Recent Submarine Pillow Lavas in the Catania Area, Eastern Sicily [and Dicussion]

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Recent submarine pillow lavas in the Catania area, eastern Sicily

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A series of scuba dives were made during the summer of 1971 to examine the development and morphology of pillow lavas. A prehistoric and a fourteenth-century lava flow were sampled, and the subaerial to submarine transition observed and photographed. The structure of the pillows formed is believed to be dependent on rate of flow and general topography. The lack of hyaloclastite is discussed and related to the pillow formation. The development of palagonite rims to the pillows by the contact of sea water on sideromelane is described. Comparative analyses obtained by electron microprobe are presented. These results indicate a leaching of Si, Ca, Na and K in the altered portions of the pillows. The possible role of this chemical exchange to the bulk chemical composition of the oceans is discussed.

Introduction

In the summer of 1971 an Oxford University geological expedition, joined by the author, visited eastern Sicily. Its purpose was to investigate any changes that may occur to lavas when the flows enter the sea. Mt Etna is flanked by many subsidiary eruptive centres, and some

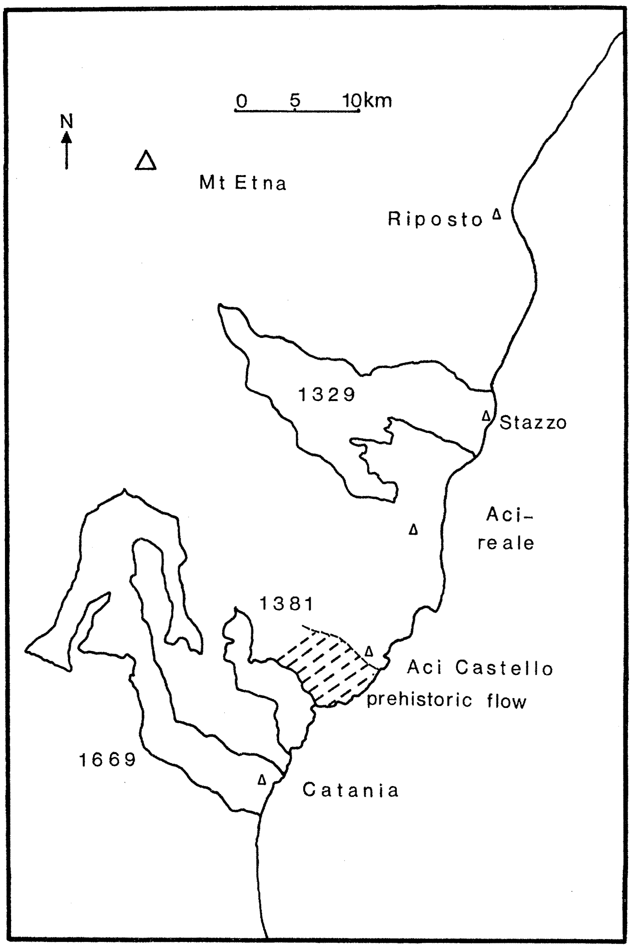

Figure 1. The location of sampled lava flows and other historic flows. Figures are the years of eruption A.D.

of the lavas that have issued from these vents provide excellent exposures for submarine and subaerial observations. Upon the recommendation of Professor R. Cristofolini of the University of Catania, it was decided to concentrate on the A.D. 1329 flow, north of Acireale, and a prehistoric flow in the vicinity of Aci Castello (figure 1). The A.D. 1669 flow also reached the sea at Catania, but the density of shipping near this city made diving hazardous.

Standard self-contained underwater breathing apparatus (scuba) was used to examine the submarine exposures. Underwater sampling with ordinary geological hammers is not difficult, providing the diver is well weighted. An underwater camera was very useful for recording the morphology of the lavas, allowing further consideration of their mode of formation. Generally visibility and lighting conditions in the Mediterranean during the midsummer are good. The selective filtering of red light by sea water is not important for photographing geological details. Total light intensity does become too low below 25 m for ordinary film.

The project was related to several aspects of marine volcanism. On an observational level, the morphology and recent development of pillow lavas was studied. This is a topic of some geological antiquity. In addition, the investigated flows passed laterally from a subaerial to a submarine environment, allowing comparative studies to be made. Sea level and, in particular, its local variation with time, is important from a stratigraphical viewpoint. Any criteria for determining the position of this boundary would be useful. Another aspect of the investigation was to determine the nature of submerged lava deltas, for which the details of formation are not fully known. Our knowledge of the evolution of the Earth's crust has recently been dramatically increased by the study of the products of submarine volcanicity. The development of ideas concerning plate tectonics has mainly involved the physical and, in particular, the magnetic properties of oceanic basalts. Recently, however, techniques for ocean-bottom sampling have become available. This has led to an increased interest in the contribution of submarine lavas to the bulk chemistry of the hydrosphere. The changes in rock compositions on contact with sea water need to be examined in order to avoid false conclusions concerning their original chemistry.

Details of rock exposure

The source of the A.D. 1329 lava flow lies at an altitude of approximately 900 m, south of the Valle del Bove (figure 1). The flow was obstructed to the south by an area of older volcanic rocks, and so followed a fairly gentle slope of 5° eastwards to the sea in the vicinity of Stazzo. The morphology of the subaerial portion of the flow varies from blocky, angular aa to ropy and contorted pahoehoe surfaces (cf. Macdonald 1953). Occasional road and quarry exposures show the flow to be formed of several units with massive central layers grading to more vesicular and clinkery material. Low, broad flow-ridges are occasionally developed, with an arching of individual layers, longitudinal and radial ribbing and jointing.

The other investigated flow entered the sea, in prehistoric times, near Punta Aguzza, south of Aci Castello (Moore, Cristofolini & lo Giudice 1971) (figure 2). Vegetation cover makes it difficult to locate the source vent or complete lateral extent of this flow. Morphological features similar to the A.D. 1329 flow are displayed, and at the shore line, deep inlets and arches which are, perhaps, the eroded remains of lava tubes, are now flooded by the sea. Again, this flow appears to be composed of several flow units. The boundary of the flow to the north, at sea level, is the ancient pillowed lava complex of Aci Castello itself. The eroded top of this formation dips gently southwards, underlying the younger flow.

It was important to be sure that the subaerial and submarine exposures are products of the same lava flows, and hence initially with the same physical and chemical properties. The marine erosion that has been active since the arrest of the flows has occasionally obscured the relationship of exposures above and below sea level. However, preservation of portions of the same unit as flow-ridges passing from land to sea indicate the contemporary relationship of the exposures examined, and allow comparisons to be made.

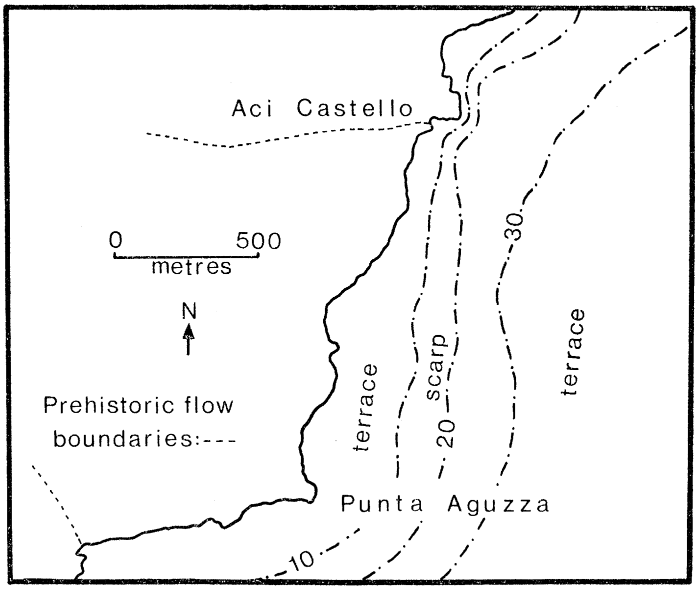

FIGURE 2. The investigated prehistoric lava flow boundaries and general submarine topography of the offshore area.

The general submarine topography appears to be related to pre-existing surfaces. In both areas investigated, these surfaces can be described as a series of terraces linked by steep scarps. These are occasionally modified by collapse and erosion. The surfaces probably indicate relative variations in sea level and consequent planation. The more recent lava flows have smoothed-out some of the irregularities of the previous topography. Terraces traced into the flows gradually become indistinct, though the broader fluctuations in level are preserved. The flows naturally followed depressions in the land surface and in the sea they have not tended to spread far laterally, unlike a sedimentary delta, from the direction of advance. Disintegrating lava blocks and boulders extend round the flanks. These vary from decimetres to metres in size. They are probably comparable with the rubble associated with terrestrial aa flows, but subsequent marine abrasion has rounded the fragments.

The surface of the central portion of the submarine lava flows displays typical pahoehoe features. These include wrinkles, small flow tongues protruding from broad flow units, and occasional flow-ridges. This morphology is developed on the level terraces of the marine section. However, where the lava has flowed over scarps linking terraces, a change in form occurs. The flow divides into a series of elongate lobes of near-cylindrical cross-section, that drape down the slope. The angle of repose can vary up to 90°. Occasionally a lobe bifurcates and this process can be repeated many times down slope. The ultimate product of this lobe division is a pillow, some of which attain nearly spherical proportions (figure 3). A complete gradation thus exists between flow lobes, pillows connected by necks, and isolated pillows. The latter have probably often rolled into positions of rest, distant from the parental flow unit. The largest pillows observed are of the order of 2 to 3 m in diameter and the elongate lobes are of similar cross-sectional width. Small wrinkles, 1 to 2 cm in wavelength, cover many of the surfaces both perpendicular and parallel to the longer axes of the units. On occasion, concentric layers coat these ridges peripherally, and only when these have been eroded can the underlying plications be seen. These features appear to represent the variations in degrees of chilling, with contortions produced by differential flow of the internal, still fluid lava. Some of the pillows display outer 'breadcrust', polygonally jointed surfaces, similar to subaerial volcanic bombs. Cross-cutting fractures expose closely spaced radial jointing, grading into a more coarsely columnar type. Many pillows have, in addition, a concentrically layered core.

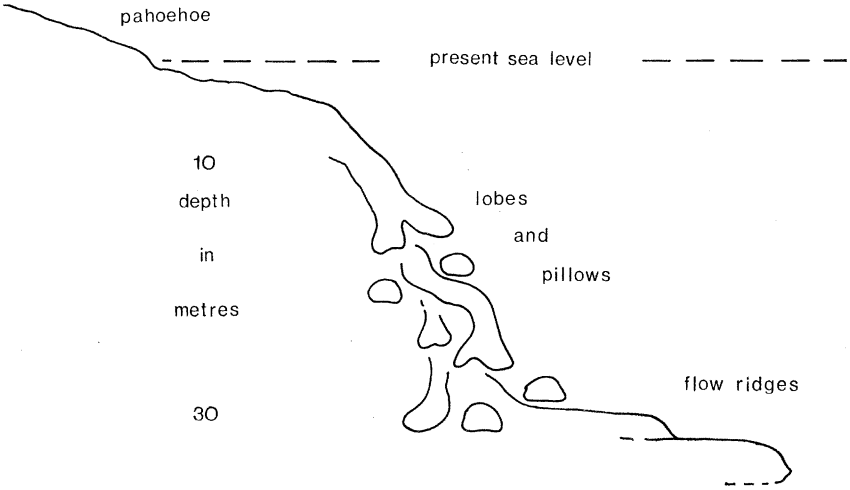

Figure 3. The general submarine flow morphologies developed in the area.

Submarine traverses were made in both areas to examine the lateral as well as the vertical changes in morphology. The older, eroded, pillow-hyaloclastite complex at Aci Castello has a distinctive appearance which is well exposed both above and below sea level. The younger flow has advanced over this formation and submarine, typically elongate and cylindrical pahoehoe toes were formed. Southwards towards the main body of the flow, these lobes lose their individuality and unite, forming a continuous sheet up to the edge of the first limiting scarp. The overall appearance of most of these steeper sections is a nest of entwined and steeply inclined lobes dividing into elongate and spherical pillows. These may rest in chance depressions on the slope and are also prominent, both whole and fragmental, at the base of the scarp near the junction with the next terrace. The reduction in angle of repose results in the development of flow-ridges. At a depth of 30 m, there is no longer a complete covering of the pre-lava surface. The ridges rest on a sandy and pebbly bottom. They are usually up to 5 or 10 m in width and similar in height. Compared with their terrestrial counterparts they are of greater relative elevation. Longitudinal ribbing and a central rift are prominent features. A generally similar sequence of lateral morphological variation is displayed by the A.D. 1329 flow, south of Stazzo. In addition, some of the flow-ridges developed have been eroded to reveal internal, vertical, columnar jointing. The ridges in both areas examined terminate bluntly and the main propagating force of the lava seems to have been largely spent by the time the deeper terraces are reached.

Pillow formation

The aqueous environment seems to be generally accepted as essential for the generation of pillow form in lavas. Several hypotheses have been advanced to explain this association. The resemblance to an emulsion has been noted in the past (Snyder & Fraser 1963). If two liquids of differing surface tension are mixed, spherical bounding surfaces are formed. However, the density contrast between magma and water is so large that any lava sphere is likely to collapse unless a chilled skin of sufficient strength is rapidly formed. Alternatively, the effective density contrast might be reduced when the lava sphere is in free fall (Solomon 1969). The globular shape is more likely to be produced because of the effectiveness of water compared with air as a cooling medium. This is partly due to the higher thermal conductivity of water and also to its high latent heat of vaporization. The heat required to raise the temperature of a given volume of water enclosing lava is much greater than a similar volume of air. Thus a chill skin is likely to form much more rapidly, and be thicker on lava in water. This may help to stabilize lava forms that would otherwise be only of a temporary nature.

Any tendency for a given body of lava to spread laterally is likely to be reduced in an aqueous environment. The effectiveness of the chilling means that the alternation of rupture of a lava skin, globular extrusion, and renewed chilling will take place more frequently. The result of this, for a lava issuing from a subaqueous vent, is to build up a structure with greater vertical thickness than a comparable terrestrial flow. The comparison of Icelandic intraglacial volcanoes, submarine Pacific seamounts and subaerial volcanic piles (Jones 1966) suggests that this is so. Once any steep primary slope has been generated, conditions favourable for pillow formation exist. Lava issuing from a vent, apically or laterally, will be subject eventually to flow on this slope. Rupture of any chill skin might lead from the extrusion of an elongate pillow connected by a thin neck, to conditions where complete separation occurs. A section through the gross structure might expose a set of these lava forms grading into feeder channels and dykes.

The volatile content and its degree of separation in a lava is ultimately a function of load pressure. The vesicularity of pillows has been used as an index of depth of formation (Jones 1969). If the combined strength of chilled skin and pressure exerted by the load of water is less than the internal vapour pressure of the lava, disintegration will occur. The deposit known as hyaloclastite is produced by the fragmentation of basaltic magma, its chilling to sideromelane, and subsequent accumulation. The initial fragmentation might also be assisted by rate of flow and grade of the slope. Studies on Icelandic intraglacial volcanoes (Jones 1966) and of pillow lavas in the Columbia River Plateau (Fuller 1931) indicate that the main generation zone is at shallow depths near the water surface, but the accumulation of the particles, as hyaloclastite, may occur deeper.

The studied Etna lava flows were erupted subaerially and were probably degassed to some extent before entering the sea. It seems that the relatively slow flow on a gently graded surface, combined with volatile loss, prevented the fragmentation of these flows into glass fragments in the marine environment. Local currents are probably effective at winnowing small fragments of rock to other depositional sites, but even the interstices of the pillows and lobes, underwater, are free of detritus.

Initially the form of the submarine Etna lavas remained little different from typical subaerial pahoehoe. However, at the change in slope of the previous topography, the increase in rate of flow led to the separation of elongate lobes and pillows. The addition of these to the slope surface would tend to advance the front of the scarp face. Budding at the upper limit of the face would tend to produce a series of 'foreset' bedded units, analogous to foresets in a sedimentary delta. The form of the submarine flow-ridges appears to be due to the effectiveness of aqueous chilling. This produces 'levee-type' bounding walls to the central flowing lava. On occasions, this conduit seems to have drained, leading to collapse of the roof and the production of conspicuous median rifts. Alternatively when movement ceased, the lava crystallized *in situ*, sometimes producing columnar joints.

GEOCHEMISTRY

Samples were collected from subaerial and submarine exposures of the same flows. Major and trace element analysis of fresh samples was carried out by X-ray fluorescence. The two flows examined are similar in bulk chemistry (table 1). The A.D. 1329 flow is more porphyritic, with larger phenocrysts of olivine, clinopyroxene and plagioclase in a more crystalline groundmass. Analyses of other Etna lava flows are also presented for comparative purposes in table 1.

TABLE 1

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	47.72	53.20	52.78	52.48	50.30	50.26	51.12	48.29	47.44
Al_2O_3	15.97	19.39	19.13	18.96	17.63	17.91	18.37	16.78	15.04
FeO*	12.18	7.80	8.20	8.66	10.07	9.99	8.64	10.32	10.74
MgO	7.08	2.25	2.45	2.59	4.55	4.26	4.39	12.06	11.50
CaO	9.78	7.78	7.91	8.15	9.08	9.04	8.65	8.86	8.65
Na_2O	3.49	5.30	5.26	4.87	4.19	4.21	4.51	3.01	3.71
K_2O	1.53	2.26	2.20	2.17	1.98	2.08	2.08	0.49	0.58
TiO_2	1.70	1.35	1.40	1.48	1.61	1.63	1.49	1.68	1.80
MnO	0.25	0.19	0.20	0.20	0.21	0.21	0.22	0.17	0.18
S	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00
P_2O_5	0.30	0.48	0.47	0.45	0.39	0.40	0.43	0.34	0.37
Ba	826	1212	1221	1224	1044	1071	1249	243	204
Nb	64	80	77	82	85	83	81	49	47
Zr	252	245	294	304	298	305	295	154	155
Y	23	27	26	25	25	26	25	26	25
Sr	1375	1806	1720	1745	1298	1316	1341	697	692
Rb	39	43	43	42	49	55	51	5	4
Zn	116	90	97	103	109	115	106	96	95
Cu	150	81	98	92	155	162	147	93	80
Ni	56	5	4	7	29	32	30	228	237

(1) A.D. 1669 lava flow at Catania.
(2) Subaerial A.D. 1329 lava flow at Stazzo.
(3) Submarine A.D. 1329 lava flow-ridge offshore from Stazzo.
(4) Submarine A.D. 1329 pillow lava offshore from Stazzo.
(5) Subaerial prehistoric lava flow at Punta Aguzza.
(6) Submarine prehistoric lava flow-ridge offshore from Punta Aguzza.
(7) Submarine prehistoric pillow lava offshore from Punta Aguzza.
(8) Pillow lava core from pre-Etna complex at Aci Castello.
(9) Pillow lava rim from pre-Etna complex at Aci Castello.

* All Fe recalculated as FeO.

No significant variation in chemistry was detected between fresh samples from different subaerial and subaqueous exposures. However, optical examination of thin sections revealed that the marine environment had produced surface alteration. Outward from the fresh basalt, the sideromelane (pale brown) gives way, usually at a sharp boundary, to palagonite (dark brown).

The intensity of this coloration, and presumably alteration, increases towards the exposed margin. There is another sharp contact between rock and the ubiquitous coating of calcite and marine life. This coating probably appears fairly rapidly after cooling of the lava in the Mediterranean. No evidence for any further layer separation was observed (cf. Moore 1966). The phenocryst minerals appear more resistant to alteration. The prehistoric flow, with up to 60% modal glass, has suffered more alteration than the A.D. 1329 flow. Greater penetration in the same rock surface has occurred away from invading cracks and fissures.

The submarine samples are weakly vesicular in comparison with the land specimens. No variation in degree of vesicularity of pillows was discovered, though the depth range of collection was probably too small to show any effect. There is an increase in vesicularity, on occasions, away from flow rims towards the centre of the units. The ground mass does become more glassy, with fewer microlites towards the margin, indicating that cooling proceeded inwards. Different textures were observed but no consistent orientation of minerals in pillows, either elongate or spherical, was discovered. Some phenocrysts are arranged radially and others concentrically to the pillow or lobe rim. This is apparently dependent on the last movement of the magma before chilling. Alteration has penetrated less deeply into the A.D. 1329 flow than into the prehistoric flow. This could be mainly due to the shorter length of marine exposure and also to the greater proportion of stable phenocryst minerals.

Table 2

	(1)	(2)
SiO_2	48.51	51.85
Al_2O_3	16.93	15.46
FeO*	9.37	9.56
MgO	4.24	2.91
CaO	8.93	6.04
Na_2O	3.98	5.10
K_2O	2.02	3.74
TiO_2	1.42	2.21
MnO	0.21	0.21
S	0.00	—
P_2O_5	0.39	—
total	100.00	97.08

(1) Offshore prehistoric lava flow at Punta Aguzza. Analysis obtained of whole rock by X-ray fluorescence.
(2) Analysis of the groundmass glass of the same specimen obtained by the electron microprobe.

* All Fe recalculated as FeO.

Polished thin sections, containing the full alteration sequence were prepared. Electron microprobe analyses, step-traversing from fresh to altered glass were obtained. Assuming that the phenocryst mineral assemblage is stable in the enclosing groundmass, the bulk X-ray fluorescence analysis provide a standard with which to approximately compare the analysis of the groundmass glass obtained by the microprobe. There is good agreement between the two approaches. The analysis of the fresh groundmass sideromelane, indicates that the glass is relatively depleted in Mg and Ca, and enriched in Si, K, and Na (table 2). This reflects the usual basaltic fractionation trend towards residual glass composition. Thus the analyses of the fresh glass obtained by the microprobe appear normal, with no loss of elements due to volatilization. However, preliminary examination by replicate counting of the same spot on the altered glasses indicated a volatilization, of alkali elements in particular. Therefore scanning for these elements was undertaken first, and the glass was exposed to the electron beam only during actual counting. Optical examination of the section surface revealed no structural damage after analysis, so it is hoped that element loss was minimal. However, comparison of analyses of fresh and altered basaltic glass from Alaska (Muffler, Short, Keith & Smith 1969), obtained by wet chemical and electron microprobe methods, indicates that alkali loss in the altered glass is exaggerated by the latter process. This suggests that results obtained in this study, which lack a comparison with alternative analytical methods, should be viewed with caution. (For electron microprobe operating conditions, see table 3.)

TABLE 3. ELECTRON MICROPROBE OPERATING CONDITIONS (CAMBRIDGE GEOSCAN MK 2)

Accelerating voltage: 15 kV. Specimen current: 0.04 μA. Diameter of electron beam: 4 μm. Counting time 20 s.

element	line	crystal	counter
Si	$K\alpha_1$	KAP	flow
Al	$K\alpha_1$	KAP	flow
Fe	$K\alpha_1$	LiF	flow
Mg	$K\alpha_1$	KAP	flow
Ca	$K\alpha_1$	quartz	flow
Na	$K\alpha_1$	KAP	flow
K	$K\alpha_1$	quartz	flow
Ti	$K\alpha_1$	LiF	sealed
Mn	$K\alpha_1$	LiF	sealed
Ni	$K\alpha_1$	LiF	sealed
Cr	$K\alpha_1$	LiF	sealed

The results obtained suggest that with progressive increase of alteration, a leaching of Si, Ca and alkalies Na and K takes place (table 4). There is also a fall in the percentage of the total of oxides listed. The wet chemical analysis of palagonite (Peacock & Fuller 1928) suggests that it contains up to 30 % water. This is perhaps the component replacing some of the elements in the altered glasses analysed. This replacement apparently takes place without a change in volume. The thin sections reveal no cracking or disintegration of altered, in comparison with

TABLE 4

	(1)	(2)	(3)	(4)		(5)	(6)
SiO_2	51.85	44.69	29.67	23.76	SiO_2	30.24	29.46
Al_2O_3	15.46	16.15	21.29	16.58	Al_2O_3	16.83	16.95
FeO*	9.56	8.46	7.39	11.46	FeO	18.72	15.53
MgO	2.91	6.65	10.63	13.46	Fe_2O_3	3.95	5.23
CaO	6.04	6.40	4.12	2.44	MgO	16.73	16.08
Na_2O	5.10	4.57	3.07	1.22	CaO	1.92	2.97
K_2O	3.74	0.75	0.44	0.21	Na_2O	0.27	0.84
TiO_2	2.21	2.47	1.72	2.61	K_2O	0.02	0.51
MnO	0.21	0.20	0.11	0.28	TiO_2	0.58	3.01
NiO	0.06	0.01	0.01	0.06	MnO	0.28	0.10
Cr_2O_3	0.03	0.05	0.03	0.02	H_2O^+	10.18	9.64
					H_2O^-	0.27	0.11
total	97.19	92.40	79.09	72.09	P_2O_5	0.11	trace
					CO_2	0.08	—
					total	100.18	100.43

(1) to (4) Electron microprobe spot analyses of fresh (1) and altered (2) to (4) basaltic glass. Intensity of alteration increasing from (2) to (4).

(5) and (6) wet chemical analyses of matrix surrounding pillows (Turner & Verhoogen 1960). (5) Matrix surrounding pillow lava, Newborough, Anglesea, Wales. (6) Matrix surrounding a spilite pillow, Alp Champatsch, Switzerland.

* All Fe recalculated as FeO.

fresh glass. This suggests that a genuine alteration of element proportions in the altered glass has occurred. Wet chemical analysis of altered pillow lava material from other areas is presented in table 4 for comparison. Presumably further leaching of elements takes place with continued marine exposure, but the intensity of the effect is likely to diminish as alteration penetrates deeper from the exposed flow skin. There seems to be accumulating evidence for the importance of submarine volcanism in the chemical balance of the oceans (Cann 1970). The alteration in composition of extruded lavas could be regarded as a weathering effect. The significance to the geologist is the possibility that ancient submarine lavas have suffered similar element exchange before any metamorphic alteration, metasomatism or weathering.

CONCLUSIONS

The aqueous environment seems essential for the formation of pillow lavas, but the degree of vesicularity, the thickness of any palagonite rim, and the generation of hyaloclastite can reflect local environmental conditions. Comparisons between widely separated areas needs to be made with caution. The alteration of the composition of marine exposed basaltic glass might lead to a false impression of the original affinities of the lavas examined, especially when original textural details are obscured.

I would like to acknowledge the support of the University of Oxford Exploration Club, and the assistance of Mr G. Baxter, Mr P. Lacey, Mr J. Thompson, Miss J. Dixon and Miss S. Jack on the expedition. The study was carried out during the tenure of a N.E.R.C. Studentship and the use of the facilities of the Department of Geology, University of Durham is gratefully acknowledged. The manuscript was criticized by Professor G. M. Brown, Dr G. A. L. Johnson and Mr K. J. A. Wills, to whom I extend my thanks.

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Discussion

H. TAZIEFF: I do not understand what you are suggesting about the mechanism of hyaloclastite generation: if you suppose that they are formed through a process involving the action of the gases originally included in the lava of the pillows, I would disagree, because this gas content and its corresponding vapour pressure would not be sufficiently high to disrupt the outer crust formed by chilling. The process of successive 'onion-skins' of glassy rock as described by Professor Rittman seems the best to account for the production of hyaloclastites derived from submarine lava flows. However, the bigger 'palagonitic tuff' formations are generated by a completely different mechanism, i.e. through more or less complete comminution of red-hot lava *lumps* (and not lava *flows*) that are hurled into the water by magmatic explosions; the steam trapped in the cavities and *under* these lumps explodes, breaks them, so liberating new red-hot surfaces which may, again, provoke new explosions. Eventually, most of the thermal energy of the lava is transformed into kinetic energy by this 'steam-engine', and the comminution of the lava is greater with the thickness of the water above the explosive vent (above the critical pressure, i.e. depth for water of course).

R. J. ARCULUS: I do not dispute Professor Rittman's hypothesis of the production of hyaloclastite. My point is that whether hyaloclastite was originally present or not, there is no longer any *in situ*. It is thus possible to have subaerial to submarine lava flow transitions without preserving in the stratigraphic record any hyaloclastite. Other criteria have to be utilized to distinguish sea level in this instance.

A. T. SANDERS: Can it be assumed that there is a significant amount of hyaloclastic material produced by lava on entry into the sea? Has the evidence been swept away by the strong coastal currents and deposited elsewhere? Is it worth attempting to dredge various samples from likely settling areas to determine the amount of hyaloclastic material present?

R. J. ARCULUS: I do not think that a significant amount of hyaloclastite was generated by the entry into the sea of the lava flows studied. Even if there had been, and the hyaloclastite was deposited elsewhere, the uncertainties involved in correlating dredged samples with supposed contemporary flows would prevent the determination of the original volumetric proportions.