Amphibole-bearing Basalts
from the
Submarine Volcano Kick'em-Jenny
in the
Lesser Antilles Island Arc

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Introduction

Fractionation of subsiliceous amphibole in basalt magma to enrich residual melts in silica and generate andesite magmas has long remained an attractive mechanism to petrologists (Brown and Schairer, 1971; Allen et al., 1972; Boettcher, 1973; Cawthorn et al., 1973.) The mechanism is supported by experiments on natural basalts under water-saturated conditions up to 10 kb (Yoder and Tilley, 1962) and 13 to 15 kb (Haygood, 1971) as well as water--saturated pyrolite up to 30 kb (Green, 1973), which have shown the stability limits of amphibole in hydrous basalt liquids and in near-solidus melts of model upper-mantle composition. In spite of the abundant experimental evidence and frequent occurrence of amphibole in ejected plutonic blocks (Lewis, 1973), amphibole is rarely reported as a phenocryst phase in basalts, presumably due to its breakdown at about 1 kb as magma ascends to the surface. This paper describes the occurrence of amphibole megacrysts in olivine basalt pyroclast deposits and discusses the geology and petrology of the active Kick'em-Jenny submarine volcano in the southern Grenadines of the Lesser Antilles island Arc.

Geology:

A survey of the submarine volcano Kick'em-Jenny was carried out in May 1972 from the Royal Navy oceanographic research vessel H.M.S. Hecla, including 350 km of PDR bathymetric soundings, gravity and magnetic profiles, dredging and bottom grab-sampling. Kick'em-Jenny is the only known active submarine volcano in the Lesser Antilles arc, situated 8 km north of Grenada, on the western margin of the submarine platform of Isle de Ronde (Fig. 1). Also due east of Kick'em-Jenny is Isle de Caille, possessing two very youthful craters and small lava fields forming the youngest olivine basalt lavas in the Lesser Antilles.

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Historic volcanic and seismic activity in Kick'em-Jenny after the 1939 eruption is summarized in Table 1. The 1939 eruption was preceded by heavy earthquake shocks before the appearance of a black eruption cloud on 24 July (Robson and Tomblin, 1966), but explosions and associated earth tremors lasted for one day. T-phase tremors recorded in October 1943 probably originated from an eruption in Kick'em-Jenny, although no surface manifestations were observed. Similar events took place in October 1953, October 1965 and May and August 1966, when earth tremors of the type corresponding to a large submarine explosion were recirded by seismograph stations in the Eastern Caribbean and felt locally on Isle de Ronde and Grenada. Although these phenomena, detected at distant seismograph stations, are attributed to volcanic activity in Kick'em-Jenny (Shepherd and Robson, 1967), no evidence of activity at the surface was reported.

TABLE 1:

ACTIVITY IN KICK'EM-JENNY VOLCANO

24/ 7/1939	submarine eruption, local earthquakes, eruption cloud up to 270 meters above sea level.
5/10/1943	submarine eruption, T-phases recorded in Martinique.
30/10/1953	submarine eruption, T-phases recorded throughout Eastern Caribbean, shocks felt in Grenada.
24/10/1965	submarine eruption, shocks of intensity V felt on Isle de Ronde, recorded as far as Puerto Rico.
5/ 5/1966	submarine eruption, T-phases recorded generally in Eastern Caribbean, up to 7 May.
3/ 8/1966	submarine eruption, 168 events recorded, shocks with intensity up to IV felt in Grenada, T-phases recorded up to August 6.
5/ 7/1972	submarine eruption, T-phases recorded in Eastern Caribbean, duration 5 hours.

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A bathymetric survey was carried out over Kick'em-Jenny by H.M.S. Vidal in October, 1962 and a bathymetric map based on this survey is reproduced by Robson and Tomblin (1966) which located a probable centre of eruption 232 m below sea level. Soundings by H.M.S. Lynx carried out in June 1966, after the October 1965 and May 1966 eruptions recorded a minimum depth of 192m below sea level. These differences in minimum depth may be attributed either to inadequate density of soundings or that the volcanic events of October 1965 and May 1966 had added material to the volcanic cone.

The results of the 1972 cruise of H.M.S. Hecla indicate that the volcano has the form of a cone, symmetrical in the north-south section (Fig.2) but asymmetrical in the east-west section, due to abutment of the Isle de Ronde shelf. Slopes on the smooth cone vary from 15° to 20°, but the north-south diameter is 6 km, the east-west diameter about 4 km and overall height of the volcanic cone above sea floor is 1300 m Four shallow radial valleys were located on the cone, running W, WNW and SW from the crater. The south-western valley terminates down-slope in a sedimentary fan. A distinct crater was located on several PDR runs across the cone, at 12°17.96'N and 61°38.25'W. The crater is circular, with a diameter of 180 m and a minimum depth of 15 m Minimum water depth over the crater rim was recorded 190 m. There is no evidence at hand for a breach in the crater rim and the smooth bathymetry around the crater suggests that explosive volcanic deposits (tephra) predominates and that lava flows are absent on the volcano.

An arcuate tongue of volcanic deposits extends from the south flank of the cone off to the west. The tongue is slightly elevated above the regional morphology and extends from 700 m below sea level to depths of 1300 meters. This feature is interpreted as a series of pyroclast flows or mud flows from the crater and cone region, deposited in the valley between the Grenada shelf to the south and the Kick'em-Jenny cone to the north.

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The flank region of the arc, with its characteristic irregular, hummocky bathymetry, is terminated to the east by well-defined scarps, ranging from the flank to the shallow wave cut platform of the Grenadines and Grenada. The latter area is the shelf region, ranging between depths of 100 and 400 meters. Sharp scarps, peaks and irregular topography characterize the shelf region and the central part of the shelf area investigated, adjacent to and east of Kick'em-Jenny volcano, exhibits two distinctive scarp series and inspection of a number of close-spaced PDR profiles has led to the reconstruction of two major normal faults in this area (Fig.1). The western fault can be traced for a distance of over 2 km in a north-southerly direction. It is a normal fault, with a down-throw on the western side ranging from 70 to 150 meters. This fault marks the eastern boundry of the Kick'em-Jenny volcanics, which have probably been piled up against the fault-scarp. The southern and northern traces of this fault are obliterated by the overlapping volcanic deposits. This fault reappears however, south of the recent volcanics on the shelf region north of Grenada, where the strike and throw are comparable. The eastern fault system is a complex of branching faults (Fig. 1), mappable over 3 km in a north-south direction. These faults form a series of scarps with a down-throw of 150 meters to the west, continued on the Grenada shelf to the south. Bottom grab-sampling on the shelf east of the volcano indicate the predominance of unconsolidated calcareous mud deposits on the leeward shelf, probably derived from the coral reefs near and to windward of Isle de Ronde.

Most PDR profiles of the shelf region show a well-defined terrace at 72 meters depth in the area investigated. The terrace varies in width up to 1 km and most likely represents a former low sea level stand from the Pleistocene (Fig. 1). Eustatic changes in sea level during the Wurm-Wisconsin interglacial resulted in a world-wide drop in sea level of about 100 meters below present level (Fairbridge,

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1961). Based on data from Barbados, Mesolella et al. (1969) postulate a low level stand 125 to 170 thousand years before present and boreholes in Barbados have recently authenticated such a level (Steinen et al., 1971), where a sea level at 75± 10 meters below present level was dated as ranging from 105-125 thousand years ago. This compares well with the terrace on the shelf near Kick'em-Jenny, and we conclude that this dates from a period of low sea level during the Pleistocene.

Attempts were made to collect bottom sediment cores on the flanks of the volcano but this proved impractical due to the coarse grain of the pyroclast deposits. Coring inside the crater proved successful, however, and 30 cm of unsorted black tephra was collected, with a 1 cm thick top layer of red-orange mud. Chemical analysis of the mud (KEJ021B, Table 3) shows a high ferric oxide content but otherwise a roughly basaltic composition. A comparable mud layer was deposited in the crater lake of the Soufriere volcano during the 1971-1972 eruption (Aspinall et al., 1973), due to fragmentation of hot lava and transport of silt-grade particles of glass and minerals by convective currents in the lake. The red-orange mud in the Kick'em-Jenny crater probably originated similarly by interaction between hot pyroclastics and sea-water, resulting in spalling and fragmentation of volcanic glass which would be suspended around and above the crater until turbulent activity ceased. Leaching of the mud by hot sea water and volcanic gases may account for the deviation from a basaltic composition, but the extremely high ferric content was also observed in the Soufriere crater mud, where it has been suggested that iron was brought in by the volcanic gases as ferric chloride, but precipitated as a ferric oxide or hydroxide on entering the crater lake. A similar origin may be invoked for the high ferric iron in the Kick'em-Jenny mud. The presence of red-orange mud of possible hydrothermal origin inside the crater lead to the lowering of a temperature-salinity-probe to the crater floor to test the possible presence of fumarolic activity, but both temperature (14.55°C) and salinity were normal for this water depth.

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Petrography

Dredging and bottom grab-sampling yielded 25 kg of volcanic "bombs", scoria and lapilli from various parts of the cone and crater during the H.M.S. Hecla cruise. In addition, we have access to a small collection of somewhat oxidized and altered dredge samples collected by the yacht Insula in August 1966 in the vicinity of Kick'em-Jenny. In contrast, a striking feature of all the Kick'em-Jenny samples collected in 1972 is their freshness and lack of associated organic material or calcaceous detritus, which must be viewed as a strong indication of eruptions within the last few years or in the interval between 1966 and 1972.

The principal rock type recovered from Kick'em-Jenny is black scoria, bombs and lapilli of olivine basalt composition, but in addition a few small blocks of non-vesicular andesitic basalt were also recovered. They contain phenocrysts of zoned plagioclase, clinopyroxene and subhedral to euhedral amphibole and probably represent xenoliths from the basement or older Kick'em-Jenny volcanics.

A dredge near the crater included chips of a 10 mm thick pale grey and semi-consolidated andesitic ash layer, consisting principally of very fine glass shards (0.10-0.01 mm) and fragments of plagioclase, clinopyroxene and amphibole.

The olivine basalt pyroclastic ejecta of Kick'em-Jenny are all highly porphyritic rocks with from 25 to 50% phenocrysts of amphibole, plagioclase, clinopyroxene and olivine. Plagioclase phenocrysts (An_{70-80}) are invariably present as zoned subhedral crystals, with rare inclusions of the other three phenocryst minerals. Plagioclase is a subordinate phenocryst phase in the most magnesian basalt samples (4%) and enriched in the MgO-poor samples, but this modal variation is not reflected in the calcium and alumina percentages. Clinopyroxene phenocrysts are subordinate but always present as large, euhedral individuals with olivine inclusions. Olivine phenocrysts are very variable in abundance, but from large inclusion-free and euhedral

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crystals in the more magnesian samples. Olivine is also a groundmass constituent in the Kick'em-Jenny basalts.

The most notable petrographic feature of the basalts is the presence of euhedral to subhedral amphibole megacrysts, up to 2 cm in length, which make up to 16% of the rock. They are pleochroic from olive-green to yellow-brown and generally surrounded by an oxidized rim. Inclusions of plagioclase, clinopyroxene and olivine are very common in the amphiboles. Amphiboles were hand-picked from six tephra samples chemically analyzed, but four analyses were rejected because of suspected plagioclase inclusions in view of the high Al_2O_3 content. Two chemical analyses and two microprobe analyses are presented in Table 2, along with structural formulas of the amphiboles which all contain tetrahedral Al in the half-unit cell due to the low silica content. They are all sub-silicic amphiboles, with 5 to 7.5% normative nepheline. According to the nomenclature of Leake (1968) the Kick'em-Jenny amphiboles would be classified in the ferroan pargasite to Tschermakite range. They are identical to amphiboles from the igneous comulate blocks of Soufriere volcano, St. Vincent, except for double the K_2O content in the Kick'em-Jenny amphiboles (Lewis, 1973).

Experimental melting runs on basalt compositions at 5 to 10 kb under hydrous conditions have produced calcic amphiboles similar to those from Kick'em-Jenny. Helz (1973) has demonstrated the temperature dependance of Al and Ti variations and the effect of bulk composition in amphibole chemistry, crystallizing ferroan pargasite from Hualailai alkali basalt at 5 kb, closely comparable to Kick'em-Jenny amphiboles except for slightly higher Al content of the latter, reflecting the higher overall Al_2O_3 content of the Kick'em-Jenny olivine basalt. In an experimental study of calc-alkaline olivine basalts from Grenada, Cawthorn et al. (1973) report the crystallization of amphibole below 1050°C under hydrous pressure of 5 kb. Although similar to Kick'em-Jenny amphiboles, the experimentally produced Grenada amphiboles are significantly lower in TiO_2 and higher in SiO_2, probably reflecting different

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conditions of pressure and temperature of crystallization. Similarly, the Tschermakitic amphiboles produced by hydrous melting experiments at 5 and 8 kb from olivine tholeiite by Holloway and Burnham (1972) are comparable but differing in FeO + Fe_2O_3 MgO ratio from the Kick'em-Jenny amphiboles, in keeping with differing bulk compositions, as this ratio is less than unity in the Kick'em-Jenny basalts and amphiboles, but greater than unity in the Hawaiian olivine tholeiite and amphiboles. On the other hand, hydrous melting experiments carried out at 10 kb on high-alumina olivine tholeiite (Green and Ringwood, 1968) crystallized amphiboles nearly identical to those from Kick'em-Jenny. Although no exact anologies exist, the available experimental data indicates that the pressure and temperature conditions at the time of crystallization of the Kick'em-Jenny amphiboles were between 5 and 10 kb at about 1000°C in a hydrous or water-undersaturated magma.

A single plutonic xenolith of biotite-bearing gabbro with a cumulate texture was dredged from Kick'em-Jenny. The 3 cm-diameter fragment consists principally of equidimensional plagioclase (An_{80-90}), with clinopyroxene occurring as euhedral crystals or poikilitic with plagioclase. Rare euhedral grains of olivine are enclosed by plagioclase. The xenolith contains patches of slightly vesicular yellow-brown glass which contains remnants of amphibole and seems largely a fusion product of this mineral. Yellowish to pale-brown, pleochroic and corroded crystals of mica, up to 1 mm in diameter, are also present in association with the interstitial glass. The mica is uniaxial, optically negative and probably of biotite composition. Both amphibole and biotite show advanced reaction, but appear to have been poikilitic phases in the cumulate texture.

Petrochemistry:

The chemical composition of the Kick'em-Jenny olivine basalts is shown in Table 3, along with analyses of a basaltic andesite xenolith, andesitic ash, and the hydrothermal red-orange mud from the crater. The basalts range from alkali olivine

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basalt (018) to olivine basalts and olivine tholeiites in normative classification but the more basic samples lie in or near the critical plane of silica undersaturation (Yoder and Tilley, 1962). The non-committal term olivine basalt is preferred for these rocks, as well as many similar basalts from the southern part of the Lesser Antilles arc. They are similar to typical alkali olivine basalts in having a low silica content, high alkalis ang magnesia, but are much higher in Al_2O_3 and lower in total iron, P_2O_5 and TiO_2. Again the Kick'em-Jenny basalts differ from high-alumina basalts in having higher alkalis and lower silica than the latter. A suite of undersaturated lavas, ranging from picrites and basanites to alkali olivine basalts and sub-alkaline basalts has been recently described from neighbouring Grenada, (Sigurdsson et al., 1973) showing strong affinities with the Kick'em-Jenny basalts. These alkalic and variably undersaturated rocks from Kick'em-Jenny, Grenada and the southern Grenadines are not comparable to the high-potash basaltic suites (shoshonites) described from some circum-Pacific island arcs (Jakes and White, 1-72), but can be regarded as an alkali olivine basalt to alkali picrite suite, on the basic end of the calc-alkaline rock association as previously suggested by Sigurdsson et al (1973).

Discussion:

Fractionation and origin of the magma:

The chemical variation among the Kick'em-Jenny basalts (Fig. 3) is principally dominated by MgO decrease, increase in Na_2O and K_2O, minor increase in Al_2O_3 and decrease in total iron, TiO_2 and CaO. Assuming that the observed variations is due to extraction of one or more of the phenocryst phases present in the basalts, the generation of the observed differentiation trends has been attempted by use of subtraction diagrams. The principal constraints on any extraction model are, of course, the observed chemical variation stated above and the composition of the extracted phases. Thus the alumina trend excludes the extraction of large amounts of

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calcic plagioclase, but agrees well with amphibole extraction. Amphibole alone, however, cannot account for the observed MgO-depletion and some extraction of olivine is needed. Subtraction of ferroan pargasitic amphibole, olivine (Fo_{80}) and plagioclase (An_{90}) in the proportion 2:1:1 from the olivine basalts (46.5% SiO_2) will reproduce closely the observed chemical variation. The theoretical crystal extract, with a silica content of 42%, differs significantly from the ejected cumulate blocks of the Soufriere, St. Vincent, which are similarly considered a crystal extract from a differentiating hydrous basalt magma (Lewis, 1973). The latter are much higher in Al_2O_3 and CaO, but lower in MgO and Na_2O, reflecting a lower amphibole /plagioclase ratio than the hypothetical extract, probably due to both different bulk composition of Kick'em-Jenny (alkalic) and Soufriere (sub-alkaline) magmas, as well as differing conditions at time of crystallization.

The credibility of any extract or crystal fractionation model diminishes with the increasing volume of crystal cumulate required to account for the observed variation and in the Kick'em-Jenny magma chamber the removal of 45% of the original liquid, as cumulate phases of amphibole and plagioclase, is required to produce the compositional change from 46.5% to 50% SiO_2. Extrapolation of this process of extraction to the genesis of andesitic melts of the Lesser Antillean volcanoes, would clearly demand the accumulation of large gabbroic masses, as much larger percentages of liquid are removed. The evidence from Kick'em-Jenny shows that amphibole fractionation does take place within the basaltic range, but the question whether this efficient mechanism of silica enrichment is responsible for generation of andesitic melts must be further examined in view of the geological constraints, particularly the problems of large cumulate masses required by the amphibole fractionation hypothesis.

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The Kick'em-Jenny megaphenocryst and phenocryst assemblage suggests that the minerals amphibole, olivine, clinopyroxene and plagioclase were more or less stable together. Olivine is invariably inclusion-free and interpreted as the first mineral to crystallize, whereas clinopyroxene phenocrysts contain olivine inclusions in some cases. Plagioclase phenocrysts contain rare inclusions of amphibole, clinopyroxene and olivine, whereas amphibole megaphenocrysts contain abundant inclusions of the three other phases. The order of crystallization of the phenocryst phases is probably the following: olivine-clinopyroxene-plagioclase-amphibole. Experimental studies on hydrous (H_2O-saturated) or anhydrous basaltic compositions do not provide us with this assemblage or order of crystallization of major phenocryst phases at any pressure. At water-saturated conditions plagioclase, for example, appears much later than indicated in the Kick'em-Jenny magma and probably after the disappearance of clinopyroxene (Helz, 1973). A more satisfactory analogue to the Kick'em-Jenny mineral assemblage may be found in the phase relations of water-undersaturated basaltic melts as deduced from interpolation between the experimentally determined phase relationships for dry and water-saturated basaltic liquids (Green and Ringwood, 1967; Haygood, 1971; Yoder and Tilley, 1962; Helz, 1973). Fig. 4 is a schematic isobaric section at 5 kb for an alkali basalt-water system interpolated from the dry and water-saturated results. This diagram can only serve as a rough guide to the phase relations due to lack of experimental data in the water-undersaturated region, but it does, however, serve to indicate that the stability fields of amphibole and plagioclase are expanded with respect to water-saturated conditions and that the mineral assemblage olivine, clinopyroxene, amphibole and plagioclase is probably stable in alkali basalt melts with 1% H_2O at 5 kb pressure. The presence of 28 to 49 modal % megaphenocrysts and phenocrysts, together with the observed chemical variation in the Kick'em-Jenny olivine basalts

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testifies to some crystallization at depth prior to eruption. The depth of crystallization, as inferred from the mineralogy, can only be stated in very general terms. The presence of plagioclase restricts the crystallization range to less than 10 kb in a hydrous melt of alkali olivine basalt composition and similarly the coexistance of amphibole with olivine (and pyroxene) requires crystallization at depths in excess of 2 kb and probably 3 kb (Yoder and Tilley, 1962.) In view of these restrictions we feel justified in comparing the phase relations at 5 kb in experimental systems of alkali olivine basalt composition to those of Kick'em-Jenny magma just prior to its eruption.

The alkali olivine basalt and sub-alkali basalt series of Grenada have previously been shown to be very closely associated with, and probably the fractionation product of primary alkali picrites (Sigurdsson et al., 1973). It is proposed that the comparable olivine basalts of neighbouring Kick'em-Jenny are similarly derived from alkali picrite magma which, during ascent to a reservoir at 15 to 20 km depth has acquired olivine basalt composition principally by crystallization of olivine during ascent. The main episode of crystallization occurred in the Kick'em-Jenny magma reservoir, where partial equilibration of the assemblage olivine-pyroxene-amphibole-plagioclase-liquid occurred before eruption.

The occurreance of a biotite-bearing cumulate gabbro block in the ejecta has an important bearing on the petrogenesis in Kick'em-Jenny. Phlogopite or biotite are a common near-solidus phase in hydrous melting studies of alkali basalt (Helz, 1973; Yoder and Tilley, 1962). Due to the early breakdown of trioctahedral micas above the solidus , they normally only coexist with amphibole and plagioclase plus liquid in the water-saturated melt, but our interpretation of possible phase relations at H_2O-undersaturated conditions suggest that the cumulate assemblage biotite-plagioclase-amphibole can coexist with olivine or clinopyroxene and liquid (Fig. 4).

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The biotite-bearing xenolith may represent either total crystallization of Kick'em-Jenny olivine basalt magma under near-equilibrium conditions, or alternatively, a cumulate extract. In the case of the latter, the possible extraction of a potash-rich mica from the alkali picrite and alkali olivine basalt magmas of the Lesser Antilles could be important, along with amphibole fractionation, in accounting for the sharp fall in "incompatible" element contents observed between the strongly undersaturated lavas and the olivine basalts of Grenada (Sigurdsson et al., 1973)

Green (1970) has proposed that alkali picrite magma may be the partial melt of upper mantle pyrolite with about 0.5% H_2O at 25km depth. While the origin of the Grenada alkali picrites is not under review in this paper, we feel that in view of their possible significance to the petrogenesis of the Kick'em-Jenny melt, the possible alternative of the formation of alkali picrites by breakdown of sub-silicic amphibole should be pointed out: Experimental results indicate that amphibole is stable up to 15-25 kb (Essene et al., 1970) or even up to 29 kb (Green 1973), supporting Oxburgh's (1964) hypothesis that amphibole may exist in lower crust and upper mantle. The formation of island arc magmas by reactions involving breakdown of amphibole has been proposed (Fitton, 1971), as an underthrust slab of amphibolite or amphibole-rich metabasalt undergoes partial melting during descent. The recent experimental data of Holloway and Burnham (1972) are especially pertinent in this context, as regards melting at low presurres (5 and 8 kb), and demonstrate the ease of formation of basaltic and andesitic liquid from a hydrous basalt source, involving essentially the incongruent breakdown of amphibole to liquid and clinopyroxene where the calculated composition of the liquid produced by extensive amphibole melting is closely comparable to alkali picrite or basanite (op. cit. p. 21)

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The breakdown of amphibole and other dehydration reactions will remove most of the water from an underthrust slab at presurres of 25 to 39 kb or about 100 km depth, apart from minor amounts of water contained in the more stable accessory phlogopite, and it seems reasonable to assume that magma generation will be enhanced by these reactions and occur preferentially at this depth. The liquid composition of a partial melt from amphibolite at this depth is unkown, but is dependent on the near-solidus phases, most likely amphibole, phlogopite and pyroxene. Unfortunately, the available high-pressure experimental studies on synthetic systems (Kushiro, 1972) and hypothetical mantle composition in the presence of water (Green, 1973) are not directly applicable to amphibolite melting, as well as being still somewhat contradictory as regards composition of the first liquid formed.

The data of Hart and Aldrich (1967) on the K/Rb ratios of amphiboles from various environments put certain limitations on a magma genesis model involving the melting of amphibolite. Ratios ranging from 100 to 5000 and averaging 1120 were reported for 50 amphiboles, whereas K/Rb ratios in the Grenada alkali picrites range from 300 to 500 (Sigurdsson et al., 1973). The model of extensive amphibolite melting to give rise to the alkali picrite is therefore not favoured by the bulk of the K/Rb data.

While the question of the origin of the basaltic "primary" magma in the Lesser Antilles is still wide open, it is clear that the presence of water and hydrous minerals plays a major role. It is hoped that present studies on trace element distribution will provide discrimination between the hypotheses of partial melting of upper mantle "pyrolite" on one hand and melting of amphibolite in the underthrust slab on the other.

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Text to figures:

Fig. 1	Geological map of Kick'em-Jenny volcano and surroundings, as deduced from PDR profiles and bottom sampling.
Fig. 2	A bathymetric profile in a north-south direction across the cone and crater of Kick'em-Jenny.
Fig. 3	Chemical variation in Kick'em-Jenny basalts on the basis of silica content. The diagram also illustrates the extraction of amphibole, olivine and plagioclase required to generate the observed trend. The heavy lines show the possible silica range of extract material required to produce the trend.
Fig. 4	A Schematic isobaric section through the system alkali basalt - water at 5 kb pressure, based on data from Yoder and Tilley (1962), Green and Ringwood (1967), Wylie (1971), Helz (1973), and Cawthorn et al. (1973).

TABLE 2 cont'd

Si	5.9325	8.00	5.9946	8.00	6.1140	8.00	6.1498	8.00
Al^{IV}	2.0675		2.0054		1.8860		1.8502	
Al^{VI}	0.5900	5.00	0.6399	4.84	0.5600	5.13	0.3850	5.22
Ti	0.2167		0.2281		0.2691		0.3507	
Fe^{+3}	0.5315		0.5456		-		-	
Fe^{+2}	0.6313		0.6945		1.1240		1.4453	
Mn	0.0155		0.0172		0.0323		-	
Mg	3.0118		2.7159		3.1470		3.0382	
Ca	1.5919	2.33	1.5972	2.33	1.8662	2.65	1.7379	2.59
Na	0.6106		0.6110		0.6902		0.7371	
K	0.1290		0.1222		0.0979		0.1116	
OH	2.5801		2.7538		-		-	
Mg value	0.70		0.66		0.73		0.68	

EXPLANATION TO TABLE 2

Chemical analyses marked KEJ018A and 020A were carried out by "rapid" methods on hand-picked phenocrysts from pyroclast dredge samples. Analyses KEJ017(1) and 017(2) are electron microprobe determinations by R. Arculus on phenocrysts in a single pyroclast fragment. Total in KEJ017(1) includes 0.02% Cr_2O_3. Structural formulas in number of ions on the basis of 24 oxygens and 23 oxygens for chemical and micro-probe analyses, respectively. Mg values are calculated from the amounts $Mg/Fe^3 + Fe^2 + Mn + Mg$ in the half-unit cell.

TABLE 2

Amphibole analyses and structural formulas

	KEJ018A	KEJ020A	KEJ017(1)	KEJ017(2)
SiO_2	41.45	41.86	42.05	42.06
TiO_2	2.01	2.12	2.46	3.19
Al_2O_3	15.75	15.67	14.27	12.97
Fe_2O_3	4.94	5.07	-	-
FeO	5.34	5.89	9.25	11.82
MnO	0.13	0.14	0.26	-
MgO	14.12	12.72	14.52	13.94
CaO	10.38	10.41	11.98	11.09
Na_2O	2.20	2.20	2.45	2.60
K_2O	0.71	0.67	0.53	0.60
H_2O^+	2.70	2.88	-	-
H_2O^-	0.04	0.06	-	-
P_2O_5	0.01	0.01	-	-
Total	99.78	99.70	97.79*	97.67

... Table 2 cont'd

EXPLANATION TO TABLE 3:

1 Black scoria from dredge across crater at 12°17'50" W and 61°38'14" N and depth of 200 m. Basalt with euhedral phenocrysts of olivine (11.7 vol. %), clinopyroxene (8.5%), plagioclase (4.4%) and megacrysts of amphibole (3.9%). Groundmass olivine.

2 Groundmass of scoria 017.

3 Black lapilli and sand recovered with a Shipek grab sampler from 220 m at 12°17'55" N and 61°38'17" W. Basalt with phenocrysts of olivine (4.0%), clinopyroxene (4.5%) and plagioclase (24.7%) and megacrysts of amphibole (16.2%). Olivine is present in groundmass. Mean diameter of the poorly sorted sample is 4 mm.

4 Grab samples of black lapilli and sand from 220 m at 12°17'50" N and 61°38'19" W. Mean diameter 5 mm.

5 Black olivine basalt lapilli and sand from 760 m at 12°17'05" N and 61°38'52" W. Mean diameter 1 mm. Poor sorting.

6 Groundmass of lapilli 014.

7 Grab sample from 1140 m at 12°18'05" N and 61°39'42" W, consisting of well sorted, black olivine basalt sand, mean diameter 0.4 mm.

8 Black lapilli from dredge in crater. Basalt with phenocrysts ofeuhedral olivine (5.5%), clinopyroxene (2.3%), plagioclase (24.9%) and megacrysts of amphibole (2.5%).

9 Grab sample of black lapilli (mean diameter 1 mm.) from 560 m at 12°17'58" N and 61°38'47" W. Basalt with phenocrysts of olivine (3.3%), clinopyroxene (5.1%), plagioclase (26.6%) and megacrysts of amphibole (2.6%).

10 Grab sample of black lapilli and sand (mean diameter 2 mm.) from 1030 m at 12°18'30" N and 61°39'27" W. Glassy basalt with phenocrysts of euhedral olivine (3.5%, clinopyroxene (1.3%), plagioclase (22.9%) and rare amphibole (0.2%).

11 Xenolith from dredge in crater. Andesitic basalt with phenocrysts of clinopyroxene (2.7%), plagioclase (24.1%) and amphibole (4.1%).

12 Grey, semi-consolidated andesitic ash layer (8-10 mm thick) from grab sample near crater. Principally colourless glass, R.I. 1.53, 0.01 to 0.05 mm. in diameter, and fragments of plagioclase clinopyroxene and amphibole.

13 Red-orange mud layer, 10 mm. thick, overlying tephra in piston core from crater at 200 m. 12°17'50" N and 61°38'16" W. Total includes: 1.75% S, 0.25% Cl and 2.68% other volatiles.

TABLE 3

CHEMICAL ANALYSES OF KICK'EM-JENNY DREDGE SAMPLES

	1 017	2 017G	3 018	4 11(2)	5 014	6 014G	7 009	8 020	9 010	10 005	11 017E	12 017B	13 021B
SiO_2	46.40	47.49	46.58	46.92	47.06	48.44	49.25	49.66	50.14	50.20	53.19	59.29	30.35
TiO_2	1.03	0.96	1.20	1.00	1.03	0.89	1.01	0.93	0.90	0.90	0.81	0.82	0.51
Al_2O_3	19.56	18.53	19.76	17.87	18.37	18.23	18.94	19.61	20.79	20.00	19.35	14.96	10.29
Fe_2O_3	2.48	2.80	2.87	2.64	2.91	2.79	2.55	2.52	1.95	2.34	2.72	0.98	27.10
FeO	6.12	5.88	6.04	6.69	5.95	5.76	5.86	5.88	6.04	6.00	4.91	4.44	1.21
MnO	0.14	0.15	0.17	0.16	0.16	0.15	0.16	0.18	0.17	0.16	0.15	0.07	0.06
MgO	9.86	9.99	8.06	10.48	9.53	9.22	6.66	5.64	3.79	4.89	4.23	3.26	4.88
CaO	10.42	10.67	11.07	10.74	10.16	10.52	9.71	9.67	10.74	10.49	8.83	8.63	4.61
Na_2O	2.23	2.25	2.47	2.18	2.35	2.22	2.66	2.92	3.15	3.17	3.03	3.35	5.06
K_2O	0.06	0.65	0.68	0.52	0.65	0.78	0.96	0.96	1.15	1.00	1.08	0.71	0.76
H_2O^+	0.54	0.52	0.82	0.50	1.01	0.60	1.36	1.55	0.61	0.52	0.65	2.95	7.06
H_2O^-	0.19	0.12	0.12	0.20	0.32	0.15	0.29	0.30	0.15	0.20	0.20	0.26	2.99
P_2O_5	0.05	0.05	0.08	0.06	0.08	0.09	0.10	0.10	0.10	0.10	0.09	0.05	0.41
TOTAL	99.62	100.11	99.92	99.96	99.58	99.81	99.49	99.91	99.95	99.97	99.25	99.77	99.97*

TABLE 3, Continued

NORMS

	1 017	2 017G	3 018	4 11(2)	5 014	6 014G	7 009	8 020	9 010	10 005	11 017E	12 017B
Qz	-	-	-	-	-	-	-	-	-	-	5.3	14.5
Or	3.5	4.0	4.0	3.0	4.0	4.5	6.0	6.0	7.0	6.0	6.5	4.5
Ab	20.0	20.0	20.4	19.5	21.0	21.0	20.0	24.5	26.5	28.5	27.5	31.5
An	41.5	38.2	41.0	37.3	37.8	37.5	37.3	38.0	39.2	37.5	36.7	24.5
Ne	-	-	1.2	-	-	-	-	-	-	-	-	-
Di	8.0	11.5	10.4	12.6	10.3	11.6	9.4	8.0	11.0	11.2	5.4	16.0
Ol	16.0	17.1	17.5	19.5	15.1	10.5	4.2	3.0	4.2	5.7	-	-
Hy	4.0	5.0	-	4.0	7.2	11.8	14.4	14.2	6.4	7.2	14.2	6.7
Mt	2.5	2.9	3.0	2.7	3.0	2.9	2.7	2.7	2.1	2.4	2.9	1.1
Il	1.4	1.4	1.6	1.4	1.4	1.2	1.4	1.4	1.2	1.2	1.2	1.2
Ap	-	-	0.3	-	-	-	-	0.3	0.3	0.3	0.3	-