# 4. GEOCHEMISTRY AND MINERALOGY OF VOLCANIC ROCKS FROM ODP SITES 650, 651, 655, AND 654 IN THE TYRRHENIAN SEA1

L. Beccaluva,<sup>2</sup> E. Bonatti,<sup>3, 4</sup> C. Dupuy,<sup>5</sup> G. Ferrara,<sup>4, 6</sup> F. Innocenti,<sup>4</sup> F. Lucchini,<sup>7</sup> P. Macera,<sup>4</sup> R. Petrini,<sup>6</sup> P. L. Rossi,7 G. Serri,4 M. Seyler,3 and F. Siena8

### ABSTRACT

During ODP Leg 107, the basement of the Tyrrhenian Sea was drilled at Site 650, located in the Marsili basin, and at Sites 651 and 655, both located in the Vavilov basin. In addition, a lava flow was drilled at Site 654 on the Sardinia rifted margin. Mineral and whole rock major and trace element chemistry, including rare earth element (REE) and Sr and Nd isotopic ratios, were determined in samples of these rocks.

Site 654 lava was sampled within uppermost Pliocene postrift sediments. This lava is a basaltic andesite of intraplate affinity, and is analogous to some Plio-Pleistocene tholeiitic lavas from Sardinia. Site 650 basalts, drilled beneath 1.7-1.9-Ma-old basal sediment, are strongly altered and vesicular suggesting a rapid subsidence of the Marsili basin. Based on incompatible trace elements, these basalts show calc-alkaline affinity like some products of the Marsili seamount and the Eolian arc. The basement of the two sites drilled within Vavilov basin shows contrasting petrologies. Site 655, located along the Gortani ridge in the western part of the basin, drilled a 116-m-thick sequence of basalt flows beneath 3.4-3.6-Ma-old basal sediments. These basalts are chemically relatively homogeneous and show affinity to transitional MORB. Four units consisting of slightly differentiated basaltic lavas, have been identified. Site 655 basalts are geochemically similar to the high Ti lavas from DSDP Leg 42, Site 373 (Vavilov Basin). The basement at Site 651, overlain by 40 m of metalliferous dolostone covered by fossiliferous sediments with an age of 2 Ma, consists of two basalt units separated by a dolerite-albitite intrusive body; serpentinized harzburgites were drilled for 30 m at the base of the hole. The two basalt units of Site 651 are distinct petrochemically, though both show incompatible elements affinity with high-K calc-alkaline/calc-alkaline magmas from Eolian arc. The cpx chemistry and high K/Na ratio of the lower unit lavas suggest a weak alkaline tendency of potassic lineage.

Leg 107 basement rock data, together with data from DSDP Site 373 and from dredged samples, indicate that the deepest basins of the central Tyrrhenian Sea are underlain by a complex back-arc basin crust produced by magmas with incompatible element affinities to transitional MORB (Site 655 and DSDP Site 373), and to calc-alkaline and high-K calc-alkaline converging plate margin basalts (Sites 650 and 651). This petrogenetic complexity is in accordance with the back-arc setting of the Vavilov and Marsili basins. Other back-arc basin basalts, particularly those from ensialic basins such as the Bransfield Strait (Antarctica), show a comparable petrogenetic complexity (cf., Sounders and Tarney, 1984).

## **INTRODUCTION**

One of the objectives of Leg 107 was to investigate the nature of the basement of the two deep basins of the Tyrrhenian sea floored by thin crust, i.e., the Marsili and the Vavilov basins (Fig. 1). Recent geophysical data (Steinmetz et al., 1983) indicate that the Vavilov and Marsili basins are largely underlain by relatively thin, oceanic-type crust. Three sites reached the basement, which was drilled for 31.9 m at Site 650 (Marsili basin, Fig. 1) and for 164.4 and 116.23 m at Sites 651 and 655 respectively (Vavilov basin, Fig. 1). While volcanic rocks with basaltic composition were recovered both at Sites 655 and 650, the nature and structure of the basement at Site 651 was found to be more complex, consisting of two basalt units separated by an intrusive doleritic and leucocratic unit, and overlying serpentinized peridotites. In addition, a lava flow a few meters thick interbedded in sediments was drilled at Site 654, in the Sardinia

rifted passive margin (Fig. 1). This work reports petrological, mineralogical, geochemical, and isotopic data obtained so far on the volcanic rocks drilled in the Tyrrhenian Sea during Leg 107.

#### ANALYTICAL PROCEDURES

X-ray fluorescence analyses were performed on powder pellets using an automated Philips PW 1450 spectrometer. Major elements (Tables 1 and 2) were determined using a full matrix correction procedure (Franzini et al., 1975) and atomic absorption and wet chemical methods (see footnotes in Table 1). XRF trace element analyses were performed by correcting full matrix effects using experimentally determined correction coefficients (Leoni and Saitta, 1976). The precision of trace elements (Tables 3 and 4) determined by XRF and atomic absorption (Cr, Co, Rb and Sr) is estimated, for abundances greater than 10 ppm, to better than 5%. Accuracy is given in Leoni and Saitta (1976) for XRF and Dostal et al. (1983) for atomic absorption. For elements analyzed by instrumental neutron activation (REE, Th, Hf, and Sc; Table 5) the precision is generally better than 10%-12% with the exception of Tb, where it reaches 20% (Dupuy et al., 1979; Dostal et al., 1983). Microprobe data (Tables 6-10) were obtained at the University of Modena, with a SEMQ-ARL unit, and at Lamont-Doherty Geological Observatory with a four-spectrometer fully automated Camebax unit. In both cases natural silicates and oxides were used as standards, and the raw data were corrected with a ZAF program using the Bence and Albee (1969) factors. Sr and Nd isotopic compositions (Tables 3 and 4) were determined at Istituto di Geocronologia e Geochimica Isotopica, CNR, Pisa, using a single collector Isomass 54E spectrometer, standard chemical methods, and the procedures of Ludwig (1982) for data acquisition and reduction.

<sup>&</sup>lt;sup>1</sup> Kastens, K. A., Mascle, J., et al., 1990. Proc. ODP, Sci. Results, 107: College Station, TX (Ocean Drilling Program).

<sup>&</sup>lt;sup>2</sup> Istituto di Mineralogia, Ferrara, Italy.

<sup>&</sup>lt;sup>3</sup> Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY 10964.

<sup>&</sup>lt;sup>4</sup> Dipartimento di Scienze della Terra, Pisa, Italy.

<sup>&</sup>lt;sup>5</sup> Centre Geologique et Geophysique, Montpellier, France.

<sup>&</sup>lt;sup>6</sup> Istituto Geocronologia e Geochimica Isotopica, CNR, Pisa, Italy. <sup>7</sup> Dipartimento di Scienze Mineralogiche, Bologna, Italy.

<sup>&</sup>lt;sup>8</sup> Istituto di Scienze della Terra, Catania, Italy.



Figure 1. Location of the sites drilled during ODP Leg 107 in the Tyrrhenian sea (after Kastens et al., 1986).

# **SITE 650**

### **Geological Outline**

The site is located near the western rim of the bathyal plane of the Marsili basin (Fig. 1). Hole 650A reached a penetration of 633.8 m from a water depth of 3516.3. The basement was encountered 601.9 m below the seafloor (mbsf), and was drilled for 31.9 m. The age of the base of the sedimentary sequence, determined by biostratigraphy and by magnetostratigraphy, is 1.7-1.9 Ma (Shipboard Scientific Party, 1987). The basal sediments consist of a 10-cm-thick layer of almost pure dolomite overlain by approximately 10 m of altered nannofossil ooze with dolomite, authigenic feldspars, zeolites, and iron-manganese oxides. The extrapolated present-day temperature at sediment/ basement contact is approximately 100°C (Shipboard Scientific Party, 1987). Several lines of evidence indicate that the drilled

3	650-66-2	650-67-2	650-67-2	650-68-1	650-69-CC	651-44-2	651-44-2	651-46-1	651-49-1	651-49-1	651-53-2	651-53-2
Sample	115-118	92-95	114-116	77-81	26-29	108-111	140-144	78-80	79-81	136-138	114-116	120-122
SiO <sub>2</sub>	52.67	54.82	55.53	50.49	52.88	49.91	51.90	51.28	52.75	49.04	52.87	52.56
TiO <sub>2</sub>	1.38	1.24	1.21	1.30	1.17	1.86	1.51	1.62	1.32	1.11	1.39	1.27
Al <sub>2</sub> O <sub>3</sub>	19.21	19.63	19.89	19.43	17.44	15.72	16.34	16.52	15.39	16.08	15.05	15.88
Fe <sub>2</sub> O <sub>3</sub>	4.84	5.74	7.08	9.22	8.99	8.74	8.56	9.93	8.53	4.98	5.09	7.75
FeO	nd	nd	nd	nd	nd	1.39	nd	nd	nd	5.00	3.11	nd
MnO	0.12	0.06	0.04	0.09	0.08	0.07	0.09	0.09	0.12	0.15	0.11	0.13
MgO	2.00	2.31	1.93	2.24	3.93	6.53	8.42	7.50	7.10	8.22	7.18	7.34
CaO	9.10	6.13	5.37	6.88	6.58	6.53	5.32	5.51	7.06	9.47	6.78	7.11
Na <sub>2</sub> O	4.44	3.88	4.47	4.41	4.33	3.86	3.72	3.78	3.56	1.97	3.22	3.39
K <sub>2</sub> Õ	0.57	0.63	0.85	0.64	1.20	1.40	0.81	0.80	1.68	0.79	2.37	2.18
P205	0.27	0.07	0.13	0.36	0.23	0.31	0.15	0.17	0.20	0.25	0.28	0.26
LÕI	5.41	5.48	3.50	5.14	3.16	3.68	3.19	2.80	2.29	2.95	2.56	2.13
C.I.P.W. No	rms											
Q	3.60	15.75	8.76	0.62	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00
or	3.37	3.72	5.02	3.78	7.09	8.27	4.79	4.73	9.93	4.67	14.00	12.88
ab	37.57	32.83	37.82	37.31	36.64	32.66	31.48	31.98	30.12	16.67	27.24	28.68
an	30.80	7.00	25.79	31.33	24.61	21.43	25.41	25.75	21.05	32.70	19.61	21.67
С	0.00	0.00	2.16	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00
di	10.37	19.00	0.00	0.38	5.42	7.30	0.00	0.39	10.28	10.31	9.89	9.62
hy	4.37	2.19	12.49	15.92	17.52	9.51	28.11	25.18	18.01	26.88	18.70	13.89
ol	0.00	0.00	0.00	0.00	0.00	10.36	1.56	3.12	3.13	0.96	2.82	6.08
mt	0.83	0.99	1.22	1.59	1.55	1.77	1.48	1.71	1.47	1.82	1.47	1.34
il	2.62	2.36	2.30	2.47	2.22	3.53	2.87	3.08	2.51	2.11	2.64	2.41
ap	0.63	0.16	0.30	0.83	0.53	0.72	0.35	0.39	0.46	0.58	0.65	0.60
DI	44.54	52.30	51.60	41.72	44.19	40.93	36.26	36.71	40.05	21.34	41.25	41.57
MgV	48.17	47.51	38.01	35.33	49.57	58.81	68.87	62.94	65.18	63.69	65.39	68.05

Table 1. Major elements and CIPW norms of volcanic rocks from Holes 650A and 651A.

Note: Norms and MgV calculated assuming  $Fe_2O_3/FeO = 0.15$ . Major elements analyses by XRF (Franzini et al., 1975), except MgO and Na<sub>2</sub>O (AAS), FeO (titrimetric), and LOI (gravimetric). Analyses with FeO carried out at Dip. Scienze della Terra (University of Pisa); others with total iron as  $Fe_2O_3$ , averages of analyses performed at DST, Universities of Bologna and Pisa.

basaltic section represents the top of the oldest basement of the Marsili basin (Shipboard Scientific Party, 1987). The simplified igneous stratigraphy with some geochemical parameters of the analyzed samples is reported in Figure 2.

## **Texture and Mineralogy**

Petrographically, the rocks of Hole 650 are strongly altered vesicular basalts. Vesicularity is variable between 22.8 and 37.1%, which indicates on the basis of Macpherson (1984) model a depth of 2-3 km and, therefore, an average rate of subsidence of about 1 mm/yr (Pareschi et al., in press). The texture of the basalt is characterized by a network of skeletal plagioclase microliths of labradoritic composition (Table 8; Fig. 3) which reach bow-tie to fan spherulitic morphologies in the first meter or so of the basement (Core 66). Intergranular clinopyroxene of endiopside to augitic composition (Table 7; Fig. 4) is present as relict in significant amounts only at the bottom of the hole (Core 69). Here the basalt is more crystalline than elsewhere in the section. Pseudomorphs after hopper-type olivine microphenocrysts are common in all the samples. In Core 66 olivine pseudomorphs consist largely of carbonates, whereas they are made of Fe-hydroxides and clay minerals in the other cores. Glassy mesostasis altered to clay minerals and Fe-hydroxides form the main part of the rock volume. Vesicles and cavities are commonly bordered or filled mostly by carbonates but also by zeolites and clay minerals. These secondary minerals sometimes occur also in the veins.

Two adjacent samples from Core 67 (intervals 92–95, 114– 116 cm), although both strongly altered, show different degrees of alteration, which reaches a maximum in the interval 92–95, where even plagioclase is almost completely replaced by secondary minerals, largely zeolites.

Olivine is a significant phase in the whole sequence and the plagioclase relicts are compositionally  $An_{68-59}$  (Fig. 3). Clinopy-

roxene (cpx) chemistry of the least altered Site 650 basalt (Table 7; Figs. 4 and 5) suggests an affinity to subalkaline rather than alkaline magmas.

#### Geochemistry

The chemical affinity of Site 650 lavas is difficult to assess on the basis of whole rock analyses due to elemental remobilization related to basalt-seawater interaction. Physical conditions, such as proximity to the water-rock interface at the time of eruption (maximum 26 mbsf for Core 69), high permeability, and a present-day top of basement temperature of approximately 100°C, probably caused superposition of a present-day hydrothermal alteration under reducing conditions and an earlier lowtemperature seafloor weathering under oxidizing conditions.

Assuming an original basaltic composition, as suggested by the abundant and widespread olivine and labradoritic plagioclase microphenocrysts and the high Cr content (228-388 ppm, Table 3), the low MgO abundance (3.93-1.93 wt%, Table 1) is probably caused by Mg depletion due to basalt seawater interaction at low temperature under oxidizing conditions (Bonatti, 1970; Staudigel and Hart, 1983). CaO appears to be extracted by seawater as well. Later it is redeposited as calcite in veins and amygdules, thus explaining the "normal" CaO content observed in Core 66. CaO and MgO loss from the basaltic basement and precipitation of dolomite in the basal 10 m of sediments, are probably related to the same alteration process. Loss on ignition (LOI) reaches the lowest value in the sample which is least altered petrographically (Core 69). The same correlation holds also for the two samples from Core 67. Assuming that they come from the same lava flow (the two samples are only 10 cm apart) and that the flow was compositionally homogeneous in origin, it appears that even elements commonly considered to be alteration-resistant, such as Zr and Y (Pearce and Cann, 1973; Hart et al., 1974), are to some extent mobile during Site 650 low tem-

Table 2. Major elements and CIPW norms of volcanic rocks from Holes 655B and 654A.

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Sample	655-1-4 42-46	655-1-4 116-118	655-2-2 126-129	655-2-2 129-131	655-3-3 132-135	655-4-1 112-114	655-5-1 23-25	655-6-1 52-54	655-6-1 54-56	655-7-3 55-57	
SiO <sub>2</sub>	50.36	47.65	48.37	46.05	52.43	48.33	48.28	47.50	48.59	45.61	
TiO <sub>2</sub>	1.46	1.53	1.56	1.60	1.43	1.57	1.55	1.53	1.59	1.48	
Al <sub>2</sub> O <sub>3</sub>	15.95	16.48	17.56	16.68	15.61	16.93	15.99	16.04	16.50	15.54	
Fe <sub>2</sub> O <sub>3</sub>	9.70	3.59	9.63	7.28	5.49	10.67	3.73	9.40	5.08	9.41	
FeO	nd	6.10	nd	2.71	3.14	nd	5.21	nd	4.18	nd	
MnO	0.13	0.15	0.15	0.16	0.09	0.18	0.17	0.16	0.17	0.16	
MgO	7.12	6.70	6.22	5.25	6.21	6.52	6.38	6.14	5.67	6.23	
CaO	9.37	11.21	10.39	11.61	8.83	10.42	11.53	12.07	10.73	13.25	
Na <sub>2</sub> O	3.52	3.33	3.43	3.79	3.94	3.50	3.89	3.51	4.15	3.31	
K <sub>2</sub> Õ	0.34	0.50	0.37	0.69	0.61	0.27	0.34	0.44	0.57	0.40	
P205	0.20	0.13	0.24	0.29	0.21	0.14	0.17	0.15	0.19	0.14	
LÕI	1.86	2.63	2.08	3.88	2.01	1.46	2.76	3.06	2.58	4.47	
C.I.P.W. No	rms										
Q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
or	2.01	2.95	2.19	4.08	3.60	1.60	2.01	2.60	3.37	2.36	
ab	29.78	23.50	29.02	18.76	33.34	28.83	24.79	21.98	26.50	14.74	
an	26.72	28.54	31.43	26.46	23.11	29.69	25.16	26.71	24.71	26.36	
ne	0.00	2.53	0.00	7.21	0.00	0.43	4.40	4.18	4.67	7.19	
di	15.04	21.45	15.17	24.10	15.77	17.29	25.26	26.31	22.38	31.43	
hy	11.97	0.00	1.22	0.00	14.87	0.00	0.00	0.00	0.00	0.00	
ol	6.87	13.16	12.87	9.41	2.11	14.62	10.38	9.46	10.27	7.86	
mt	1.67	1.79	1.66	1.77	1.55	1.84	1.64	1.62	1.68	1.62	
il	2.77	2.91	2.96	3.04	2.72	2.98	2.94	2.91	3.02	2.81	
ap	0.46	0.30	0.56	0.67	0.49	0.32	0.39	0.35	0.44	0.32	
DI	31.79	28.99	31.21	30.05	36.94	30.85	31.20	28.76	34.54	24.29	
MgV	62.27	59.23	59.23	53.43	60.86	57.88	60.11	59.50	56.73	59.82	

Note: Norms and MgV calculated assuming  $Fe_2O_3/FeO = 0.15$ . Major elements analyses by XRF (Franzini et al., 1975), except MgO and Na<sub>2</sub>O (AAS), FeO (titrimetric), and LOI (gravimetric). Analyses with FeO carried out at Dip. Scienze della Terra (University of Pisa); others with total iron as  $Fe_2O_3$ , averages of analyses performed at DST, Universities of Bologna and Pisa.

perature basalt-seawater interaction (Fig. 2) together with K, Na, P, Fe, and Ba. To what extent the Ni and Co variations are due to this process or to olivine accumulation is not clear (Fig. 2).

Values for Ti, Nb, Cr, V, Sc, and Th, which show variations within the range of experimental uncertainty (Fig. 2), might represent original compositions. Hart et al. (1974) suggested that these elements do not move during seafloor weathering of glasses. This apparently holds also for Th (Table 5) and middle REE (Fig. 6A). The increasing degree of alteration apparently produces in Core 67 a slight increase of Yb, Ce, Nd, and strong depletion of Yb, Lu, and Y.

The magmatic affinity of Site 650 lavas cannot be derived, therefore, from the alkali-silica diagram and CIPW normative composition. Evaluation of the petrogenetic affinity of Site 650 basalts on the basis of Ti, Zr, Y, and Sr (Figs. 7 and 8) is ambiguous. Assuming a plate margin character (see later section) these basalts appear to have affinity with IAT and CAB in the Ti/Zr/Sr diagram and with OFB in the Ti/Zr diagram. Evidently Site 650 basalts have TiO<sub>2</sub> content slightly greater than typical calcalkaline basalts including those of the Mediterranean region (Fig. 4) but comparable to western US/Andean analogues (cf., Ewart, 1982).

A MORB-normalized incompatible element pattern is on a first-order approximation, intermediate between calc-alkaline basalts from Santorini (Aegean Arc) and high K calc-alkaline basaltic andesites from Stromboli (Eolian Arc) except for Ti and Yb (Fig. 9). However, due to elemental mobilization of K, Rb, Ba, P, Y, and Yb, we have to be careful to use this information for the interpretation of the original chemistry of the Site 650 rocks. Nevertheless, the high Th/Nb, Th/Ti, and Ce/Nb ratios (i.e., elements nearly unaffected by alteration) indicate a close affinity to convergent plate margin volcanism, particularly to calc-alkaline basic rocks of present-day Mediterranean island arc (Fig. 9). This interpretation is confirmed by the Th/Zr vs. Nb/Zr diagram (Fig. 10) where basalts from Site 650 fall well

within the field of orogenic lavas, very close to those of the Santorini calc-alkaline series. The Zr/Y ratios greater than 4 and Th peak in the MORB normalized diagram (Fig. 9) are more typical of converging plate margin volcanism on continental rather than oceanic crust (cf., Pearce, 1983). In addition to the upper unit of the Marsili basin crust (Site 650), Quaternary volcanism with calc-alkaline nature is common in and around the Marsili basin: the upper part of the Marsili (Selli et al., 1977, Beccaluva et. al., 1985) and Palinuro seamounts (Colantoni et al., 1981) as well as in the Eolian arc.

### **SITE 654**

### **Geological Outline**

This site is located approximately 75 km east of the Sardinia coast (Fig. 1), on a fault-bounded tilted block of the upper continental margin of Sardinia, 2175 m below sea level. The crustal thickness of 20 km (Steinmetz et al., 1983) implies crustal thinning which occurred during the upper Tortonian-upper Messinian rifting of the eastern Sardinia margin (Scientific Shipboard Party, 1987).

An interval of 2 m (between 71 and 73 mbsf), of which only 30 cm were recovered, of non-vesicular, aphanitic, olivine phyric basalt was encountered within late Pliocene, post-rift sediments, a few meters below the Plio-Pleistocene boundary (about 1.8 Ma). The basalt represents a lava flow rather than a sill. However, it is not clear whether it is an "in situ" lava flow or a resedimented boulder.

## **Texture and Mineralogy**

Petrographically, the two studied samples are nearly identical. They are characterized by microphenocrysts of hopper-type olivine (Fo<sub>82-83</sub>) (Table 9) and skeletal plagioclase  $An_{62-51}$  (Table 8) in a spherulitic groundmass with fan-like clinopyroxene and opaques. Minor amounts of interstitial, fresh glass is present,

655-9-3 655-10-3 655-10-3 655-10-3 655-10-3 655-11-3 655-12-1 655-12-1 655-12-4 654-9-CC 654-9-CC 18-21 12-15 19-22 49-52 53-56 88-91 95-97 98-100 17-21 00-04 16-19 47.29 47.36 47.08 50.78 50.59 50.43 54.45 46.10 50.56 47.66 54.12 1.69 1.53 1.53 1.41 1.39 1.46 1.32 1.24 1.38 1.54 1.58 17.32 16.94 17.24 15.10 15.73 17.28 15.59 16.34 16.64 14.80 15.12 10.70 10.76 6.34 6.54 9.31 10.02 7.51 9.10 9.23 3.42 9.61 nd nd 3.63 2.84 1.86 6.19 nd nd nd nd nd 0.19 0.17 0.18 0.13 0.14 0.16 0.14 0.13 0.16 0.12 0.13 4.06 5.20 5.14 6.88 6.70 4.54 6.95 6.76 6.74 7.09 7.33 11.51 11.75 12.11 10.11 10.35 13.43 9.95 9.83 12.01 7.15 7.10 3.91 3.44 3.55 3.59 3.57 3.54 3.52 3.40 3.27 3.50 3.52 0.50 0.33 0.40 0.35 0.32 0.35 0.38 0.33 0.33 0.59 0.60 0.28 0.23 0.20 0.18 0.17 0.22 0.17 0.19 0.18 0.17 0.18 2.55 2.29 2.60 2.09 1.72 2.90 2.06 1.70 2.39 1.60 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 3.81 3.77 2.95 1.95 2.36 2.07 2.07 1.95 1.89 1.95 3.49 3.55 2.25 24.14 24.25 21.51 22.69 29.78 30.38 30.21 16.40 29.78 28.77 29.61 28.23 29.81 29.92 24.05 25.95 30.23 29.75 23.68 28.35 22.93 25.62 4.85 2.63 4.62 0.00 0.00 2.70 7.34 0.00 0.00 0.00 0.00 22.51 22.29 23.81 20.33 19.80 28.94 15.70 23.57 9.29 8.38 18.41 0.00 0.00 0.00 9.02 11.08 0.00 7.79 0.00 9.39 23.85 24.30 8.12 10.54 0.00 9.51 6.76 7.16 6.23 7.31 7.33 11.57 0.00 1.84 1.86 1.79 1.67 1.73 1.59 1.78 1.66 1.61 1.65 1.57 3.21 2.91 2.91 2.68 2.36 2.62 3.00 2.92 2.64 2.77 2.51 0.65 0.53 0.46 0.42 0.39 0.51 0.32 0.42 0.44 0.42 0.39 31.94 28.83 28.49 32.44 32.10 25.81 32.03 30.72 27.34 36.91 37.10 46.04 52.08 52.70 61.47 62.22 59.54 61.81 50.47 61.98 64.43 62.39

Table 3. Trace elements (ppm) and isotopic composition of volcanic rocks from Holes 650A and 651A.<sup>a</sup>

Sample	<sup>b</sup> 650-66-2 115-118	<sup>b</sup> 650-67-2 92-95	<sup>b</sup> 650-67-2 114-116	<sup>b</sup> 650-68-1 77-81	<sup>b</sup> 650-69-CC 26-29	651-44-2 108-111	<sup>b</sup> 651-44-2 140-144	<sup>b</sup> 651-46-1 78-80	<sup>b</sup> 651-49-1 79-81	651-49-1 136-138	651-53-2 114-116	<sup>b</sup> 651-53-2 120-122
Sc	21	26 °25	25 °25	17	22 °25		24 °27	26	24 °26			24 °27
V	260	221	218	258	246	318	278	306	238	233	239	235
Cr	298	388 d411	d398	398	228 d230	96	100 d94	100	79 d <sub>82</sub>	153	229	d213
Co	17	<sup>26</sup> d <sub>24</sub>	d16	20	28 d26		<sup>29</sup> <sup>d</sup> 28	32	427 28			d <sup>27</sup> d <sup>25</sup>
Ni	134	206	164	133	97	50	50	51	52	156	83	71
Rb	7	10 dg	9 d9	9	<sup>19</sup> <sup>d</sup> 20	12	6 d4	7	29 d <sub>31</sub>	17	39	35 d36
Sr	397	332 d314	342 d332	397	398 d385	291	277 d268	304	<sup>244</sup> d237	248	372	d355 d358
Ba	159	120	160	179	216	190	151	153	172	137	270	255
La	16	9	8		13	16	15	15	12	9	18	19
Y	27	11	14	19	20	32	29	32	26	24	23	24
Zr	136	105	78	79	92	129	131	133	118	93	136	133
Nb	5	5	4	3	4	9	10	11	7	6	10	10
<sup>e87</sup> Sr/ <sup>86</sup> Sr <sup>e143</sup> Nd/ <sup>144</sup> Nd						0.70576(3)				0.70438(2) 0.51294(3)	0.70733(2)	

<sup>a</sup> XRF analyses following the method of Leoni and Saitta (1977).

Table 2 (continued).

<sup>b</sup> Average of two determinations carried out at DST, Universities of Bologna and Pisa; other analyses at DST, University of Pisa.

<sup>c</sup> INAA following Dostal et al., 1983 (Centre Geologique at Geophysique, Montpellier).

d AAS (CGG, Montpellier).

tic andesite (Table 9).

<sup>e</sup> The reported errors on the Sr and Nd isotope-ratios are at 95% confidence level. The <sup>87</sup>Sr/<sup>86</sup>Sr ratios are relative to NBS987 = 0.71026(2). The <sup>143</sup>Nd/<sup>144</sup>Nd ratios are reported to La Jolla STD = 0.51186.

particularly in the interval 0-4 cm. The glass is compositionally a basaltic andesite (Table 6). The clinopyroxene chemistry (Table 7; Figs. 4 and 5) reflects

the qz-normative character of the basaltic andesite liquid. The

high Fs molecule for a cpx crystallized from a melt with Mg

number of around 60 is probably due to the high cooling rate

which is implied by the rock texture (Lofgren 1979). Euhedral

chromite is commonly included in the olivine microphenocrysts. Olivine and glass are partially replaced by clay minerals. The

forsterite and Ni content of olivine is relatively high for a basal-

## Geochemistry

The lava flow of Hole 654A, although it can be petrographically classified as a basalt, is in term of major element chemistry a basaltic andesite (Alk-silica, Le Bas et al., 1986) with a quartz normative character (Table 1). The analysis of interstitial glass reveals both a very small degree of evolution relative to the whole rock composition (D.I. 40.2 vs. 36.9 and Mg 57.5 vs. 59.5; Tables 1 and 5), and the insensitivity of rock chemistry, even for alkalis, to the minor low temperature alteration suffered by the samples. In spite of the high (approximately 54

Table 4. Trace elements (ppm) and isotopic composition of volcanic rocks from holes 655B and 6	able 4.	e 4.	Trace	elements	(ppm)	and	isotopic	c composition	l of	volcanic	rocks	from	holes	655B	and	654	A	
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Sample	<sup>b</sup> 655-1-4 42-46	655-1-4 116-118	<sup>b</sup> 655-2-2 126-129	655-2-2 129-131	655-3-3 132-135	<sup>b</sup> 655-4-1 112-114	655-5-1 23-25	<sup>b</sup> 655-6-1 52-54	655-6-1 54-56	<sup>b</sup> 655-7-3 55-57	<sup>b</sup> 655-9-3 18-21
Sc	27 °30		28			33 c35		33		33	35
v	238	241	265	256	220	304	267	268	271	261	314
Cr	d135	160	145	132	107	d118	145	160	149	157	195
Co	33 d32		31			<sup>32</sup> d <sub>33</sub>		29		32	36
Ni	107	86	88	90	84	66	82	94	82	99	83
Rb	d23	6	5	6	7	4 d1	3	5	5	6	5
Sr	196 d <sub>194</sub>	195	209	215	192	191 d <sub>185</sub>	217	220	217	227	226
Ba	62	77	67	85	94	71	103	98	114	95	79
La	7	4	7	5	5	6	6	7	9	7	8
Y	26	27	29	29	28	30	30	31	30	32	32
Zr	107	115	109	109	111	97	126	129	131	124	119
Nb	6	7	7	7	7	6	7	7	7	7	7
<sup>87</sup> Sr/ <sup>86</sup> Sr		0.70384(2)		0.70393(5)	0.70372(3)		0.70451(2)		0.70434(1)		

<sup>a</sup> XRF analyses following the method of Leoni and Saitta (1977).

<sup>b</sup> Average of two determinations carried out at DST, Universities of Bologna and Pisa; other analyses at DST, University of Pisa.

<sup>c</sup> INAA following Dostal et. al., 1983 (Centre Geologique at Geophysique, Montpellier).

d AAS (CGG, Montpellier).

The reported errors on the Sr and Nd isotope-ratios are at 95% confidence level. The  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  ratios are relative to NBS987 = 0.71026(2). The  ${}^{143}\text{Nd}/{}^{144}\text{Nd}$  ratios are reported to La Jolla STD = 0.51186.

wt%) silica content, the basaltic andesite is relatively primitive as indicated by the Mg, Cr, Ni, and Co contents (Tables 1 and 4). In contrast, the Sc and V contents are low. This is reflected by the high Ti/V ratio (65-69) (Shervais, 1982) which, together with the Ti, Zr, and Y abundances (Fig. 7) indicate affinity with intraplate tholeiitic rather than orogenic calc-alkaline associations. The REE pattern (Fig. 6B), although characterized by a strong Yb and Lu depletion, is, as a whole, comparable to that of some intraplate tholeiitic series from Hawaii (Roden et al., 1984) and from Sardinia (Beccaluva et al., 1984a). The incompatible elements normalized to MORB (Fig. 11A) show in general a pattern similar to within-plate tholeiitic basalts. High field strength elements such as Zr, Hf, Ti, Y, and Yb, as well as Sc, are variably depleted relatively to these basalts. This is a peculiarity Site 654 lavas share with those produced by Plio-Pleistocene tholeiitic fissural volcanism of central Sardinia Plateau. particularly those from Campeda (Beccaluva et al., 1984a). However, the Campeda (Sardinia) basaltic andesite contains orthopyroxene phenocrysts contrary to the Site 654 rocks (Beccaluva et al., 1977).

### Isotopes

The Sr and Nd isotopic composition of one sample from Core 9 is 0.70488 and 0.51244 respectively. As this sample underwent minor seawater alteration, the measured isotope ratios might be mainly inherited from mantle source. Nevertheless, the question of crustal contamination might be evaluated before attempting detailed investigations using isotopes. In general, the observed Sr and Nd isotopic values are close to those reported for some continental basalts (Fig. 12), e.g., from the Mahabaleshwar formation (Deccan) (Cox and Hawkesworth, 1984), which are assumed to be either uncontaminated or slightly contaminated by continental crust. Furthermore, the isotopic data of sample from Site 654 overlap the field defined by the Rio Grande Rift or Walvis ridge basalts (Woerner et al., 1986).

### **SITE 655**

## **Geological Outline**

This site is located at the western edge of the Vavilov Basin, on a north-south trending ridge (Gortani Ridge), 5 km wide and 40 km long, which lies near the transition between stretched continental and inferred oceanic crust (Fig. 1).

Two holes were drilled 3290 m below sea level. The first (655A) encountered basement 79.9 mbsf and drilled it for a thickness of 10.5 m. The hemipelagic sediments change in color from pale yellow to brownish in the lowermost 6 m of the section above basement. A layer few cm thick of dark brown dolostone is found right at the contact with the basalt. The second hole (655B) was located about 15-20 m west of 655A. The basement, drilled for 116.2 m (cored for 114.9 m) down to 196.1 mbsf, consists entirely of lava flows, marked by curved chilled margins. The distribution and morphology of the chilled margins suggest that the flows are made primarily of pillow basalt and their average thickness is roughly 2 m. The age of the base of the sediments (Hole 655A) determined by biostratigraphy and constrained by the reverse magnetization of the whole basalt pile is estimated at between 3.4 and 3.6 Ma (Shipboard Scientific Party, 1987).

Moho depth of about 6 km below the seafloor (Steinmetz et al., 1983; Recq et al., 1984), and a positive magnetic anomaly of 170 gammas are consistent with the hypothesis that the Gortani Ridge represents "in situ" oceanic crust of the Vavilov basin. The location of Site 655 close to the transition with continental crust to the west suggests that the basaltic rocks recovered at this site are the record of the early stages of volcanism of the Vavilov Basin oceanic crust north of the Vavilov Seamount (Fig. 1).

### **Texture and Mineralogy**

Based on geochemistry and petrography, the basement of Hole 655B can be subdivided in four units (Fig. 13).

Unit I (five samples from Cores 1, 2, and 3): The basalt, particularly in the first two cores, contains frequent veins, fractures, and holes filled largely with carbonates and/or zeolites. Phenocrysts of plagioclase ( $An_{83-62}$ ) up to 5 mm in diameter and occasionally as corroded megacrysts, and of olivine ( $Fo_{85-82}$ ) are present in the rock. Augitic cpx is commonly confined to the groundmass, but it has been found as microphenocrysts. It may reach endiopsidic conposition (Table 7; Fig. 4). The texture is, therefore, porphyric and the rocks commonly aphanitic, except for one doleritic sample (Core 3). Although the crystal size is Table 4 (continued).

<sup>b</sup> 655-10-3 12-15	655-10-3 19-22	655-10-3 49-52	<sup>b</sup> 655-10-3 53-56	<sup>b</sup> 655-11-3 88-91	655-12-1 95-97	<sup>b</sup> 655-12-1 98-100	<sup>b</sup> 655-12-4 17-21	654-9-CC 0-04	<sup>b</sup> 654-9-CC 16-19
34			34	33		29 c28	35		16 c14
285	264	218	234	271	204	208	238	138	143
225	221	197	200	214	204 d194	188	210	273	248 d243
34			32	33		32 d <sub>32</sub>	30		38 d <sub>38</sub>
100	104	122	115	110	128	123	118	181	172
4	4	3	3	4	2	4 d2	3	7	d7
221	219	207	202	224	201	200 d199	204	478	478 d471
69	75	71	68	74	67	61	73	152	155
5	4			7	4	5	4	9	8
28	27	26	26	28	25	24	26	15	15
116	116	107	105	106	102	99	108	75	80
7	6 0.70395(2)	6 0.70375(5) 0.51309(1)	6	6	6	6 0.70375(2) 0.51311(6)	6	8 0.70488(3) 0.51244(4)	11

Table 5. REE, Th and Hf of volcanic rocks from Holes 650A, 651A, 654A, and 655B.

650-67-2 114-116	650-67-2 92-95	650-69-CC 26-29	651-44-2 140-144	651-49-1 79-81	651-53-2 120-122	654-9-CC 16-19	655-1-4 42-46	655-4-1 112-114	655-12-1 98-100
8.3	9.3	13.7	13.5	11.6	17.2	8.3	5.4	4.9	5.0
19	21	29	29.5	25.5	36.6	19.5	14.2	12.8	13.5
9.1	10.7	14.4	15.2	13.9	17.1	15.2	10.9	9.5	9.0
2.53	2.81	3.65	4.16	3.74	4.12	4.29	3.27	3.41	2.95
0.91	0.85	1.11	1.28	1.16	1.17	1.53	1.15	1.22	1.08
0.44	0.44	0.65	0.89	0.69	0.65	0.59	0.73	0.85	0.7
1.32	0.9	1.88	2.69	2.45	2.29	1.11	2.59	2.71	2.22
0.207	0.134	0.304	0.422	0.392	0.372	0.183	0.422	0.448	0.373
4.5	4.6	5.3	4.1	4.0	9.5	1.1	0.73	0.64	0.88
1.9	2.1	1.9	2.9	2.7	2.9	2.1	2.3	2.2	2.1
	650-67-2 114-116 8.3 19 9.1 2.53 0.91 0.44 1.32 0.207 4.5 1.9	$\begin{array}{cccc} 650{-}67{-}2\\ 114{-}116\\ 92{-}95\\ \end{array}\\ \begin{array}{c} 8.3\\ 9.3\\ 19\\ 21\\ 9.1\\ 10.7\\ 2.53\\ 2.81\\ 0.91\\ 0.85\\ 0.44\\ 0.44\\ 1.32\\ 0.9\\ 0.207\\ 0.134\\ 4.5\\ 4.6\\ 1.9\\ 2.1\\ \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$						

Note: Analyses carried out at the Centre Geologique et Geophysique, Montpellier, by INAA according to the methodology reported in Dostal et al. (1983).

Table 6. Microprobe analyses of	f groundmass (gm), chiller	d margin (cm), glasses (gl) of	of volcanic rocks from Holes 65	1A, 655A, 655B, and 654A.
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		Site 651					Si	te 655				Site 654
Sample	651-54-1 58-60 gl	651-44-2 20-21 gm	651-44-2 20-21 cm	655A-10-1 60-64 cm	655A-10-1 83-87 cm	655A-12-1 14-16 cm	655A-10-1 60-64 gm	655A-10-1 83-87 gm	655B-1-5 25-28 cm	655B-7-2 115-119 cm	655B-7-2 115-119 gm	654-9-4 00-04 g
SiO <sub>2</sub>	51.57	54.98	56.38	51.23	50.89	51.13	51.33	50.34	52.22	53.38	53.10	56.32
TiO <sub>2</sub>	1.29	1.34	1.36	1.40	1.34	1.35	1.35	1.43	1.45	1.56	1.36	1.56
Al <sub>2</sub> Õ <sub>3</sub>	17.71	19.15	17.02	16.97	16.90	16.97	17.50	17.49	16.54	16.27	18.47	15.33
FeO	6.65	6.70	7.47	7.67	7.87	7.83	7.33	7.52	7.77	7.74	6.86	8.14
MnO	0.13	0.14	0.14	0.16	0.17	0.15	0.13	0.17	0.15	0.14	0.16	0.10
MgO	6.40	4.59	4.79	5.80	5.83	5.82	6.12	6.51	5.90	5.23	4.54	5.49
CaO	10.82	9.13	8.21	10.06	9.90	9.90	11.31	11.59	10.00	9.28	9.86	8.45
Na <sub>2</sub> O	2.27	3.46	2.28	3.22	3.15	3.07	3.57	3.46	3.55	3.56	4.12	3.60
K <sub>2</sub> Õ	0.91	0.49	1.17	0.36	0.38	0.38	0.14	0.18	0.36	0.52	0.21	0.60
Total	97.75	99.98	98.82	96.87	96.43	96.60	98.78	98.69	97.94	97.68	98.68	99.59
.I.P.W. No	rms											
0	2.39	5.02	11.40	0.70	0.61	1.26	0.00	0.00	0.23	2.88	0.42	6.18
Or	5.38	2.90	6.91	2.13	2.25	2.25	0.83	1.06	2.13	3.07	1.24	3.55
Ab	19.21	29.28	19.29	27.24	26.65	25.98	30.21	29.28	30.04	30.12	34.86	30.46
An	35.45	35.27	32.75	30.79	30.85	31.40	31.31	31.66	28.13	26.88	31.28	23.90
Di	14.77	8.20	6.55	15.61	14.93	14.47	20.18	21.00	17.53	15.68	14.45	14.75
Hy	16.93	15.57	18.00	16.38	17.19	17.28	6.77	1.87	15.74	14.70	12.62	16.33
OI	0.00	0.00	0.00	0.00	0.00	0.00	5.62	9.76	0.00	0.00	0.00	0.00
Mt	1.27	1.28	1.43	1.47	1.51	1.50	1.40	1.44	1.49	1.48	1.31	1.56
11	2.45	2.55	2.58	2.66	2.55	2.56	2.56	2.72	2.75	2.96	2.58	2.96
DI	26.97	37.19	37.61	30.07	29.51	29.48	31.03	30.34	32.40	36.07	36.52	40.19
MgV	66.07	58.09	56.48	60.48	59.98	60.06	62.82	63.66	60.58	57.76	57.25	57.71

Table	7	. Representative micropi	obe analyses and	atomic prop	portions of clino	pyroxenes from L	eg 107	basalts.

	650-6 26	9-CC -29		651- 140	-44-2 -144				651-49-1 79-81			651-49-1 79-81
Sample	mph-c	mph-r	ph-c	ph-r	ph-ç	ph-r	mph-c	mph-r	mph-c	mph-r	mph-c	mph-r
SiO <sub>2</sub>	48.73	48.77	48.52	51.79	50.68	50.17	51.18	49.75	52.81	53.05	52.02	48.39
TiO <sub>2</sub>	1.09	0.91	1.45	0.89	0.74	0.85	0.91	1.49	0.49	0.53	0.74	1.72
Al <sub>2</sub> O <sub>3</sub>	5.36	4.97	5.24	3.11	4.65	4.89	4.61	4.86	2.66	1.86	3.03	4.40
Fe <sub>2</sub> O <sub>3</sub>	1.55	1.93	1.57	0.20	0.65	0.89	0.01	0.33	0.07	0.21	0.30	1.42
FeO	6.51	5.44	7.63	7.63	5.57	5.57	7.59	8.86	6.62	7.37	7.37	9.57
MnO	0.13	0.13	0.24	0.19	0.16	0.14	0.21	0.37	0.13	0.13	0.20	0.26
MgO	14.34	14.98	14.87	15.73	16.06	16.01	15.18	13.99	17.54	17.78	16.42	13.14
CaO	21.70	22.22	20.03	20.06	20.57	20.63	19.76	19.91	19.01	18.65	19.55	20.66
Na <sub>2</sub> O	0.39	0.34	0.41	0.32	0.35	0.32	0.34	0.36	0.25	0.24	0.25	0.44
Cr <sub>2</sub> O <sub>2</sub>	0.19	0.29	0.04	0.10	0.57	0.52	0.13	0.08	0.37	0.14	0.03	0.00
Mg#	0.65	0.68	0.62	0.67	0.72	0.72	0.67	0.60	0.72	0.70	0.68	0.55
Si	1.820	1.820	1.815	1.913	1.866	1.851	1.887	1.855	1.933	1.946	1.917	1.830
Ti	0.031	0.026	0.041	0.025	0.021	0.023	0.025	0.042	0.014	0.015	0.021	0.049
Al(IV)	0.180	0.180	0.185	0.087	0.134	0.149	0.113	0.145	0.067	0.054	0.083	0.170
Al(VI)	0.056	0.039	0.046	0.048	0.067	0.063	0.088	0.068	0.047	0.027	0.049	0.026
Fe <sup>3+</sup>	0.043	0.054	0.044	0.005	0.018	0.025	0.000	0.009	0.002	0.006	0.008	0.040
Fe <sup>2+</sup>	0.203	0.170	0.239	0.236	0.172	0.172	0.234	0.276	0.202	0.226	0.227	0.302
Mn	0.004	0.004	0.008	0.006	0.005	0.004	0.007	0.012	0.004	0.005	0.006	0.008
Mg	0.798	0.833	0.829	0.866	0.881	0.880	0.834	0.777	0.957	0.972	0.902	0.741
Ca	0.868	0.888	0.802	0.794	0.811	0.815	0.781	0.795	0.745	0.733	0.772	0.837
N	0.028	0.025	0.030	0.023	0.025	0.023	0.024	0.026	0.018	0.017	0.017	0.033
Cr	0.006	0.009	0.001	0.005	0.003	0.016	0.015	0.004	0.002	0.011	0.004	0.000
En	45.72	47.13	47.25	47.05	49.97	50.09	47.19	44.15	51.58	51.17	48.81	41.46
Fs	11.88	9.84	14.04	13.12	10.02	10.02	13.62	16.34	11.13	12.18	12.62	17.39
Wo	42.40	43.03	38.71	39.83	40.01	39.89	39.19	39.51	37.29	36.65	38.57	41.15

<sup>a</sup> Abbreviations: ph = phenocryst; mph = microphenocryst; G = groundmass; c = core; r = rim. Fe<sub>2</sub>O<sub>3</sub> calculated according to Papike (1974).

Table 8. Representative microprobe analyses and atomic proportions of plagioclase from Leg 107 basalts. Abbreviations as in Table 7.

Sample	650-66-2 115-118		650-69-CC 26-29		651-44-2 140-144		651- 79-	-49-1 -81	651- 120	-53-2 -122	655-1-5 25-28 Hole B	655 42 Ho	-1-4 -46 le B	
Sample	G	G	G	G	ph-c	ph-r	G	mph-c	mph-r	G	G	G(6)	ph-c	ph-r
SiO <sub>2</sub>	54.80	53.88	51.59	52.40	51.64	51.65	51.46	53.86	56.80	56.05	53.03	47.94	53.97	53.16
Al <sub>2</sub> O <sub>3</sub>	27.52	28.69	26.69	29.23	30.11	30.21	30.12	27.55	26.09	26.71	28.87	33.04	29.03	30.36
FeO	0.73	0.56	0.81	0.81	0.61	0.68	0.65	1.05	0.90	0.87	0.65	0.37	0.63	0.54
MgO	0.27	0.19	0.29	0.25	0.19	0.17	0.16	0.23	0.12	0.08	0.23		0.18	0.21
CaO	11.94	12.62	13.95	13.52	13.46	13.32	13.59	11.89	9.65	10.35	13.03	15.57	12.34	11.74
Na <sub>2</sub> O	4.46	3.92	3.48	3.60	3.67	3.83	3.84	4.77	6.02	5.60	3.95	2.45	3.75	3.86
K <sub>2</sub> Õ	0.15	0.09	0.11	0.13	0.28	0.09	0.11	0.18	0.31	0.26	0.16	0.03	0.06	0.07
Si	2.482	2.440	2.355	2.387	2.354	2.353	2.347	2.454	2.565	2.534	2.411		2.439	2.400
Al	1.649	1.532	1.598	1.569	1.618	1.622	1.620	1.480	1.389	1.423	1.547		1.547	1.616
Fe	0.028	0.021	0.031	0.031	0.023	0.026	0.025	0.040	0.034	0.033	0.025		0.024	0.020
Mg	0.018	0.013	0.020	0.017	0.013	0.012	0.011	0.016	0.008	0.005	0.015		0.012	0.014
Ca	0.579	0.612	0.682	0.660	0.658	0.650	0.664	0.580	0.467	0.501	0.635		0.597	0.568
Na	0.392	0.344	0.308	0.318	0.325	0.339	0.340	0.421	0.527	0.491	0.348		0.329	0.338
K	0.009	0.005	0.006	0.008	0.016	0.005	0.006	0.010	0.018	0.015	0.009		0.003	0.004
An	59.08	63.68	68.47	66.94	65.87	65.39	65.74	57.37	46.15	49.75	64.01	77.66	64.26	62.42
Ab	40.00	35.80	30.92	32.25	32.53	34.10	33.66	41.64	52.08	48.76	35.08	22.16	35.41	37.14
Or	0.92	0.52	0.60	0.81	1.60	0.50	0.59	0.99	1.78	1.49	0.91	0.18	0.32	0.44

relatively coarse, a significant amount of interstitial glassy mesostasis is present, though it is totally altered to clay minerals. Plagioclase with anorthite content from 66% to 44%, Ti-magnetite, and augitic cpx have been analyzed (Tables 7, 8, and 10).

Unit II (one sample, Core 4): This sample is chemically (see next section) and petrographically different from the other samples of Site 655. It has low modal abundances of olivine (largely replaced by Fe-hydroxides and clays) and abundant glomerophyres of co-crystallized plagioclase and poikilitic clinopyroxene. As far as phenocrysts, in this sample cpx reaches the highest abundance among the Site 655 basalts. The groundmass consists of altered glass with few microlites.

Unit III (four samples from Cores 5, 6, and 7): The samples are petrographically homogeneous. They consist of olivine (Fo<sub>82-85</sub>)

and plagioclase  $(An_{68-63})$  phenocrysts often in a glomerophyric association, and occasionally in intergrowth with minor augitic cpx (Table 7). Contrary to unit II, olivine is here dominant over cpx. The groundmass is made of altered glass. Vesicles are commonly filled with carbonates. Brecciated basaltic fragments cemented with carbonates are common in this unit.

Unit IV (nine samples from Cores 9, 10, 11, and 12): Veins and vugs are rare in this unit. The incidence of carbonate as secondary phases is minimal, and zeolites are the dominant lightcolored secondary minerals. When present, carbonates are largely confined to the amygdules and in veins and vugs associated with zeolites and red clay minerals (celadonite?), which appear to have precipitated before zeolites and carbonates. Amygdules, vugs, and veins filled only by clay minerals are also common.

651 120	-53-2 -122		655-6-1 52-54 Hole B		655 115- Hol	-7-2 -119 le B	655-10-1 83-87 Hole A	655-12-1 14-16 Hole A	654-9-CC 15-17	
G-c	G-r	mph	mph	mph	mph(2)	G(3)	mph(4)	mph(3)	G(3)	
48.19	48.56	51.48	52.50	52.27	51.12	50.97	49.26	48.70	49.51	
2.33	2.34	1.29	0.86	0.87	0.90	1.00	1.05	1.29	1.34	
6.16	6.79	4.66	3.50	3.51	3.82	4.02	4.58	5.51	3.07	
0.21	0.00	0.00	0.00	0.00						
8.67	7.72	6.83	6.28	6.43	5.80	6.58	5.85	6.18	14.65	
0.17	0.16	0.50	0.17	0.16	0.10	0.20	0.11	0.16	0.32	
11.96	11.99	14.69	15.46	15.28	16.13	16.74	16.03	15.82	13.11	
21.50	21.87	19.48	20.50	20.70	21.50	20.17	20.85	20.28	16.69	
0.48	0.38	0.32	0.32	0.28	0.29	0.29	0.32	0.31	0.44	
0.23	0.19	0.62	0.41	0.50	0.61	0.60	0.88	0.64	0.01	
0.57	0.61	0.68	0.71	0.70	0.83	0.81	0.83	0.82	0.61	
1.807	1.808	1.893	1.925	1.920	1.878	1.867	1.838	1.817	1.893	
0.066	0.065	0.036	0.024	0.024	0.024	0.027	0.030	0.036	0.039	
0.193	0.192	0.107	0.075	0.080	0.122	0.133	0.162	0.183	0.107	
0.079	0.107	0.095	0.076	0.072	0.044	0.040	0.040	0.060	0.032	
0.006	0.000	0.000	0.000	0.000						
0.275	0.240	0.210	0.193	0.197	0.178	0.202	0.182	0.193	0.469	
0.005	0.005	0.016	0.005	0.003	0.006	0.004	0.004	0.010		
0.668	0.665	0.805	0.845	0.836	0.846	0.915	0.892	0.880	0.746	
0.864	0.873	0.771	0.805	0.815	0.883	0.792	0.834	0.811	0.686	
0.035	0.028	0.023	0.023	0.020	0.020	0.020	0.023	0.023	0.032	
0.007	0.006	0.018	0.012	0.015	0.018	0.018	0.026	0.019	0.000	
39.60	40.44	47.24	47.52	46.98	46.23	47.75	46.65	46.58	39.10	
16.63	14.91	13.24	11.13	11.37	9.48	10.85	9.73	10.49	25.07	
43.77	44.64	39.52	41.35	41.46	44.30	41.40	43.63	42.94	35.83	

#### Table 7 (Continued).

### Table 8 (continued).

655-3-3 136-139 Hole B		655-6-1 52-54 Hole B		655-7-2 115-119 Hole B	655-10-3 53-56 Hole B		655-12-1 98-100 Hole B		654-9-4 04	654-9-CC 15-17		654-9-CC 16-19			
G-c(3)	G-r(2)	ph-c	ph-c	G	mph(2)	G	ph-c	ph-r	ph-c	ph-r	G(3)	G-c(3)	G-r(2)	ph-c	ph-r
50.79	52.49	52.90	53.50	54.47	51.90	54.84	47.47	50.87	50.03	51.53	55.62	53.23	55.02	53.44	53.07
30.50	29.22	29.16	29.20	28.20	30.44	27.72	32.98	30.69	31.27	30.88	26.98	29.07	27.13	29.18	29.03
0.57	0.84	0.53	0.56	0.66	0.56	0.94	0.67	0.61	0.39	0.42	0.85	0.64	0.79	0.56	0.72
		0.17	0.18	0.21		0.28	0.05	0.10	0.26	0.17				0.17	0.23
13.22	11.57	13.32	12.57	12.28	13.00	11.64	17.12	14.53	14.53	13.75	10.70	11.75	10.25	12.40	12.24
3.67	4.56	3.75	3.77	4.00	3.84	4.35	1.63	3.08	2.84	3.15	4.95	4.46	5.25	4.09	4.52
0.07	0.08	0.06	0.13	0.09	0.08	0.08	0.03	0.06	0.02	0.05	0.12	0.08	0.11	0.07	0.08
		2.403	2.423	2.464		2.482	2.184	2.322	2.287	2.341				2.421	2.411
		1.561	1.559	1.504		1.479	1.788	1.651	1.685	1.653				1.558	1.555
		0.020	0.021	0.025		0.036	0.026	0.023	0.015	0.016				0.021	0.027
		0.011	0.012	0.014		0.019	0.003	0.007	0.018	0.012				0.012	0.016
		0.648	0.610	0.595		0.565	0.844	0.710	0.712	0.669				0.602	0.596
		0.330	0.331	0.351		0.382	0.146	0.273	0.251	0.277				0.359	0.398
		0.003	0.008	0.005		0.005	0.002	0.004	0.001	0.003				0.004	0.005
66.29	58.10	66.06	64.28	62.57	64.87	59.35	85.08	71.94	73.86	70.50	54.01	59.02	51.59	62.38	59.66
33.30	41.42	33.65	34.88	36.91	34.65	40.13	14.72	27.66	26.04	39.19	45.27	40.47	47.74	37.20	39.84
0.42	0.48	0.31	0.84	0.53	0.48	0.53	0.20	0.41	0.10	0.32	0.73	0.51	0.67	0.41	0.50

Most of the samples of this unit show an intersertal groundmass, with scarce interstitial glassy mesostasis altered largely to clay minerals. Unit IV is distinct because in addition to having a high Cr content (see later section and Fig. 13), it contains corroded cpx phenocrysts, sometimes in clusters. Olivine (Fo<sub>87-86</sub>) and plagioclase (An<sub>85-60</sub>) are the dominant phenocrysts.

Dominance of olivine and plagioclase over cpx among the phenocrysts characterizes all the samples from Site 655, except those of Core 4 (unit II).

## Geochemistry

None of the samples escaped interaction with seawater. Secondary phases are carbonates, zeolites, clay minerals, and Fehydroxides. The absence of albite, chlorite, and sphene suggests that the alteration process took place at low temperature, probably below  $150^{\circ}$ -200°C (Alt et al., 1986). The effect of alteration on whole rock chemistry is difficult to evaluate, although experimental data have been obtained on element mobilization during basalt-seawater interaction at low temperature (Seyfried and Bishoff, 1979; Mottl and Holland, 1978; Menzies and Seyfried, 1979; Seyfried and Mottl, 1982). Direction and magnitude of chemical exchange depend on factors such as temperature, water/rock ratio, pH, oxidation state, degree of crystallinity, etc. These factors may change within the same structural site, for instance during the evolution of hydrothermal systems at spreading centers. Chemical exchange can be estimated by relating major element chemistry of fresh glasses to that of the associated altered whole rock, or by comparing basalts with different de-

Table 9. Representative microprobe analyses and atomic proportions of olivines from Leg 107 basalts. Abbreviations as in Table 7.

	651-44-2 20-21		651-44-2 140-144		655-6-1 52-54 Hole B		655-7-2 115-119 Hole B	655-10-3 53-56 Hole B		655-10-1 83-87 Hole A	655-12-1 98-100 Hole B		654-9-CC 15-17	654-9-CC 16-19	
Sample	(4)	ph-c	ph-r	mph	ph	ph	ph	ph-c	ph-r	mph(2)	ph-c	ph-r	ph(10)	ph-c	ph-r
SiO <sub>2</sub>	40.45	38.86	38.24	39.72	40.77	41.83	39.62	39.59	39.55	39.80	39.89	39.40	39.36	39.33	39.67
TiO <sub>2</sub>	0.01	0.00	0.04	0.04	0.00	0.01	0.00	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Al <sub>2</sub> O <sub>3</sub>	0.06	0.00	0.00	0.06	0.03	0.04	0.01	0.04	0.05	0.04	0.05	0.00	0.05	0.00	0.00
FeO	10.97	17.15	17.53	16.42	16.71	13.76	16.50	13.45	13.41	16.22	12.75	12.58	19.96	16.37	16.85
MnO	0.18	0.17	0.19	0.18	0.22	0.21	0.27	0.21	0.23	0.31	0.15	0.20	0.18	0.21	0.19
MgO	48.36	43.36	43.59	43.02	41.89	43.79	44.10	46.27	46.21	44.21	46.66	47.24	44.47	43.60	43.86
CaO	0.22	0.16	0.16	0.26	0.14	0.21	0.17	0.29	0.30	0.29	0.28	0.31	0.19	0.21	0.20
Cr2O2	0.08	0.07	0.03	0.07	0.06	0.04	120/010101	0.00	0.04	-	0.05	0.09	-	0.08	0.04
NiÕ	-	0.24	0.23	0.22	0.16	0.10		0.13	0.19	—	0.18	0.19	-	0.20	0.17
Si	0.994	0.988	0.976	1.005	1.029	1.039	0.995	0.989	0.989	0.996	0.993	0.982	0.991	0.996	1.005
Ti	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	0.001	0.000	0.000	0.002	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.000	0.001	0.000	0.000
Fe	0.225	0.365	0.374	0.347	0.353	0.286	0.347	0.281	0.280	0.340	0.265	0.262	0.336	0.346	0.357
Mn	0.004	0.004	0.004	0.004	0.005	0.005	0.006	0.004	0.005	0.006	0.003	0.004	0.039	0.004	0.004
Mg	1.771	1.644	1.658	1.622	1.575	1.621	1.651	1.723	1.722	1.650	1.731	1.755	1.669	1.645	1.618
Ca	0.005	0.004	0.004	0.007	0.004	0.006	0.005	0.008	0.008	0.007	0.008	0.008	0.051	0.006	0.006
Cr	0.001	0.001	0.001	0.001	0.001	0.001		0.000	0.001	_	0.001	0.002		0.002	0.001
Ni	_	0.005	0.005	0.005	0.003	0.002		0.003	0.004	-	0.004	0.004	—	0.004	0.004
Fo	88.55	81.83	81.59	82.36	82.01	85.01	82.41	85.97	86.00	82.65	86.71	87.00	83.07	82.60	81.93

Table 10. Microprobe analyses of oxides from Leg 107 basalts.

		655-3-3
	641-44-2	115-119
	20-21	Hole B
Sample	sp(2)	mt
Al <sub>2</sub> O <sub>3</sub>	23.10	2.21
TiÕ <sub>2</sub>	0.88	15.98
Fe2O2	6.49	36.50
FeO	14.39	44.30
MnO	0.00	0.53
MgO	14.58	1.07
Cr <sub>2</sub> O <sub>3</sub>	41.49	0.05
Al	6.559	0.096
Ti	0.159	0.442
Fe <sup>3+</sup>	1.177	1.011
Fe <sup>2+</sup>	2.901	1.363
Mn	0.000	0.016
Mg	5.236	0.058
Cr	7.904	0.002
Mg#	0.64	
Cr#	0.55	

grees of petrographic alteration but belonging to the same flow unit. In this latter case, trace element mobility can also be evaluated.

In terms of normative mineralogy, alteration produces undersaturation of the whole rock relative to fresh glasses both as chilled margin and groundmass interstitial mesostasis (Fig. 14A). Data are only available for units I and III. Alteration of glassy groundmass produces a strong decrease of silica and an increase of  $K_2O$  and LOI. Na<sub>2</sub>O shows erratic variations probably due to presence of zeolites. CaO enrichment appears to be largely dependent on carbonates, which are abundant in most of the altered samples.

The effect of these alteration processes is the appearance of nepheline in the CIPW norms of basalts, which originally should be either slightly qz-normative or weakly olivine normative (Fig. 14A). The appearance of nepheline depends to a large extent, on rock crystallinity. All samples with glassy groundmass are ne-normative together with two rocks from Cores 9 and 11, where alteration is so advanced that plagioclase is replaced largely by carbonate and zeolites. The samples with small amount of altered interstitial glass and fresh plagioclase 1-4 (42-46 cm), 10-3 (49-52 cm), and 10-3 (53-56 cm) appear to have suffered minor silica mobilization which is reflected in an olivine-hypersthene normative character.

We note that fresh chilled margins are all slightly qz-normative whereas groundmass glasses show a variable normative character (Table 6; Fig. 14A). These fresh glasses from Site 655 are within the range of MORB glasses (Melson et al., 1976). However, the rocks with altered glassy groundmass (Fig. 42A) fall outside the range of normal, transitional, and plume-type MORB from Atlantic Ocean (Schilling et al., 1983), probably because of silica loss during alteration.

Alteration processes caused stronger element mobilization in the upper part of the Site 655 sequence than deeper into the hole. Alteration-related increase of the concentration of CaO, Na<sub>2</sub>O, Rb, Ba, and decrease of SiO<sub>2</sub> and MgO content, are the strongest in unit I (Fig. 13). Sr does not appear to be significantly affected, as found also by Hart et al. (1974) in a study of seafloor weathering of basalts. P<sub>2</sub>O<sub>5</sub> and Na<sub>2</sub>O appear to be mobile but their variations are erratic (Fig. 13). Ti, Zr, Y, Nb, Cr, and V, which show no change outside the experimental error, appear to have been virtually immobile during the low temperature alteration suffered by unit I samples. Similar consideration can be applied to unit III, which consists of basalt with altered glassy groundmass.

The least altered samples of the entire 655B sequence are from two unit IV lava flows (10-3, 49-52 cm/55-56 cm and 12-1, 95-97 cm/98-100 cm). Except for LOI and Fe<sup>++</sup>/Fe<sup>+++</sup>, they have retained a major element chemistry comparable to that of some fresh glasses of unit I (Tables 2 and 6). All the analyzed elements within the same flow unit show variations which are within the experimental error, arguing against small scale elemental mobilization (Fig. 13). Comparison with other more altered lavas from unit IV suggest chemical changes comparable to those of unit I, with decrease of SiO<sub>2</sub> and increase of CaO. Mobilization of Na, K, Rb, Ba, if any, was very small throughout unit IV. Variations of P, Ti, Zr, Y, V, and Mg in this unit are compatible with magmatic processes, except for one sample (Core 11).

In conclusion, it appears that Ti, Zr, Y, Nb, V and probably Cr, Sc, Co and Ni, and Sr were not significantly modified by the low temperature alteration suffered by most of the Site 655 samples. Therefore, we have used these elements, in addition to REE,



Figure 2. Simplified igneous stratigraphy of Hole 650A with some geochemical parameters of analyzed samples.

Th, and Hf of the least altered samples, to determine the magma types of the lavas drilled at this site. The Ti, Zr, Y, and Sr distribution (Figs. 7 and 8) indicates a close affinity with MORB for the whole Site 655 basalt sequence. The incompatible and REE patterns of three representative samples (Fig. 11B) suggest their affinity with transitional rather than normal MORB (Pearce, 1982; Sun et al., 1979; Le Roex et al., 1983; Schilling et al., 1983). The three selected basalts are less light REE enriched relative to high-Ti and low-Ti groups of Site 373 (Barberi et al., 1977). If the whole incompatible element pattern is considered (Fig. 11B), Site 655 basalts are compositionally closer to the high-Ti group rather than the low-Ti group of Site 373, particularly for Sm, Ti, Y, Yb, and Sc. It should be noted that Th/Nb

or (Th/Ta) ratios of Site 373 and 655 basalts are higher than typical transitional MORB (Fig. 10 and 11B). This is a common feature of back-arc basin basalts (Sounders and Tarney, 1984) and has been ascribed, particularly for the low-Ti group Site 373 basalts, to a slight enrichment in subduction zone components of their mantle source (Beccaluva et al. 1982). One sample of unit II shows Zr/Y, Zr, Ti, La, Sm, and Ti/Y lower than the other Site 655 basalts, and REE patterns with a slight depletion of La relative to Sm, indicating that this sample more than any other Tyrrhenian sea basalt (Fig. 6B), approaches normal MORB.

None of the samples from Site 655 represent unmodified mantle melts. Mg# is rather constant ( $60 \pm 3$ ) in the upper three



Figure 3. Plagioclase (An-Ab-Or mol%) and olivine (Fo-Fa mol%) plots of Leg 107 basalts. Arrows indicate compositional zoning from core to rim.

units and varies between 65 and 45 in the lower unit. Here Ti, P, Zr, Y, V, and Sr correlate positively with Mg whereas Ni correlates negatively with it (Fig. 13). This could be explained by olivine-dominated crystal fractionation, though other geochemical tracers, as the  $P_2O_5$  content or the variability of the Sr isotopic composition, indicate that alteration processes are superimposed on simple fractional crystallization. The variation of Ti, Zr, Y, V, Sr, Ni, and Mg# with depth in unit IV can be qualitatively interpreted with a model involving at least two episodes of mixing between primitive and fractionated magmas in a reservoir, followed by olivine-dominated fractionation. Open system fractionation of the type suggested here for unit IV is the dominant process for the formation of oceanic crust at accreting plate margins both in mid-oceanic ridges and back arc basins.

### Isotopes

The Sr isotopic composition of eight samples from Hole 655B ranges between 0.70372 and 0.70451. No clear correlation is observed between the Sr isotope ratio and the sub-bottom depth of these rocks; all the samples from units I, II, and IV show approximately the same range of Sr isotopic composition, while two samples from Cores 5 and 6 have a higher and relatively similar <sup>87</sup>/<sup>86</sup>Sr ratios (0.70451). Different degrees of interaction with seawater might have produced an increase of the <sup>87</sup>/<sup>86</sup>Sr ratios. However, some geochemical tracers of seawater interaction, like the alkalis, do not correlate with the Sr isotopic composition, suggesting that the elemental fluxes between seawater and basalt probably followed different directions under



Figure 4. Clinopyroxene (Wo-En-Fs mol%) of Leg 107 basalts. Arrows indicate compositional zoning from core to rim.



Figure 5. Clinopyroxene (Ti vs. Ca + Na mol%) of Leg 107 basalts after Leterrier et al. (1982).

changing conditions. With the exception of two samples from unit III, the increase of Sr isotope ratio is well correlated with decreasing silica and increasing CaO contents (Fig. 15A, -B). This is in agreement with the previously reported effect of seawater alteration, i.e., silica decrease in the groundmass, and carbonate precipitation.

In order to evaluate the pristine isotopic features of the source(s) of these magmas, two samples with the lowest <sup>87</sup>/<sup>86</sup>Sr

ratios were analyzed for Nd isotopes. The values range from 0.51309 to 0.51311 and are identical within the analytical uncertainties. Assuming that low temperature seawater interaction does not affect the Nd isotopic composition, the observed values suggest a possible MORB-like source for these samples (Fig. 12).

## **SITE 651**

### **Geological Outline**

This site is located on the eastern flank of a basement swell which bisects the Vavilov basin north of Vavilov seamount (Fig. 1). The basin is floored by oceanic-type crust with Moho depth less than 8 km (Steinmetz et al., 1983; Recq et al., 1984).

Drilling of Hole 651A started at a water depth of 3578 m; the basement was encountered 386.5 mbsf. Two basalt units have been identified: unit 1, upper basalt, 78 m thick down to 464 mbsf; and unit 3, lower basalts and basaltic breccias, 30 m thick, from 492 to 522 mbsf. Both units consist of several lava flows of basaltic composition, with low degree of vesicularity, and carbonates in veins and as breccia cement. Between unit 1 and 3, from approximately 464 to 492 mbsf, there is a complex unit (unit 2) which consists predominantly of dolerite, metadolerite, and coarse-grained albitite. This unit represents probably intrusives basaltic sills or dikes. One sample taken from the lower part of unit 1 is a dolerite (49-1, 136–138 cm) in close contact with one piece of leucocratic albitite. This sample is probably part of unit 2.

Directly above the basement a 40-m-thick unit has been recovered (basal sediments, 348-388 mbsf) of metalliferous dolostone which is overlain by fossiliferous sediments with foraminiferous/nannoplancton age about 2 Ma. *Globorotalia crassaformis*, tentatively identified in the carbonate cement of a breccia at 465 mbsf, suggests an age of about 3.1 Ma of the breccia right below the basaltic lava flows of unit 1 (Shipboard Scientific Party, 1987).

The lower unit (unit 4) of the Site 651 section consists of serpentinized harzburgitic peridotites (522–551 mbsf) with tectonitic fabric, which are described elsewhere (Bonatti et al., this volume).



Figure 6. Chondrite normalized (Taylor and Gorton, 1977) REE abundances in selected samples from Holes 650A and 651A (A) and Holes 655B and 654A (B). Data from Table 5. In **B**, two basalts of the high-Ti and low-Ti group from DSDP Leg 42A, Site 373A (Barberi et al., 1977) and basaltic andesite from the Campeda Plateau (Sardinia; Beccaluva et al., 1984a) are also reported.



Figure 7. Ti-Zr-Y diagram. Field A, island arc tholeiites; field B, island arc tholeiites, ocean floor basalts, calc-alkaline basalts; field C, calc-alkaline basalts; field D, within-plate basalts (after Pearce and Cann, 1973). The arrow indicates the alteration trend of adjacent samples (Core 67) deduced from petrographic observations.

## **Texture and Mineralogy**

Only seven samples from 4 cores out of 14, where basaltic igneous rocks were recovered, have been thoroughly investigated for this report. This allows only an overview of mineralogical, petrographical, and geochemical variations with depth.

The samples of the upper basalt (unit 1) are mineralogically and geochemically (see later section) distinct from those of the lower basalt (unit 3). Distinct mineralogical features of the lower basalt unit (Core 53) are the occurrence of laths of primary brown amphibole in the groundmass, and cpx close to salitic composition, in contrast to augites in the unit 1 basalts of Cores 44 and 49 (Fig. 4; Table 7). This suggests a weak alkaline tendency of the magma of the lower basalt unit (Fig. 5). In general, Site 651 samples show subaphyric texture with microphenocrysts of altered olivine and highly zoned plagioclase and cpx set in an intersertal groundmass with minor altered glass, except Sample 44-2 (108-111 cm) where some relict patches of petrographically fresh glass have been identified. Groundmass minerals are very elongated. Olivine occasionally reaches chain-type morphology (Lofgren, 1979). In the other samples from Cores 44 and 46, the same microphenocrysts are set in altered glassy groundmass with scattered microlites, largely plagioclase. Secondary minerals include in the upper unit clay minerals, zeolites, Fe-hydroxides, and minor carbonates. Plagioclase and cpx are generally well preserved, particularly in the rocks with glassy groundmass.

Amygdules are generally filled with zeolites and/or clay minerals; rarely by calcite. These features suggest basalt-seawater interaction at low temperature. However, the occurrence of abundant chlorite, talc, and minor actinolite, in the upper core of unit 3 basalt indicate that these rocks also suffered metamorphism under lower greenschist facies (Elthon, 1981; Alt et. al., 1986). Relicts of olivine (Fo<sub>89-82</sub>) have been identified only in



Figure 8. A. Ti-Zr-Sr diagram for plate margin volcanism. Fields: A, island arc tholeiites; B, calc-alkaline basalts; C, ocean floor basalts. B. Ti-Zr diagram for plate margin volcanism. Field A, island arc tholeiites; field C, calc-alkaline basalts; field D, ocean floor basalts; field B, all three magma types (After Pearce and Cann, 1973).

Core 44 (Table 9; Fig. 3). One crystal of chromite was also analyzed (Table 10). Cpx is well preserved whereas plagioclase is partly replaced by secondary minerals. Plagioclase composition from An<sub>72</sub> to An<sub>46</sub> have been found among microphenocrysts (Table 8) of the upper unit 1 and An<sub>64-50</sub> in those of the lower unit 3 basalt (Core 53). Cpx composition of the basalts of the lower unit 3 (Table 1) shown in Ti vs. Ca + Na diagram (Fig. 5), suggests an alkaline tendency for the magmas of unit 3, whereas those of the upper unit 1 fall largely in the field of subalkaline magmas where cpx from volcanic arc tholeiites and calc-alkaline magmas, mid-ocean ridge basalts, and within-plate tholeiites overlap. A dolerite, probably a pebble, found at the base of the basaltic lava sequence of unit 1, is holocrystalline phaneritic. The texture tends to be subophitic with euhedral, unaltered, highly zoned cpx, locally poikilitic, with rims partly altered to actinolite. Patches of chlorite-actinolite aggregates are probably pseudomorphs after olivine. Fe-Ti oxides are partly replaced by sphene. Minor amounts of biotite, partly altered to chlorite, and quartz are found interstitially. Locally biotite appears to grow on the rim of cpx. Biotite and interstitial quartz are also present as primary phases. Secondary phases such as actinolite, chlorite, and sphene are in equilibrium with calcic plagioclase and indicate that the dolerite was subjected to hydrothermal metamorphism which took place at relatively high temperature, close to the transition of upper greenschist facies to lower actinolite facies (Elthon, 1981). This dolerite belongs to the doleritealbitite intrusive sequence of unit 2.

### Geochemistry

As all the samples have suffered a variable degree of hydrothermal alteration, the interpretation of their chemistry must be done with care. Two samples from the lower basalt unit (Core 53) with the range of elemental concentrations almost within the experimental error for all the analyzed elements, suggest that the metasomatic changes induced by the hydrothermal metamorphism were in this instance homogenous on a small scale. This is not the case for two samples of Core 44 spaced 30 cm apart and probably belonging to the same flow unit despite their different texture (vitrophyric vs. intersertal). Variations outside the experimental error of major element concentrations and of Rb, Ba, and V (Fig. 16) suggest alteration-dependent small scale inhomogeneity, probably favored by the different degree of crystallinity of the samples. In the sample with altered glassy groundmass 44-2 (140-144 cm) corundum appears in the norm. Comparison with fresh glass about 1 m above in Core 44 (Table 6) indicates a strong loss of CaO and large increase of Mg and Na. This is the case also for other samples with altered glassy groundmass (Core 46).

As in Site 655 basalts, chemical exchange with seawater is most severe in samples which originally were made largely of glass. However, the effect of alteration on CaO and MgO is opposite in the two sites. Since CaO is depleted during basalt seawater interaction within a wide range of thermal and chemical conditions, the enrichment of this element in the glassy samples of Site 655 is probably due to late precipitation of carbonate. This process has not occurred at Site 651, where amygdules are mostly filled by clay minerals and/or zeolites. The opposite behavior of Mg in Sites 651 and 655 basalts could be explained by basalt-seawater interaction at different temperatures, higher for Site 651 resulting in Mg depletion (Bonatti, 1970; Sevfried and Bischoff, 1979). Secondary minerals indicate that basalt-seawater interaction within similar depths below the basalt/sediment interface took place at higher temperature in Site 651 than in Site 655. This suggests a higher geothermal gradient at Site 651, induced perhaps locally by the injection of doleritic sills or dikes such as those represented by unit 2.

The normative Ne-Ol-Di-Hy-Qz diagram (Fig. 14B) shows the alteration processes produced a slight silica undersaturation of lavas which were originally slightly Qz-normative, as indicated by the fresh glass analysis (Table 6; Fig. 14B). The alteration trends are also in this case strongly dependent on the degree of crystallinity. The loss of Ca in the two samples with the altered glassy groundmass were so severe as to result in absence of normative diopside. Crystalline samples are less altered, and rocks with intersertal texture contain remnants of interstitial glass (Table 6). The mobility of minor and trace elements which show small scale dishomogeneous distribution, such as  $TiO_2$ ,  $P_2O_5$ , Rb, Ba, Sr, and V (Fig. 16) is more difficult to evaluate. Assuming that the original compositions of the two adjacent samples from Core 44 lava were similar, it appears that Ti, P, K, Rb, Ba,



Figure 9. N-MORB normalized trace element patterns of selected basalts from Sites 650 (A) and 651 (B). Data from Table 5. The most primitive calc-alkaline basalts from Santorini, Aegean Arc (Innocenti et al., 1981) and a high-K basaltic andesite from Stromboli, Eolian arc (Rosi and Serri, unpubl. data) are reported as reference for Mediterranean ensialic island arc calc-alkaline volcanism.

and V are depleted in the most altered samples. Whether or not  $K_2O$  is effectively removed by alteration in the upper basalt unit is critical for the interpretation of the petrogenetic affinity of the section. Experimental data show that the direction of  $K_2O$  mobility in basalt-seawater interaction is strongly dependent on temperature. All experiments performed at temperature greater than 150°C show that  $K_2O$  is efficiently removed from the basalt, while the reverse is true at 70°C (Seyfried and Bischoff, 1979; Seyfried and Mottl, 1982). The observed alteration trend (Fig. 16) suggests water-rock reactions at temperatures greater

than  $140^{\circ}-150^{\circ}$ C. In conclusion, we will not take into consideration the two rocks with the glassy groundmass 44-2 (140–144 cm), 46-1 (78–80 cm) in evaluating the affinity of the original magma types because here mobilization has involved elements, such as Ti or V, commonly assumed immobile during hydrothermal metamorphism. Therefore, the original petrogenetic affinity of Site 651 basalts will be evaluated only on the basis of samples with intersertal groundmass (44-2, 108–111 cm, 49-1, 79–81 cm, 53-2, 114–116 cm/120–122 cm). The most striking geochemical feature of these samples is a relatively high K<sub>2</sub>O



Figure 10. Th/Zr vs. Nb/Zr diagram (after Beccaluva et al., 1984b). Intraplate/mid-ocean ridge and convergent plate margin volcanism are clearly discriminated. Lipari high-K calc-alkaline andesites (Kiels et al., 1978); Filicudi, high-K calc-alkaline basaltic andesites and andesites (Villari, 1980); Stromboli, high-K calc-alkaline and shoshonitic basalts as well as leucite-tephrites (Dupuy et al., 1981; Rosi and Serri, unpubl. data); Santorini, calc-alkaline basalts and andesite (Mitropulos et al., 1987), Leg 42, basalts (Barberi et al., 1977; Hamelin et al., 1979). NM and EM, normal and enriched MORBs respectively (Sun, 1980). N-MORB, typical normal MORB used as normalizing values in diagram of Figure 9 (cf., Pearce, 1983). Where not detected Nb was calculated from Nb/Ta in primordial mantle of Wood (1979). Other symbols as in Figure 7.



Figure 11. N-MORB normalized trace element patterns of Site 654 (A) and Site 655 (B). Typical compositions of within-plate tholeiitic and alkali basalts and normal and transitional MORB are from Pearce (1982). Campeda basaltic andesite (Sardinia) is from Beccaluva et al. (1984a).

content, except for the dolerite (Table 1). Several lines suggest that the original magmas of the basalts from Site 651 were more potassic (and more alkaline, Core 53) than those drilled at the other sites (655 and 373) of the Vavilov basin. Plagioclase of Site 651 is slightly but significantly richer in orthoclase molecule at the same anorthite content (Fig. 3). This indicates a greater  $K_2O$  content in the melts as confirmed by fresh glass analysis ( $K_2O = 0.49\%$ -1.17% for Site 651 vs.  $K_2O = 0.14\%$ -0.52% for Site 655). Relicts of biotite largely altered to chlorite in the dolerite suggest  $K_2O$  leaching during the greenschist facies metamorphism of the dolerite itself (Seyfried and Mottl, 1982).

Normative composition of the fresh glasses argues for a silica saturation or minor silica undersaturation of the original magmas (Cores 44 and 54). Cpx chemistry and groundmass brown amphibole, show a weak alkaline tendency in Core 53 basalts. Accordingly, the relatively high  $K_2O$  content (2.18%–2.37%) does not contrast with the relict mineralogy. Cpx chemistry of unit 1 lavas (Table 7; Fig. 5) argues for a subalkaline nature of the original magmas. In terms of the Ti, Zr, Y, and Sr ratios (Figs. 7 and 8), the magmas from Site 651 are intermediate between MORB and calc-alkaline basalts. Incompatible elements patterns indicate a close affinity to converging plate margin volcanism (Fig. 9), particularly in Core 53; closely comparable mag-



Figure 12. <sup>87</sup>Sr/<sup>86</sup>Sr vs. <sup>143</sup>Nd/<sup>144</sup>N "mantle array" correlation diagram. Samples from Hole 655 overlap the field defined for some altered MORBs (Bor Ming et al., 1980). One sample from Hole 651A shows Sr and Nd isotope ratio close to those defined for Grenada arc volcanics (Lesser Antilles; Hawkesworth et al., 1979), and Nd isotope ratios in the range of some oceanic islands. One sample from Hole 654A plots close to the field of some continental basalt (e.g., Mahabaleshwar, Deccan; Cox and Hawkesworth, 1984). In the same diagram are also reported the fields postulated for mantle sources of Parana' flood basalts (Petrini et al., 1987). Other references are taken from Zindler et al. (1984).

mas are found in Mediterranean island arcs (Stromboli high-K calc-alkaline basaltic andesites and Santorini basalts; Fig. 12). The close similarity between Stromboli and Site 651 (Core 53) lavas, also for low field strength elements such as Ba, Rb, K, and Sr, argues for igneous rather than alteration dependent patterns. The relative distribution of refractory elements such as Th and Nb normalized to Zr (Fig. 9) confirms a close affinity of Site 651 lavas with orogenic volcanism in particular with the high-K calc-alkaline and calc-alkaline series from the Eolian arc (Beccaluva et al., 1982). We note that a Ti-negative anomaly is absent in Site 651 lavas, in contrast to the Eolian Arc magmas. A relatively high TiO<sub>2</sub> content (between 1.3% and 1.6%) is relatively common in calc-alkaline basalts from western U.S. and the Andes (Ewart, 1982).

The basalts of unit 3 (Core 53) and unit 1 (Cores 44, 46, and 49) represent slightly evolved basaltic products from distinctly different magma types. In addition to the mineralogy discussed earlier, the more alkaline character of unit 3 lavas relative to unit 1 lavas is suggested also by higher Zr/Y (Table 3), Th/Nb (Fig. 10), La/Sm, and Tb/Yb ratios which result in crossing REE patterns (Fig. 6A). Mineralogy and glass chemistry suggest a subalkaline nature for unit 1 magmas.

In conclusion, at least two separate magma types with incompatible element affinity to K-rich calc-alkaline/calc-alkaline magmas from the Eolian Arc have been identified among the all Hole 651A lava flows. Higher bulk TiO<sub>2</sub> content than Eolian Arc lavas, and cpx chemistry, particularly in Core 53, suggest a tendency towards alkaline magmas, which appears to be of potassic lineage given the high  $K_2O/Na_2O$  ratio of the rocks and of the plagioclase.

### Isotopes

The Sr isotopic composition of three samples from Hole 651A, ranges from 0.70438 to 0.70733. The <sup>143/144</sup>Nd, measured in one sample (49-1, 136–138 cm) gave a value of 0.51294. The Sr isotopic composition correlates with the Rb and K content indicating that either the radiogenic Sr content has been modified by basalt/seawater interaction, or it reflects the pristine isotopic composition of the mantle source. As the Nd isotope ratio in not greatly affected by seawater alteration, the measured value indicates a time-integrated LREE chondrite-depleted mantle source. The Nd isotopes do not discriminate between different geotectonic settings (Fig. 12). Furthermore, the time-integrated nature of the source of these magmas, as inferred from Nd iso-

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Figure 13. Simplified igneous stratigraphy of Hole 655B with some geochemical parameters of analyzed samples.



Figure 13 (continued).



Figure 14. Ne-Ol-Di-Hy-Qz normative diagram for whole rock and glass analyses from Holes 655A and 655B (A) and Hole 651A (B).

topes, is in apparent contrast with the enriched nature indicated by the Sm/Nd ratios of rocks from this site (Sm/Nd = 0.195). As it appears that the REE were not significantly affected by seawater interaction processes, this would imply a relatively recent enrichment of LREE in the source region.

## CONCLUSIONS

The data obtained from basaltic rocks drilled during ODP Leg 107, together with data from DSDP Site 373 and from rocks dredged at various sites in the Tyrrhenian Sea, lead to the following conclusions:

1. Site 654 basaltic andesite from the Sardinia margin is similar in petrochemistry and inferred age of eruption (around 1.8 Ma) to Plio-Pleistocene tholeiitic lavas from Sardinia, which show an intraplate affinity. This is consistent with an origin of Site 654 rocks by basaltic injections related to extension of the east Sardinia margin some 5 Ma later than the rifting phase (upper Tortonian-Messinian).

2. Site 650 basalt from the Marsili basin though strongly altered, appears to have calc-alkaline affinity. The most recent activity of the Marsili seamount produced also calc-alkaline lavas (Selli et al., 1977). The degree of vesicularity of the Site 650 lavas indicates that the Marsili basin has been affected, since 1.7-1.9 Ma, by strong subsidence of about 1 mm/yr (Pareschi et al., in press).

3. Basalts from Sites 655 and 651, both from the Vavilov basin, show contrasting petrology. Site 655 rocks have affinity with transitional MORB similarly to lavas drilled at DSDP Site 373 (Barberi et al., 1977). Site 651 drilled two distinct basalt units, showing affinity with high-K calc-alkaline/calc-alkaline lavas prevalent in the Eolian Arc.

4. The general petrogenetic affinity ranging from transitional MORB (Site 655 and DSDP Site 373) to calc-alkaline and high-K calc-alkaline orogenic basalts (Sites 650 and 651) is consistent with the back arc setting of the Vavilov and Marsili basins. Accordingly, the DSDP Site 373 and ODP Sites 650, 651, and 655 lavas can be defined as back arc basin basalts. Indeed, available data on volcanic rocks from back arc basin floored by oceanic crust show that magma types ranging from MORB to island arc

basalt, both with tholeiitic and calc-alkaline nature, are well represented (cf., Saunders and Tarney, 1984). The calc-alkaline/ high-K calc-alkaline component is more marked in magmas erupted in ensialic basins floored by oceanic crust such as Bransfield Strait (Antarctica) and Tyrrhenian Sea.

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Date of initial receipt: 5 April 1988 Date of acceptance: 10 February 1989 Ms 107B-140



Figure 15. A. Silica vs.  ${}^{87}$ Sr/ ${}^{86}$ Sr diagram for samples from Site 655. Excluding two samples from unit III, a general inverse correlation is observed between the SiO<sub>2</sub> (recalculated on a water-free basis) and the Sr isotopic composition. B. CaO vs.  ${}^{87}$ Sr/ ${}^{86}$ Sr diagram; samples with the higher Sr isotopic composition show the higher CaO content (CaO recalculated on a water-free basis).



Figure 16. Simplified igneous stratigraphy of Hole 651A with some geochemical parameters of analyzed samples.



Figure 16 (continued).