rocks drilled at Site 830 occur in the Matanui Formation, of lower Miocene age (Mitchell, 1966). The similarity of basalt compositions to those on nearby Malakula, plus the paucity of detrital hornblende relative to those in the sequence at Site 827, suggest a greater contribution of detritus from Malakula Island in the Site 830 deposits with respect to those of Site 827.

CONCLUSIONS

1. Site 827 recovered coarse volcaniclastic and epiclastic reworked lava breccias beneath upper Pliocene volcaniclastic siltstone. Clasts of basalt and subordinate dacite occur in a matrix that contains abundant detrital plagioclase, augite, amphibole, and altered vitric ash. Based on compositions of phenocryst minerals, and particularly the presence of amphibole, these rocks are considered to be derived from calc-alkaline lavas. Petrographically identical lavas occur in the late Oligocene to middle Miocene Santo Volcanic Group on Espiritu Santo Island, some 35 km further east, and the Site 827 rocks are inferred to have derived from this source area and may have emplaced as submarine lahars and rubble avalanches.

2. Site 829 recovered basalts and comagmatic dolerites and gabbroic rocks, plus a single clast of serpentinized harzburgite in a faultdisrupted sequence of rocks ranging from pre-middle Oligocene to Pleistocene age. Major and trace element characteristics of the mafic igneous rocks are transitional between typical normal MORB and island arc tholeiites, and Pb and Sr isotopic ratios are more radiogenic than typical MORB. Petrographically and compositionally very similar rocks occur at Site 828 on the North d'Entrecasteaux Ridge (Fig. 13). We conclude that the rocks drilled at Site 829 were accreted into the forearc of the New Hebrides Island Arc during collision of the DEZ with the arc. 3. Site 830, located in the forearc between the colliding Bougainville Guyot and the central New Hebrides Island Arc, yielded coarse volcaniclastic and epiclastic rocks below Pleistocene volcaniclastic silts. Clasts in these rocks have major element, trace element, and Pb isotopic compositions similar to New Hebrides Island Arc lavas that pre-date the collision of the d'Entrecasteaux Ridge. Volcanic breccias of the lower Miocene Matanui Formation of Malakula Island may be the source of the Site 830 volcaniclastics.

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