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THE ORIGIN OF COMPLEX MANTLING RELATIONSHIPS IN CLINOPYROXENE FROM THE NEW ENGLAND SEAMOUNTS

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ABSTRACT

Electron-microprobe data are reported for clinopyroxenes in basanites and tephrites recovered by the Deep Sea Drilling Project from the New England Seamounts, western North Atlantic. Many of the larger phenocrysts show multiple zoning, with partial resorption indicating a complex petrogenetic history. High $^{VI}Al/^{IV}Al$ values suggest that cores of pyroxene phenocrysts of both Al–Ti augite and a diopside with an iron-rich salite composition are of high-pressure origin. Augite and titanian salite occur as rims on the phenocrysts and as microphenocrysts; these pyroxenes show low-pressure characteristics. Origin of the phenocrysts by disaggregation of mantle xenoliths or by crystallization from highly-evolved, alkaline magmas is inconsistent with the mineral chemistry of the iron-rich salites. The occurrence of an iron-rich salite core in Al–Ti augite and *vice versa* suggests alternating conditions of crystallization, perhaps due to circulation within an inhomogenous magma chamber.

Keywords: clinopyroxene, New England Seamounts, basanite, tephrite, mantling.

SOMMAIRE

On décrit, au moyen de données obtenues par microsonde électronique, le clinopyroxène des basanites et tephrites prélevées des guyots de la Nouvelle-Angleterre, lors du projet de forages sous-marins (DSDP) dans la partie occidentale de l'océan Atlantique-nord. Plusieurs des plus gros phénocristaux possèdent une zonation composée et manifestent une résorption partielle, indications d'une évolution pétrogénétique compliquée. Des valeurs élevées du rapport $^{VI}Al/^{IV}Al$ font penser que les noyaux de phénocristaux de pyroxene de chacun d'augite riche en Al–Ti et un diopside au composition salite riche en fer ont une origine à haute pression. Augite et titansalite forment un liseré autour des phénocristaux, ainsi que des microphénocristaux; ces compositions sont typiques d'une cristallisation à basse pression. Une origine des phénocristaux par désagrégation d'enclaves de roches du manteau ou par cristallisation d'un magma alcalin très évolué ne concorde pas avec le chimisme de la salite ferrifère. La présence d'un noyau de salite ferrifère dans une augite riche en Al et Ti et *vice versa* serait plutôt le résultat d'une cristallisation en alternance, peut-être due à une circulation dans une chambre magmatique hétérogène.

(Traduit par la Rédaction)

Mots-clés: clinopyroxène, guyots de la Nouvelle-Angleterre, basanite, tephrite, surcroissance.

INTRODUCTION

On Leg 43 of the Deep Sea Drilling Project, the flanks of two volcanoes of the New England Seamount Chain were drilled (Fig. 1). Both drillholes bottomed in mafic volcaniclastic breccias apparently deposited as debris flows from the crest and sides of the seamounts in penecontemporaneity with the volcanism (Tucholke, Vogt *et al.* 1979). At Nashville Seamount (Site 382), the volcanic rocks are overlain directly by Campanian sediments; at Vogel Seamount (Site 385), the volcanic rocks are overlain by unfossiliferous sediments of Maestrichtian or older age.

Houghton (1979) described five types of basalt from Sites 382 and 385. Type 1 has clinopyroxene and olivine phenocrysts in a groundmass of plagioclase and augite. In type 2, large hornblende phenocrysts are present, but olivine is absent. Type 3, the most common, has plagioclase, clinopyroxene, hornblende and minor kaersutite phenocrysts. Type 4 is devoid of phenocrysts and is highly altered. Type 5, known from a single sample, has olivine and minor plagioclase phenocrysts. Types 1 to 4 appear to be alkaline mafic rocks, whereas type 5 is a tholeiite enriched in large-ion lithophile elements (LILE). All five types are represented at Site 382, whereas basalts at Site 385 consist entirely of types 3 and 4.

Complexly zoned, phenocrystic pyroxene is widespread in these rocks. In this paper we describe the pyroxene, interpret its petrogenetic significance, and discuss the origin of the zoned pyroxene phenocrysts. The pyroxene terminology used in this paper follows that of Deer, Howie & Zussman

(1978). Note that, in nomenclature accepted by the International Mineralogical Association, salite is a variety of diopside.

Sample material

Six mafic clasts from volcaniclastic breccia beds have been studied petrographically and geochemically. Three samples are from Site 382, core 25-2, at 519 m below sea floor; three are from Site 385, core 23-1, at 378 m below the sea floor. Some of the same core samples were examined in thin section by Houghton (1979), but none corresponds to samples for which he reported whole-rock chemical data.

Petrography

The samples studied from Site 382 are breccias of vesicular lava and hyaloclastite cemented by calcite and zeolites. The mineral phases in the lavas and hyaloclastites are similar, suggesting that both groups are genetically related. The groundmass is pilotaxitic or subtrachytic and consists of feldspar microlites (average $Or_2Ab_{30}An_{68}$), clinopyroxene, olivine and titaniferous magnetite. Subhedral large phenocrysts of clinopyroxene, typically 4–5 mm in length (maximum 7 mm), make up 5 to 20% of the rock. Most of these phenocrysts contain magnetite and kaersutite inclusions. Olivine (some with sieve texture or iddingsitized), rare titaniferous magnetite, and rare kaersutite also occur as phenocrysts. All these minerals, except kaersutite, are also found as microphenocrysts. Although these samples correspond to three of Houghton's types (1, 2 and 3), particular minerals show no difference in chemistry from one type to another.

Samples from Site 385 are vesicular lavas with phenocrysts of colorless clinopyroxene and microphenocrysts of purplish brown clinopyroxene and titaniferous magnetite in a groundmass of randomly oriented feldspar microlites and interstitial clinopyroxene and opaque minerals. All feldspar crystals large enough to be analyzed are K-feldspar (average $Or_{96}Ab_2An_2$).

ZONED PYROXENE PHENOCRYSTS AND MEGACRYSTS IN ALKALINE ROCKS

Megacrystic clinopyroxene is common in mafic alkaline rocks (Brooks & Printzlau 1978) and potentially provides information about composition of and processes within the upper mantle. Wass (1979) presented a number of criteria for distinguishing accidental and cognate high-pressure mantle xenocrysts from low-pressure phenocrysts and quenched pyroxene.

Three major groups of clinopyroxene megacrysts or phenocrysts are distinguished: 1) the chrome diopside series (Wilshire & Shervais 1975), derived from disaggregated mantle rocks, 2) the Al-Ti augite series (Irving 1980), which consists of cognate pyroxene, probably from high-pressure cumulates, and 3) green, Fe-rich clinopyroxene (Babkine *et al.* 1968, Brooks & Printzlau 1978). Such green clinopyroxene is common in many alkaline lavas but is more abundant and less resorbed in potassic lavas. The green, Fe-rich clinopyroxene is commonly associated with colorless clinopyroxene, reversely zoned kaersutite megacrysts, and ultramafic nodules. Chemically, it generally contains high Fe, Na, and Mn, and

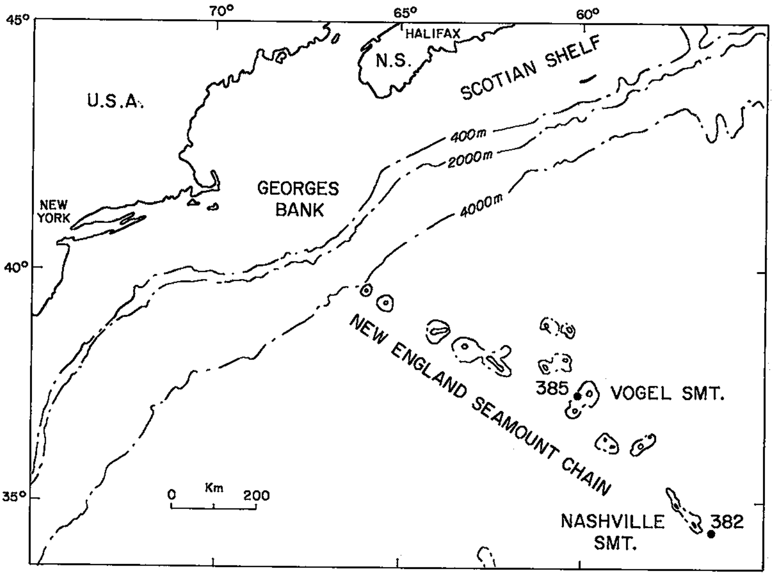

FIG. 1. Map showing location of DSDP Sites 382 and 385.

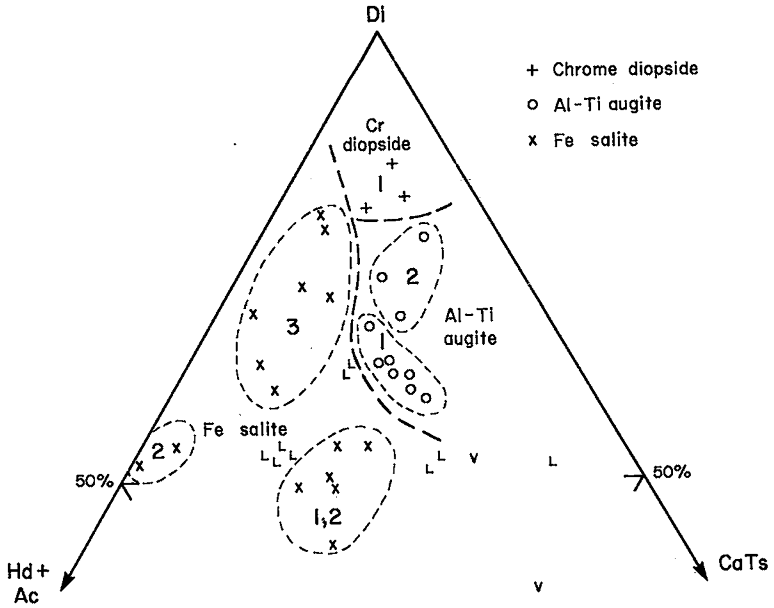

FIG. 2. Di - CaTs - (Hd+Ac) plot showing composition of various pyroxenes reported in the literature. Fields according to: (1) Wass (1979); (2) Brooks & Printzlau (1978); (3) Barton & van Bergen (1981). Individual analyses of green salite V = Vulsini (Barton *et al.* 1982); L = Lesbos (Pe-Piper 1984). Boundaries based on analyses given by Wass (1979).

shows decreasing Fe toward the rim. The chemical composition of the green pyroxene is quite variable (Fig. 2) and it is not clear that all has a common origin. Brooks & Printzlau (1978) proposed that such pyroxene crystallized from an evolved magma at mantle depths and was subsequently incorporated in a more alkaline mafic magma. Both Wass (1979) and Wilkinson (1975) suggested that the green, Fe-rich clinopyroxene represents a continuation of Al–Ti augite crystallization under high pressure, with similar ^{IV}Al/^{VI}Al and (Ti + ^{IV}Al/Si). Wass (1979) presented evidence that in some cases the Al–Ti augite and Fe-rich salite show similar compositional trends to those in low-pressure pyroxene from the same flow, demonstrating a cognate origin.

Green salite megacrysts with colorless diopside rims have been described from potassium-rich lavas from the Leucite Hills of Wyoming (Barton & van Bergen 1981). These examples of green salite have high Na but low Mn contents and are substantially poorer in Al and Fe than those described by Wass (1979) (Fig. 2). Using her criteria it is not clear that they are high-pressure forms, but the occurrence of other high-pressure mineral phases as inclusions within the diopside rims suggests that the green salite cores are xenocrysts derived from an unknown upper-mantle rock. In contrast, Barton *et al.* (1982) proposed an origin by magma mixing to account for green Fe-rich aluminous salite rimmed by colorless diopside in the potassium-rich lavas of Vulsini, Italy. The salite they described is more aluminous than that described by Wass (1979). Pe-Piper (1984) found similar aluminous salite rimmed by diopside in shoshonites from Lesbos, Greece, for which a magma-mixing origin was also proposed.

Recently, McHone (1985) published a preliminary description of complexly zoned clinopyroxene from Mesozoic lamprophyre dykes in New England; these rocks may be tectonically related to the New England Seamounts. The clinopyroxene has a green sodic

TABLE 1. CHEMICAL COMPOSITIONS AND CIPW NORMS OF THE LAVAS AND GLASSES FROM NEW ENGLAND SEAMOUNTS

	382-25-2^{+} 105-107	382-25-2^{+} 107-109	385-23-1^{+} 97-99	385-23-1^{+} 148-150	382-25-2 105-107 (Glass*)	382-25-2 107-109 (Glass*)
SiO_2	41.86	43.16	41.44	43.99	43.84	43.81
TiO_2	3.57	3.66	4.30	4.44	4.60	4.34
Al_2O_3	13.80	14.28	14.12	13.90	14.71	15.13
FeO_t	11.10	11.71	12.20	13.96	10.93	10.50
MnO	--	0.04	0.03	0.02	0.02	--
MgO	8,75	8.79	2.11	3.11	6.04	5.73
CaO	16.47	14.06	17.71	12.50	13.28	12.84
Na_2O	2.34	2.30	2.55	1.72	2.80	3.42
K_2O	1.32	1.29	4.37	5.78	2.10	2.08
P_2O_5	0.79	0.72	1.19	0.58	0.53	0.46
Total	100.00	100.00	100.00	100.00	98.85	98.31
CIPW Norms^{++}						
Lc	6.11	--	20.21	25.57	--	--
Or	--	7.61	--	1.47	12.53	12.48
Ab	--	1.98	--	--	3.14	2.84
An	23.11	24.78	14.15	13.11	21.58	20.10
Ne	10.71	9.45	11.66	7.87	11.26	14.48
Di	34.69	32.55	31.49	37.92	33.70	33.79
Hy	--	--	--	--	--	--
Ol	14.25	12.45	8.79	1.23	5.29	4.61
Mt	2.45	2.58	2.69	3.08	2.45	2.36
Il	6.77	6.94	8.15	8.41	8.82	8.37
Ap	1.83	1.67	2.76	1.34	1.24	1.09

* Each of these compositions represents the average of 10 individual electron microprobe analyses.
\+ These compositions have been recalculated to 100% on volatile-free basis.
++The norms have been calculated assuming $Fe_2O_3/(Fe_2O_3+FeO)=0.15$.

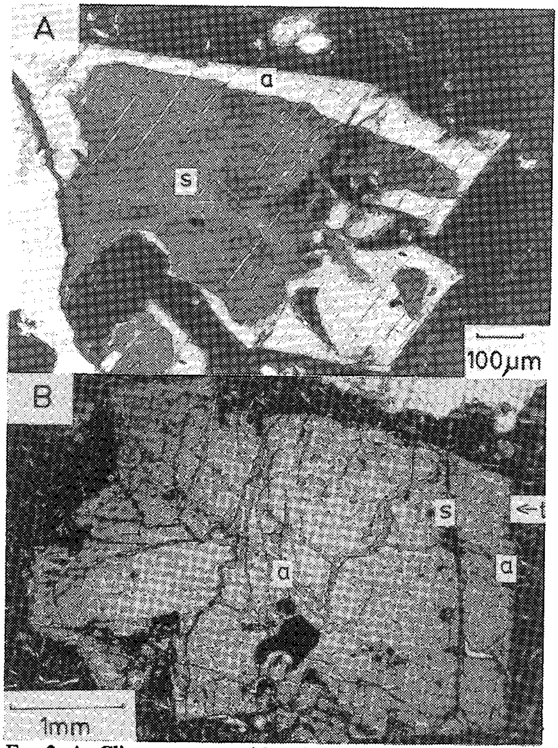

FIG. 3. A. Clinopyroxene with pale green salite core (s) and colorless augite (a) rim, both cut by exsolution lamellae (382-25-2; 107–109 cm). Crossed nicols. Scale bar 100 µm. B. Clinopyroxene with colorless augite core (a) mantled by green salite (s), then colorless augite (a), and a very thin brown titanian salite rim (t) (382-25-2; 105–107 cm). Crossed nicols. Scale bar 1mm.

core. He ascribed changes in clinopyroxene mineralogy to the crystallization of different mineral phases and changes in oxygen fugacity.

GEOCHEMISTY OF THE SEAMOUNT SAMPLES

Analyses of whole-rock samples (Table 1) were carried out by electron microprobe (MacKay 1981); a similar method was used by Houghton (1979). In addition, the glass from Site 382 was analyzed. The totals for anhydrous components in the glass analyses are in excess of 98%, which indicates low volatile contents; the rocks are thus considered unaltered. The rocks from Site 382 contain megascopic calcite in veins and amygdules, which is reflected in the substantially higher CaO contents of the whole rock than the glass. Potassium, and sodium to a lesser extent, are lower in the whole rocks than in the glass at Site 382, but this may reflect only the concentration of residual alkalis in the glass. The rocks are basanites, and the glass has a tephritic composition in terms of the classification of Zanettin (1984).

Houghton *et al.* (1979) noted that breccia from Site 385 has more secondary zeolite and less calcite. According to our data, the rocks from Site 385 are more potassic than those from Site 382. They are tephrites with K/Na greater than 1.

LARGE CLINOPYROXENE PHENOCRYSTS

Observations and comparison with other examples

Mineral analyses were performed by electron microprobe using energy dispersion (Clarke 1976).

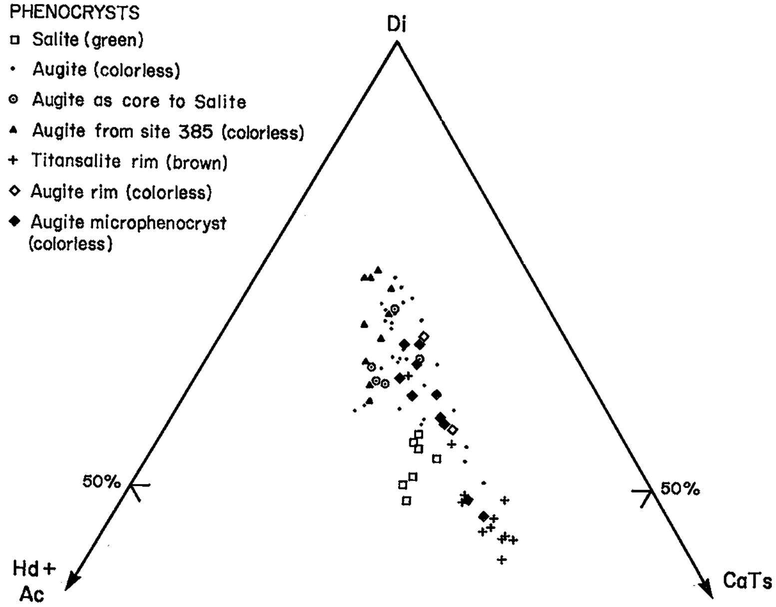

FIG. 4. Di – CaTs – (Hd + Ac) plot showing composition of pyroxenes from the New England Seamounts.

Natural minerals and synthetic oxide standards were used for calibration, and the data were reduced using the EMPADR VII program (Rucklidge & Gasparrini 1969).

The phenocrysts at Site 382 show complex zoning recognizable by color changes between zones (Fig. 3). The electron-microprobe data (Table 2) show that each of the different zones has a distinctive chemical composition (Figs. 4 to 6). Many phenocrysts have a highly resorbed green core of salite, a colorless intermediate zone of augite, and a brown rim of titanian salite. Some microphenocrysts consist of an augite core and a titanian salite rim, whereas others consist entirely of either augite or titanian salite. In a few cases, the green salite shows an inner core of euhedral to subhedral colorless augite (Fig. 3b). The euhedral character rules out the possibility that this represents a random cut in a thin section through a resorbed embayment in the salite. Exsolution lamellae which optically appear to be orthopyroxene occur in some salite and augite cores and in augite rims (Fig. 3a), but are absent in the titanian salite rims.

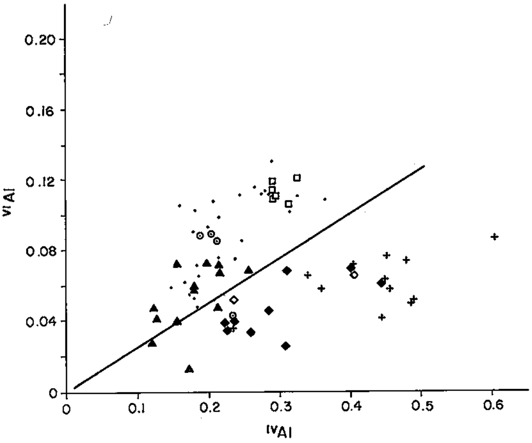

FIG. 5. Plot of ^{VI}Al *versus* ^{IV}Al for pyroxenes from the New England Seamounts. For explanation of symbols see Figure 4. Line separates high-pressure field (high ^{VI}Al) and low-pressure field (high ^{IV}Al) (after Wass 1979).

TABLE 2. REPRESENTATIVE COMPOSITIONS OF CLINOPYROXENES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	48.65	45.30	49.06	42.11	44.64	46.10	44.01	45.35	49.05	48.13	49.39	49.57	47.98	48.54
TiO_2	1.80	2.91	1.84	5.33	4.52	3.83	3.44	3.00	2.17	2.18	1.92	1.85	2.55	2.18
Al_2O_3	6.32	9.10	5.21	10.51	9.03	7.58	9.93	9.12	5.29	7.16	6.20	6.11	6.46	4.20
FeO_t	7.50	8.82	4.65	7.86	6.72	6.65	7.18	7.79	4.87	5.98	5.77	5.71	6.70	6.86
MnO	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	13.31	10.10	14.71	10.54	11.71	13.00	11.16	11.40	14.55	13.53	14.72	14.32	13.57	14.29
CaO	21.81	22.14	22.47	22.68	22.44	22.98	22.21	22.27	23.02	22.00	21.94	21.80	22.53	22.47
Na_2O	0.22	0.84	0.00	0.00	0.00	0.00	0.18	0.30	0.00	0.21	0.00	0.09	0.00	0.00
Cr_2O_3	--	--	0.80	--	0.15	--	--	--	0.46	--	0.05	--	0.09	0.07
Total	99.66	99.25	98.74	99.03	99.21	100.14	98.11	99.23	99.41	99.19	99.99	99.45	99.88	98.61
Si	1.812	1.709	1.832	1.603	1.659	1.713	1.675	1.706	1.822	1.793	1.822	1.839	1.784	1.827
Ti	0.050	0.083	0.052	0.153	0.130	0.107	0.098	0.085	0.061	0.061	0.053	0.052	0.071	0.062
^{iv}Al	0.188	0.291	0.168	0.397	0.341	0.287	0.325	0.294	0.178	0.207	0.178	0.161	0.216	0.173
^{vi}Al	0.089	0.114	0.062	0.074	0.066	0.046	0.121	0.111	0.053	0.108	0.091	0.106	0.068	0.013
Fe^{3+}	0.014	0.074	0.000	0.018	0.011	0.022	0.020	0.035	0.000	0.000	0.000	0.000	0.003	0.035
Cr	0.000	0.000	0.024	0.000	0.005	0.005	0.000	0.000	0.014	0.000	0.001	0.000	0.003	0.002
Fe^{2+}	0.220	0.205	0.145	0.233	0.203	0.185	0.208	0.210	0.151	0.186	0.178	0.177	0.206	0.181
Mn	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.739	0.568	0.819	0.598	0.667	0.720	0.633	0.639	0.805	0.751	0.809	0.792	0.752	0.801
Ca	0.870	0.895	0.899	0.925	0.919	0.915	0.906	0.898	0.916	0.878	0.867	0.867	0.898	0.906
Na	0.016	0.061	0.000	0.000	0.000	0.000	0.013	0.022	0.000	0.015	0.000	0.006	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wo	47.55	53.63	48.26	52.69	51.36	50.27	51.85	51.38	48.92	48.37	46.76	47.21	48.38	47.98
En	40.36	34.03	43.94	34.06	37.27	39.56	36.24	36.58	43.00	41.37	43.64	43.14	40.53	42.44
Fs	12.10	12.33	7.80	13.25	11.37	10.17	11.92	12.04	8.08	10.26	9.60	9.65	11.09	9.58
CaTs	16.16	25.85	14.83	32.36	28.17	24.04	27.54	25.20	15.72	17.83	15.31	14.16	18.37	15.01
Di	63.46	50.42	72.34	48.70	55.04	60.42	53.68	54.87	70.96	64.79	69.42	69.68	64.09	69.35
Hd	19.02	18.28	12.83	18.94	16.79	15.54	17.65	18.05	13.33	16.07	15.27	15.59	17.54	15.65
Ac	1.36	5.46	0.00	0.00	0.00	0.00	1.13	1.88	0.00	1.31	0.00	0.57	0.00	0.00

(Structural formulae calculated using method from Hamm and Vieten 1971)

1-4: 382-25-2; 105-107 cm, basanite lava clast. Zoned crystal, colorless core (1) (augite) mantled by green (2) (salite) then colorless zones (3) (augite) with brown rim (4) (titanian salite).

5: 382-25-2; 105-107 cm, basanite lava clast. Brown microphenocryst (titanian salite).

6: 382-25-2; 96-98 cm, hyaloclastite. Colorless microphenocryst (augite).

7-9: 382-25-2; 105-109 cm, hyaloclastite. Zoned crystal, pale green core (7-inner part: salite, 8-outer part: salite) mantled by colorless (9) (augite) pyroxene.

10-12: 382-25-2; 96-98 cm, hyaloclastite. Zoned crystal, colorless core (10) (augite) mantled by colorless (11-inner part: augite, 12-outer part: augite) pyroxene.

13-14: 382-23-4; 148-150 cm, tephrite lava clast. Zoned crystal, colorless core (13) (augite) mantled by colorless (14) (augite) pyroxene.

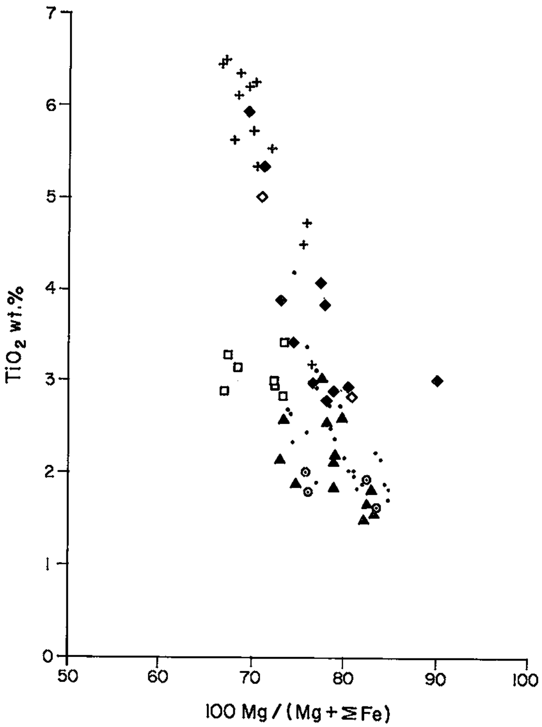

FIG. 6. Plot of TiO_2 *versus* ratio of Mg to total Mg + Fe for pyroxenes from the New England Seamounts. For explanation of symbols see Figure 4.

Aoki & Shiba (1973) suggested that a plot of ^{VI}Al against ^{IV}Al (Fig. 5) allows a discrimination of low-pressure from high-pressure clinopyroxene. According to this criterion, many samples of colorless augite and green salite are high-pressure forms, whereas the brown titanian salite rims and augite microphenocrysts have a ^{VI}Al to ^{IV}Al ratio suggestive of low-pressure crystallization. The discriminating line proposed by Aoki & Shiba (1973) for ultramafic and mafic inclusions in alkali basalt magma thus also appears to discriminate between the low-pressure titanian salite rims and augite microphenocrysts *versus* the salite and augite cores of phenocrysts in the basanitic tephritic rocks studied here. This is noteworthy, as the $^{IV}Al/^{VI}Al$ ratio should be dependent on silica activity.

The green salite is present only at Site 382 (analyses 2, 7 and 8, Table 2). Only one pair of compositions is available to illustrate zoning within a typical example (analyses 7, 8). There is an increase in Na toward the rim, but no other pronounced changes. Sodium content of all the green salite is low, generally less than 0.02 Na in the structural formula. The salite compositions fall in a similar position on a Di - (Hd + Ac) - CaTs plot (Fig. 2) as those described from Vulsini by Barton *et al.* (1982). The former have slightly lower Fe and Na, and slightly higher Ti and Al contents. They are also similar to green salite from shoshonites of Lesbos, Greece (Pe-Piper 1984), which likewise have relatively low Na. Salite from the New England Seamounts is a little more aluminous than green salite described by Wass (1979) and Brooks & Printzlau (1978), and lacks the high Na and Mn described by these authors. It also is less sodic than the green clinopyroxene cores from the New England lamprophyre dykes described by McHone (1985). The salite also has much higher Al and lower Mg and Na contents than green pyroxenes from the Leucite Hills (Barton & van Bergen 1981).

Colorless augite phenocrysts (analyses 1, 3, 9–14) are chemically distinct from the microphenocrysts (analysis 6). Augite occurring as phenocrysts is similar to high-pressure Al–Ti augites described by Wass (1979). Compositions from Site 385 (analyses 13, 14) have a lower content of Ca-Tschermaks component than those for Site 382. Core to rim traverses show first a slight increase and then a marked decrease in Al. The colorless augite core in the green salite (*e.g.*, analysis 1) does not differ systematically from normal phenocrystic augite in composition. The augite is the only clinopyroxene in which chrome content is above detection limits. None of the pyroxene compositions examined by us resembles those of chrome diopside mantle xenoliths.

Most augite microphenocrysts have higher ^{IV}Al contents than the phenocrysts, suggesting a low-pressure origin (Fig. 5). They also have a higher Ti and Mg-to-Fe ratio (Fig. 6). In some cases, the augite rim on phenocrysts shows chemical characteristics similar to those of the microphenocrysts.

The brown titanian salite (analyses 4, 5) contains 4.5 to 6.5% TiO_2 and is enriched in Ca-Tschermaks component. The compositions are typical of titanian augite and titanian salite commonly found in alkaline rocks, resembling, for example, the low-pressure clinopyroxene of Wass (1979). The crystals are zoned from a more Ti- and Al-rich core to a more Mg- and Si-rich rim.

In the Di - (Hd + Ac) - CaTs triangular plot (Fig. 4) the Fe-rich salite, phenocrystic augite, and titanian salite plot in discrete fields. The microphenocrystic augite overlaps both the phenocrystic augite and titanian salite fields. The compositions of phenocrystic augite from Sites 385 and 382 overlap. A similar pattern is seen in a ^{VI}Al *versus* ^{IV}Al plot (Fig. 5). Furthermore, the phenocrystic augite and Fe-rich salite define a steep trend of increasing ^{VI}Al with increasing ^{IV}Al. Augite from Site 385 plots at the lower end of this trend, overlapping with the almost horizontal trend defined by microphenocrystic augite and titanian salite. In a plot of TiO_2 against Mg/Fe (Fig. 6), for any particular Mg content, the Fe-rich salite and phenocrystic augite have a lower Ti content than the microphenocrystic augite and titanian salite.

Significance of the zoned crystals

The ^{VI}Al-to-^{IV}Al ratio of the Fe-rich salite and phenocrystic augite, distinctly different from that of the microphenocrystic augite, suggests that the phenocrysts are high-pressure clinopyroxenes derived from mantle. Likewise, both Wass (1979) and Brooks & Printzlau (1978) argued that the colorless Al–Ti augite and green Fe-rich salite they studied are high-pressure forms. The occurrence in rocks from the New England Seamounts of a core of colorless augite within green salite and of a green salite core within colorless augite, both showing evidence of resorption prior to crystallization of the titanian salite rims, suggests that conditions leading to the formation of both pyroxenes existed alternately at mantle depths. This alternation of Al–Ti augite and Fe-rich salite, however, cannot be explained readily by deriving either phase from a mantle xenolith; rather, it points to alternation of either crystallization conditions or compositions of magma presumably associated with basanite–tephrite magmatism. McHone (1985) has discussed possible mechanisms by which this might occur. The associated phenocrystic kaersutite and olivine are probably also of mantle origin. Furthermore, kaersutite inclusions are found in the salite cores and olivine inclusions occur in phenocrystic kaersutite. Such an interpretation contrasts with that of Barton & van Bergen (1981) for green pyroxene from the Leucite Hills, which was derived, they argued, from mantle xenoliths. It should be noted, however, that the composition of their green pyroxenes differs somewhat from that described both in this study and by Wass (1979) and Brooks & Printzlau (1978).

The phenocrystic Al–Ti augite and Fe-rich salite from the New England Seamounts form a continuous trend on plots such as ^{VI}Al *versus* ^{IV}Al (Fig. 5). This probably indicates that the pressure–temperature conditions under which the pyroxenes crystallized were similar: their Al, Ti and Fe contents may be interrelated (Campbell & Borley 1974, Wass 1979) and dependent on the appearance of phases such as titaniferous magnetite or kaersutite on the liquidus (McHone 1985). The Na-content of the salite is very low, so that it is not necessary to invoke a highly evolved alkaline magma such as that proposed by Brooks & Printzlau (1978). The microphenocrystic augite shows a range of compositions from that typical of phenocrystic high-pressure augite to that of low-pressure titanian salite, apparently reflecting changing conditions of crystallization during the rise of the magma. The titanian salite represents a continuation of crystallization within the shallow magma-chamber under low-pressure conditions.

Although abrupt changes in mineral chemistry, such as those in the zoned crystals, might result from sudden changes in pressure associated with the rise of magma, alternation of augite and salite is difficult to account for by systematic changes in parameters such as oxygen fugacity during simple ascent of magma. More probably, magma mixing is involved, resulting in abrupt and minor, but significant, changes in oxygen fugacity or Ti, Al or K activities, perhaps within a zoned magma-chamber. Our limited data do not allow more specific conclusions as to the composition of these magmas, but the data do provide mineralogical evidence that the processes of magma evolution in the seamount chain are complex, and that magma mixing, as proposed on the basis of whole-rock geochemistry by several authors (*e.g.*, Chen & Frey 1983, Thompson *et al.* 1984), is an important process.

CONCLUSIONS

1. Although all the rocks recovered by the Deep Sea Drilling Project from the New England Seamounts have suffered secondary alteration, fresh glass provides evidence as to the primary composition of the magma. The rocks are basanites and tephrites with high TiO_2 contents. The analyzed glasses are tephritic.
2. Complexly zoned pyroxene phenocrysts in these samples have a rim of low-pressure augite or titanian salite over a mantle of Al–Ti augite and a core of Fe-rich salite. Other cores are Al–Ti augite with mantles of Fe-rich salite. Microphenocrysts consist of augite similar in composition to the rim of phenocrysts. Phenocrysts of olivine and kaersutite also are present.
3. The phenocrystic Al–Ti augite and Fe-rich salite fall on the same trend on diagrams showing elemental variations, with the ^{IV}Al/^{VI}Al ratio suggesting high-pressure crystallization. The microphenocrystic augite and titanian salite rims of phenocrysts define a second trend on the ^{IV}Al/^{VI}Al diagram, a trend developed under low-pressure conditions.
4. The zoning may result from changes in the liquidus phase, or from changes in the abundance of volatiles. Alternation of phases may result from magma mixing or circulation within an inhomogeneous magma.
5. Examples of green Fe-rich salite described in the literature have a wide range of compositions. Various origins have been suggested, such as disaggregation of mantle xenoliths or crystallization from highly alkaline magma at depth. Neither of these origins seems applicable to those of the New England Seamounts, where the Fe-rich salite evidently crystallized under conditions rather similar to those of the Al–Ti augite. The higher Al content of the Fe-

rich salite may be related to its higher Ti content, which in turn could reflect the availability of Ti in the magma.

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