PILLOW BRECCIAS AND THEIR AQUAGENE TUFFS, QUADRA ISLAND, BRITISH COLUMBIA[1]

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ABSTRACT

Pillow breccias consist of whole or disaggregated volcanic pillows in an abundant matrix of cogenetic basic tuff. They form in water and are thought to be common rocks, confused at times with other volcanic breccias.

On Quadra Island, British Columbia, the breccias usually overlie ordinary pillow lava which rests in turn upon basalt flows or upon pelagic limestone. In the transition to isolated-pillow breccia the matrix increases gradationally upward to as much as 80 per cent; the pillows become isolated, diversiform, and ill-sorted. Some pillows were broken after settling but before compaction. The matrix, consisting of cogenetic globules, granules, shards, and basaltic fragments produced beneath water, is an aquagene tuff. Subaqueous shard formation is discussed. Broken-pillow breccia forming the top of the successions consists of unsorted pillow fragments set in similar aquagene tuff which is irregularly flow-laminated and somewhat resembles an ignimbrite. Laminated aquagene tuff beds with load casts in their upper surfaces occur within broken-pillow breccia.

Ordinary pillow lava accumulated in relatively clear water, isolated pillows in increasingly turbid, vapor-charged water. Increasing thicknesses of incoherent, steam-laden pillows and tuff led to instability, subaqueous slumping, and fragmentation.

INTRODUCTION

The literature on pillow structures in volcanic rocks goes back more than 130 years, and although there are many references to associations of pillows and tuffaceous rocks, almost all the discussions have emphasized the pillows themselves and close-packed accumulations of unbroken pillows. Textbook illustrations of pillow lavas invariably show the close-packed variety. Undoubtedly this is the way pillows typically occur. But pillowed volcanics in which a very large part or even the bulk of the rock is made up by a tuffaceous matrix or in which the pillows are not whole are rather common also. Possibly they are much more common than has been generally recognized. The Palagonite formation of Iceland is an example though an unusual one. These pillow-tuff rocks are not merely inclusions of pillows in a water-lain aerial pyroclastic; the tuff is intimately related to the pillows and is composed largely of basic glass usually identical with the pillow rims but altered in varying degrees. In some places these pillow-tuff rocks grade into rocks that are entirely of basic tuff.

Such rocks—in part pillow or pillow-derived and in part cogenetic basic tuff or lapilli tuff—are *pillow breccias*.[3] A study of them yields some interesting information on the genesis of pillow structure and the environment it represents. It throws some light also on the formation of volcanic tuff entirely beneath water—a rock type for which the term "aquagene tuff" is herein proposed.

A first impression of pillow breccias as one sees them in the field can be had from plate 1. These are fragmental rocks with apparent clasts of andesite-basalt of a variety of shapes, from a few inches to a few feet in diameter, set in a fine- to medium-grained matrix which may be of a different color than the large clasts but apparently also clastic itself. At least the matrix resembles a compact tuff or lapilli tuff in some expo-

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[3] The term "pillow breccia" apparently was used first in the present sense by Henderson (1953) for an occurrence in the Precambrian of the Yellowknife District with isolated unbroken pillows. It was again proposed in 1955 by Chapman for pillow-shaped fragments of diabase or gabbro in granitic material. The term had already been used by Henderson at the time of Chapman's proposal, however, and it would seem that some other equally descriptive term for rocks entirely unrelated to classical pillow lavas would be more suitable. Henderson's "pillow breccia" is equivalent to "isolated-pillow breccia" herein.

sures: but in other exposures, one may not be sure from macroscopic examination that it is not a flow lava. In some occurrences the pillows are whole but so widely scattered as to suggest the bombs in an agglomerate. In others the rock is obviously volcanic breccia or tuff-breccia. The clasts appear possibly to be explosion fragments. In still other occurrences the "fragments" are rounded but highly irregular in shape and the matrix has a recognizable foliation around their edges. These may suggest the clasts in a flow breccia.

These photographs and the description given below are from volcanics of the Vancouver group, a thick predominantly volcanic succession of Triassic eugeosynclinal rocks along the coast of British Columbia. Ordinary pillow lavas are common in the Vancouver group, often intimately associated with limestone, and there is general agreement that these are submarine in origin. "Agglomerates" and breccias are common too, and these are customarily considered to be pyroclastic or flow breccias. Some are said to indicate subaerial or near-shore erosion. The writer has been able to make a careful study of only a small part of the Vancouver volcanics in an area where breccias and pillow lavas are common. In his opinion, all the breccias he has seen are pillow breccias of submarine origin. Similar structures in the Tertiary Metchosin volcanics of southern Vancouver Island, in the Eocene basalts and palagonite breccias along the Oregon Coast, in parts of the Franciscan of California, including the Point Bonita section, and in the Miocene volcanics of the Santa Monica Mountains near Los Angeles were studied briefly. Comparisons have been made also with several occurrences of apparently similar rocks described in the literature, particularly the Precambrian "pillow breccias" described by Henderson (1953) and the Quaternary "basalt-globe breccias" of Iceland.

In this paper, the unmodified term "pillow lava" is used only for the typical close-packed or fairly close-packed accumulations of unbroken pillows—a rock generally with less than 10 per cent matrix. "Agglomerate" is taken to be a pyroclastic composed largely of volcanic bombs. Tuff is a pyroclastic rock of grain size generally less than 4 mm. regardless of the mode of origin.

I. OCCURRENCE AND KINDS OF PILLOW BRECCIA

The best opportunity afforded the author to study pillowed volcanics of the Vancouver group and pillow breccias in general has been on Quadra Island at the north end of the Strait of Georgia in British Columbia. Here the kinship between pillow lavas and the breccias is particularly well displayed. The rocks are olivine-free andesite-basalt slightly to moderately altered and not less than 6,000 feet thick. Some 90 per cent are massive amygdaloidal and porphyritic flows which are from 2 to 50 feet thick. The remaining 10 per cent or so of the section is pillow lava, breccia, tuff, and occasional thin calcareous beds associated with pillow lava. The pillow breccias are discrete layers from 2 to 600 feet thick and from a few hundred feet to a few miles in outcrop length within the volcanic succession. They occur at several horizons within the flows (fig. 1). With few exceptions, they are associated with ordinary pillow lava.

Two kinds of pillow breccia have been mapped.

a) Isolated-pillow breccia (equivalent to "pillow breccia" of Henderson).—This is the kind in which irregularly shaped but unbroken pillows are widely separated from each other by tuffaceous matrix (pls. 1, *A*, 2, *B*, *C*, *D*). On Quadra Island this kind almost always grades downward into ordinary pillow lava; in some places only a foot or so of pillow lava, in others a hundred feet or more. Commonly the transition is only a few feet thick, and the bulk of the section is readily mapped either as pillow lava or as pillow breccia. Where the boundary is not so obvious, the rock has been classified as ordinary pillow lava if the matrix amounts to less than 10 per cent of the whole; pillow breccia if the matrix is more than 10 per cent. The genetic relationship between isolated pillows and close-packed pillows when they are in association, as they are here, is fairly obvious; and undoubt-

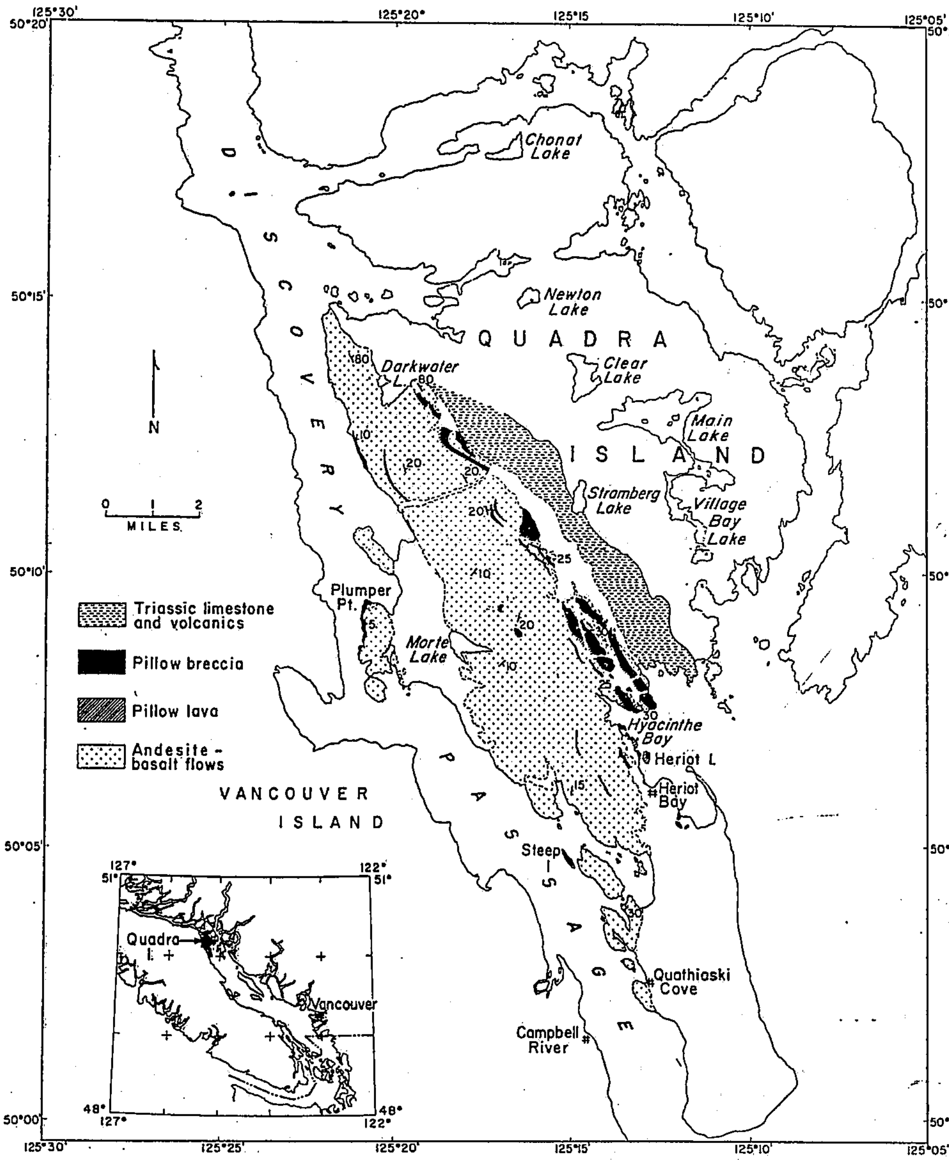
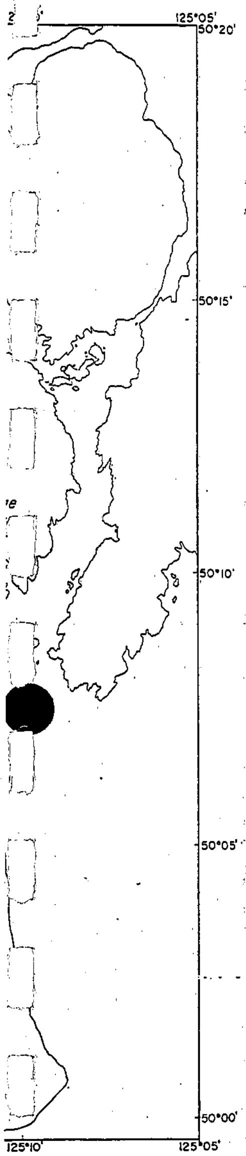


FIG. 1.—Generalized geologic map showing distribution of pillow breccias (undifferentiated) on Quadra Island, British Columbia.

PLATE 1

A, Isolated-pillow breccia with strongly deformed but only moderately isolated pillows on a glaciated and wave-washed surface, northwest coast of Quadra Island (Deepwater Bay, eastside). This unit grades downward into close-packed pillow lava 30 feet below photograph.

B, Broken-pillow breccia containing some whole pillows on a glaciated and wave-washed surface, northeast corner of Heriot Island. (*For* Vol. 70 *read* Vol. 71.)



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ted pillows on a glaciated
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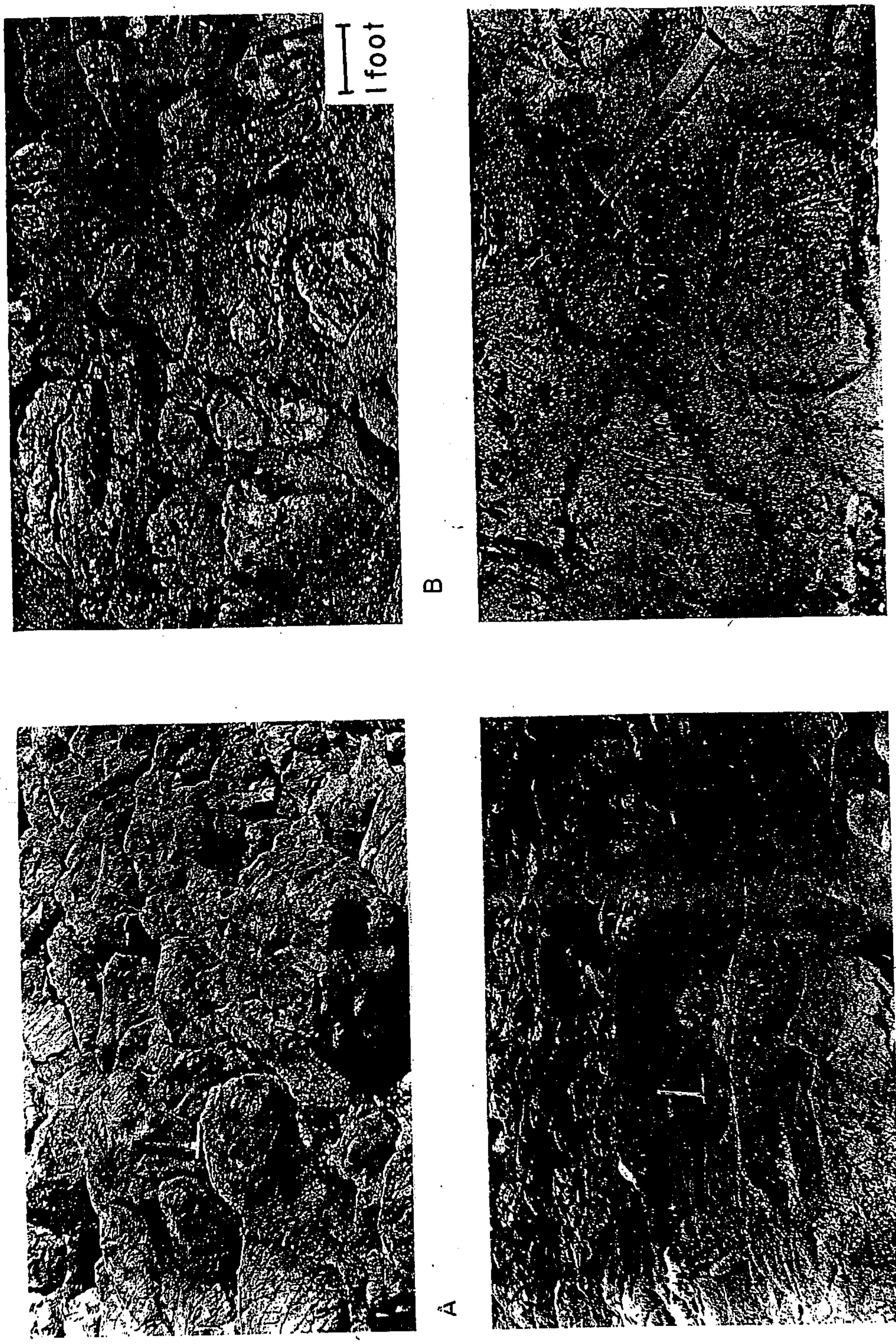
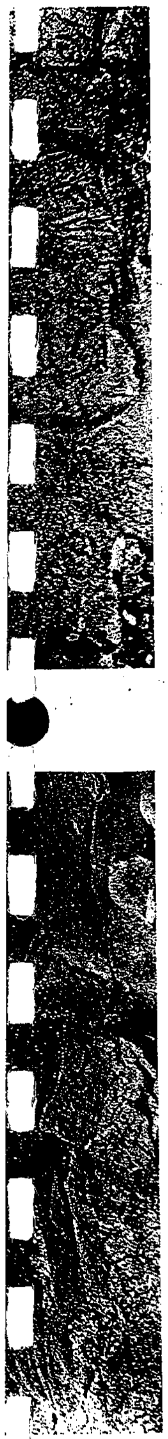
A

B

Pillow Breccias, Quadra Island, B. C.



Pillow Lava and Isolated-Pillow Breccia, Quadra Island, B. C.



D

C

Pillow Lava and Isolated-Pillow Breccia, Quadra Island, B. C.

edly many other occurrences of isolated-pillow breccia thus associated have been recognized as a variety of pillow lava (e.g., Emerson, 1897, pl. 5). Other occurrences, however, perhaps not so obviously associated have been identified incorrectly or only loosely as "agglomerate" or "breccia" or "flow breccia."

b) *Broken-pillow breccia*.—The second kind consists largely of disaggregated fragments of pillows set in the matrix (pls. 1, *B*, 4, *A*, *B*). On Quadra Island this kind almost always lies upon isolated-pillow breccia or upon ordinary pillow lava, and the basal contact is usually an abrupt gradation. Not all the clasts are necessarily pillow fragments and they may show some variety in color and texture. Laminated tuffs occur within broken-pillow breccia.

Either kind of breccia is known to occur without the other in particular outcrops and has been seen to occur without subjacent pillow lava, though this latter circumstance may be a matter of incomplete exposure. Either kind may be from a few feet to several hundred feet thick. Thickness and texture of the breccias change along strike and some breccias are observed to grade into massive flows. In mapping it commonly has not been possible to distinguish neatly between isolated-pillow and broken-pillow breccia. In these situations, the rock is a mixture or varies from one type to the other and is mapped simply as "pillow breccia." Most typically, though, as shown diagrammatically in figure 2, the succession is from ordinary pillow lava at the base up to isolated-pillow breccia and then to broken-pillow breccia at the top. Usually this succession is followed by massive flows but in a few occurrences—as on the north shore of Hyacinthe Bay for example—pillow breccia is overlain by another cycle of pillow lava and breccia.

The occasional thin calcareous beds mentioned above are found at the base of pillow lava, not within pillow breccia. The thin lenticular units of laminated tuff occur within broken-pillow breccia, not within pillow lava. Commonly in these occurrences, the laminated tuff with only a few breccia fragments grades abruptly downward into broken-pillow breccia with abundant matrix.

II. VOLCANICS CONTAINING THE BRECCIAS

Although these volcanics are clearly part of a eugeosynclinal accumulation, most of the flows are more similar mineralogically to ordinary tholeiitic flood basalts than to the spilites commonly found in this environment. Plagioclase in the relatively unaltered flows usually falls between An_{30} and An_{70} in composition and predominantly is An_{40}. Slightly less sodic compositions have been found in Vancouver group volcanics in southern Vancouver Island (Clapp, 1914, 1917: mainly An_{45}) and in northwestern Vancouver Island (Gunning, 1931; Hoadley, 1953: mostly An_{55}). The pyroxene is subcalcic augite ($2V_z = 40°$; $Z \wedge c = 40°–55°$). Only in some of the more altered flows have plagioclases more sodic than An_{30} been found. Twelve out of seventy specimens examined in thin section can be called spilites on this basis, but another dozen have plagioclase so highly altered that its composition cannot be ascertained. All of the flows determined as spilitic thus far are either closely beneath pillows or pillow breccias or near major zones of shearing. Pillows and pillow breccias are not restricted to sodic varieties, however.

Neglecting the alterations, the flows are porphyries and amygdaloids most commonly intersertal to hyalopilitic,[4] less com-

[4] For facility of expression, terms indicating the original glass content of these rocks are used throughout the paper in spite of the fact that almost all of the glass has devitrified or been replaced.

PLATE 2

A, Ordinary close-packed pillow lava eroded by waves on southeast shore of Heriot Island.
B, Isolated-pillow breccia at Plumper Point. Pillows are slightly more elongate than usual.
C, Isolated-pillow breccia south of Plumper Point showing a high ratio of matrix to pillow.
D, Typical isolated-pillow breccia in the occurrences west of Stramberg Lake. A set of epigenetic fractures is conspicuous in the pillows but not in the matrix between. (*For* Vol. 70 *read* Vol. 71.)

monly intergranular to subophitic in texture. Up to 20 per cent or more of the original rock is glassy or cryptocrystalline mesostasis usually with abundant microlites. In the porphyries plagioclase phenocrysts and glomerophenocrysts from 2 to 10 mm. across make up about 10 per cent of the rock and as 15 to 20 per cent in some. Apatite, commonly poikilitic in plagioclase, is a common accessory. Chlorite, epidote, pumpellyite,[5] tremolite, quartz, chalcedony, calcite, prehnite, and zeolites occur as alteration products and amygdule fillings apparently in a gross zonal arrangement unrelated to the

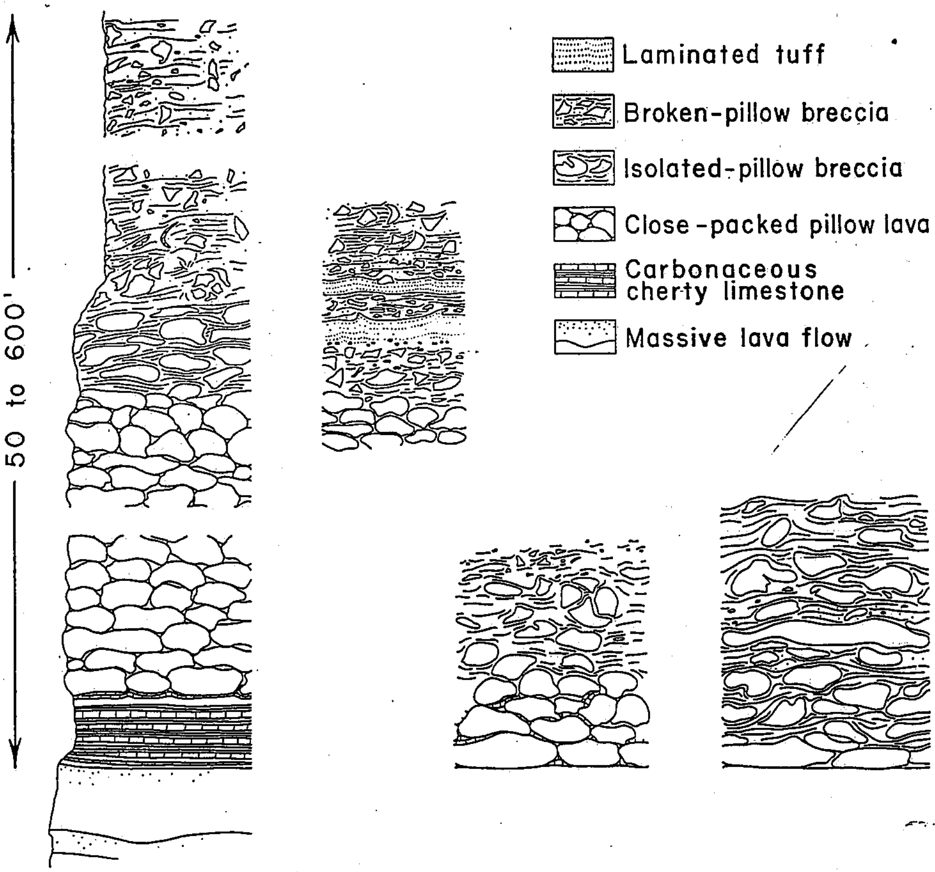


FIG. 2.—Diagram showing some typical successions in pillow-breccia occurrences on Quadra Island

euhedral laths in the groundmass up to 0.5 mm. long make up another 30 per cent. In the amygdaloids, plagioclase laths range from 0.05 to 4.00 mm. in length and phenocrysts or glomerophenocrysts are sporadic. The augite, as subhedral and euhedral crystals from 0.05 to 1.0 mm. in diameter and as glomerophenocrysts, constitutes about 40 per cent of the rock. Iron ores are present in nearly every specimen, constituting as much distribution of pillow lavas or breccias. Locally, small amounts of chalcocite, bornite, native copper, and their oxidation products fill amygdules and fractures.

With few exceptions, the flows on Quadra Island rest directly upon each other without interflow sediment or at most with only a thin selvage of cherty or carbonaceous mate-

[5] Pumpellyite was discovered in these rocks by J. L. Jambor (1960).

rial. Even very thin flows commonly show amygdaloidal tops, and this is frequently the only good basis for establishing the attitude of flows. In general, the flows are continuous and uniform over hundreds to thousands of feet along strike. Local variations in thickness and consequent variations in initial dip of 10° or so are common. The surfaces of flows where observed are not notably ropy. The volcanics are overlain on the east (fig. 1) by Upper Triassic carbonaceous limestone with thin interbedded flows partly of pillow lava (the "Lime Belt"). They are apparently underlain in the upper Campbell River area to the west of Quadra Island by Permian rocks. These volcanics are almost certainly correlative with similar ones on Texada and Lasqueti Islands fifty miles or so to the southeast (Texada formation) and probably with the Karmutsen volcanics of the Nimpkish Lake-Zeballos area 60 miles to the west.

III. SUBPILLOW SEDIMENTARY ROCKS

Some units of pillow lava on Quadra Island rest directly upon massive porphyritic or amygdaloidal flows with little or no interflow material. As is prevalent with pillow lavas, however, thin calcareous or cherty units occur here and there at the base of the pillows—and these contain marine fossils. This is significant because it indicates that volcanism ceased, at least locally, prior to the formation of pillows. The units are from a fraction of an inch to 5 feet thick and are composed of very thinly bedded, highly carbonaceous limestone, or of limestone and laminated limey chert. Invariably the bedding in the upper part of the units is distorted from the settling into place of overlying pillows. The limestone may be squashed upward between the pillows for as much as 5 or 10 feet indicating that the sediments remained appreciably plastic while the overlying pillows accumulated.

These calcareous and cherty beds record a distinctive, entirely pelagic environment. Though varied in composition, all of them are very fine grained and very poorly sorted. All are markedly carbonaceous and —with rare exceptions—are mixtures of detrital grains, and of chemical, colloidal, or biochemical precipitates or clasts therefrom.

a) Limestone.—Limestone is the more abundant component, making up essentially all of the beds in some places; only 40 per cent in others. Apart from late veinlets, calcite appears in the limestone as fossil shells, as irregular microcrystalline grains and foliate masses, and as anhedral crystals 0.5–1.5 mm. in diameter. The shells are *Halobia sp.* (Upper Triassic), a very thin-shelled pelecypod 1–2 cm. across. They tend to lie along the bedding both concave up and down and they are extremely abundant in some layers, making up as much as a third of the rock. Unbroken valves are common in non-deformed layers, but none could be shown to be articulate. Very likely many or all of the foliate microcrystalline masses which make up about half of the calcite in non-cherty layers are shell fragments also which have been smeared out by post-diagenetic deformation. Up to 50 per cent of the material in the limestone is black and aphanitic, apparently a mixture of carbonaceous substances and clay. Chlorite was determined by X-ray. Abundant carbonaceous material appears in acid insoluble residues. Scattered angular to subangular crystals of quartz, microgranular quartz, chalcedony, and alkali feldspar up to 0.05 mm. in diameter occur at random or along some laminae. Dolomite is absent.

b) Chert.—Under magnification, the "chert" turns out to be either spherulitic chalcedony (var. quartzine), that is, true chert or, more commonly, a very fine-grained wacke with microclasts of plagioclase, calcite, chalcedony, and quartz in a dark aphanitic matrix. The spherulitic chalcedony is restricted to a few beds or laminae commonly near the base of the subpillow sedimentary rock unit, suggesting that the silica from which it crystallized was present at the beginning of sedimentation. Fine-grained calcite is distributed through the chalcedony tending to increase upward in amount and grain size in a given lamina. Over the same interval, the diameter of the chalcedonic spherules tends to decrease from 1 mm. to 0.25 mm. or less. Shells of *Halobia* included in more calcic portions of the chert limit the growth of spherules, indicating further that the chalcedony crystallized after sedimentation.

c) Microwacke.—The microwacke is in discrete thin beds or laminae, usually in the upper part of a subpillow section, and shows obvious grain gradation and minute load casts upon underlying limestone laminae. The grains and clasts are (1) very small, highly irregular grains of turbid calcite constituting generally 10–20 per cent of the rock and tending to increase upward in a given lamina; (2) microlites and serrate grains of alkali feldspar and angular fragments of unzoned calcic plagioclase (An ~ 50) up to 0.2 mm. diameter making up 10–40 per cent of the rock; (3) quartz in scattered angular grains and microgranular aggregates 0.05 mm. or less in diameter constituting up to 10 per cent; and (4) chalcedony in rounded irregular aggregates about 0.1 mm. in diameter and as felted masses. The matrix constituting up to 75 per cent of the rock in the upper part of some laminae is apparently fine-grained chlorite, carbonaceous matter, and other non-resolved materials. Both the amounts and sizes of the feldspar, quartz, and chert clasts decrease upward in a given lamina.

Nothing in these subpillow sediments indicates proximity to a land area or suggests that a subaereal environment could have existed immediately prior to or soon after their deposition. Rock fragments or minerals such as muscovite, zircon, rutile, or tourmaline, which can be expected in terrestrial sediments, are completely absent. The clasts observed all could have been derived very locally from the volcanics, from shells, or from chemical or colloidal precipitates. These are very immature sediments without evidence of weathering or of erosion or sorting by competent currents. Accumulation was probably quite rapid. The very fine-grained, well-developed lamination, abundant chert and carbonaceous material, and a few scattered grains of diagenetic pyrite combined with the lack of current structures and the delicacy of the *Halobia* shells indicate a quiet and probably richly organic environment. If *Halobia* did grow in this environment, and the abundance of this single species suggests that it did, the depth, according to paleontologists, could have been anything down to several hundred feet and the basin of accumulation could have been tens of miles from any land. Even assuming that all of the *Halobia* immigrated as larvae, the period of volcanic quiescence would have been many months, perhaps a few years.

IV. PILLOW LAVA

The close-packed pillows, which on Quadra Island typically form the base of pillow breccia successions, have all the characteristics of classical pillow (ellipsoidal) lavas (pl. 2, *A*). One sees overlying pillows molded against those below; and there are balloon, bun, loaf, and bolster shapes. In some places, the pillows have a common or a preferred elongation. Some are flattened. Interstices between pillows may be filled with unsorted angular glassy material of which some, but not all, is apparently spalled from the pillows themselves; or they may be filled with quartz or other minerals found in the amygdules. The pillows have a chilled rim 1–2 cm. thick consisting largely of devitrified sideromelane and tachylyte on the outside which passes into merocrystalline lava in the body of the pillow. Typically, one or more concentric layers of amygdules occur just beneath the rim of the pillows, commonly elongate along radii of the pillows. In addition to the amygdules, some pillows have an irregular polyhedral or rounded hollow area in the center or perhaps two or more of these in irregular pillows, subsequently filled with quartz or other amygdule minerals. Radial columnar jointing is fairly evident in most pillows; a tendency to concentric jointing is less so. Very rarely a sill of columnar basalt occurs within the section of close-packed pillows.

The pillows are both porphyritic and amygdaloidal, and except for a greater proportion of glassy mesostasis and small crystals, they are essentially the same mineralogically (plagioclase An_{30-80}, subcalcic augite) as the flows immediately adjacent to the pillows or in the general area. Sodic varieties are no more or less abundant. The pyroxene commonly is finer grained and less regular in outline than in the flows and in some pillows tends to be more highly altered than the plagioclase. Hyalopilitic and hyalophitic textures are prevalent, of course. Alteration is more general in the pillows than in the flows and epigenetic quartz in fillings, and as replacements is locally much more abundant; but otherwise, the alteration minerals—largely chlorite, epidote, and pumpellyite—are the same as in adjacent flows.

Three charasteristics differentiate these close-packed pillows from the pillows of the pillow breccias described next. (1) Broken, disaggregated or split pillows are extremely uncommon except as these might be produced by entirely epigenetic processes. (2) Within the limits described above, the pillows are reasonably regular in shape; that is, they are generally spheroidal, ellipsoidal or globular; they are not involute, recurved, or highly irregular. (3) They are reasonably uniform in size, perhaps 1–4 feet in maximum diameter in a given outcrop; 2–12 feet or, rarely, 15 feet in another. Very small pillows are rare.

Microscopic description of the relationships between devitrified tachylyte and sideromelane in the rims of the pillows and between these substances and particles in the matrix between pillows is deferred to the next section since these relationships are the same in ordinary pillow lava and in isolated-pillow breccia.

V. ISOLATED-PILLOW BRECCIA

1. *The transition.*—The transition from close-packed to isolated pillows usually becomes evident in the Quadra Island exposures some 2–100 feet above the base of the succession. The change is entirely gradational with nothing to indicate that the isolated pillows are intrinsically different in their origin from the close-packed pillows below. Above the transition, one still finds both massive and amygdaloidal pillows. The pillows have chilled rims and peripheral amygdules, some of which show radial elongation. There are hollow cores and columnar joints more or less radial, though the latter are certainly less common and less obvious than in close-packed pillows. Again the main body of the pillows has an original composition like that of the flows (plagioclase—An_{30-60}; pyroxene-subcalcic augite), except that the glassy mesostasis is more abundant. The texture is like that of the close-packed pillows, and the alteration minerals are the same, though slightly more abundant. The shapes and the relative abundance of the pillows, however, have changed considerably.

The isolated-pillow breccia is a nonstratified, unsorted mixture of whole volcanic pillows, varying widely in form and size, engulfed in a volcanic matrix which itself is a tuffaceous breccia. The matrix tends to increase in abundance upward in the section to as much as 80 per cent of the rock (pl. 2, *C*). Even though it is soft, the matrix is a much tougher material than either the pillows or the massive flow. As a consequence, one frequently sees epigenetic fractures well developed in the isolated pillows and with a common orientation from pillow to pillow but hardly visible or absent in the matrix between them (pl. 2, *D*). This toughness of the matrix probably accounts for the breccias being more resistant to erosion and for their tendency to form ridges and to modify coastlines. The effect is visible at several places along Discovery Passage.

Foliation in the matrix is especially noticeable close to the isolated pillows and where the ratio of matrix to pillow is about 1:1 or less. Invariably it conforms with the surface of the pillows, following each embayment or bulge. It squeezes together in narrow areas between pillows; away from the pillows, it levels out to conform closely with the attitude of the breccia unit as a whole, though in these places it may be very indistinct. It is quite unrelated to any epigenetic fracture or shear pattern in the breccia. Without doubt, this foliation was produced during emplacement of the pillow breccia mass, settling of the isolated pillows into place, and compaction of the whole.

No other gravity-oriented structures are seen in the isolated-pillow breccia; no evidence of current transportation or erosion, no sorting, and no preferred orientation of fragments other than that described below for the globules of altered sideromelane within the matrix.

2. *Differences in form of pillows.*—Since they rarely touch each other, upper pillows in the breccia are not characteristically

molded against previously solidified lower pillows. Shapes of pillows cannot be used, therefore, to determine sedimentary facing. In a few places where the matrix is not abundant, one may find lower pillows matching the spaces between upper ones and vice versa. Many pillows are almost ovate. Some have a single re-entrant (see fig. 4 below), suggesting that they were folded over while still plastic. A few are slightly segmented or lobate, and the occasional one is highly drawn out. Only one example has been seen which might be construed as a neck connecting two pillows as though one had budded from the other. In general, the isolated pillows are completely lacking in symmetry or regularity of outline. They show no preferred orientation.

The pillows are not shaped like explosion products. They are globular rather than angular. There are no twisted forms or tails characteristic of bombs and no "breadcrust structure." Although the shapes resemble those found in some flow breccias, the peripheral arrangement of amygdules and the chilled rim completely around the pillows do not fit at all with that origin.

3. *Differences in size of pillows.*—Large and small pillows seem to have been dumped at random into the isolated-pillow breccia. Small pillows are, in general, much more common here than they are in the close-packed pillow lavas, and the proportion of small and tiny pillows tends to increase upward. In the upper parts of some sections, most of the pillows are less than 1 foot across.

Some may object to the use of the term "pillow" for spheroidal masses only a few inches across. Perhaps "spheroid" or "globe" would be more suitable, especially since the small pillow masses tend to be more spheroidal and regular in outline than the large ones. But even with these tiny masses, there is nothing to indicate an origin fundamentally different from that of larger pillows. Where large and small pillows occur together, the appearance of the central masses and the thickness and appearance of the chilled rims are the same. The ratio of chilled rim to total volume is greater for small pillows, of course, and some tiny ones are chilled right through.

The more perfectly spheroidal shape of small pillows is expectable also, since the ratio of spheroid-producing stresses (surface cohesion in the plastic lava globe) to spheroid-deforming stresses (body forces resulting from gravity upon the mass of lava within the pillow and shear stresses across the pillow associated with movement) is much greater for small globes than for large ones.

4. *Devitrified sideromelane-tachylyte rims.*—Most of the glass in these Triassic rocks has become crystalline. However, the initial textures and, to a large degree, even the colors in the pillow rims are apparently very well preserved, for one can easily recognize in them the same relations found in the rims of much younger non-devitrified pillows. These are the relations described by Peacock (1928), Fuller (1932, p. 106), Noe-Nygard (1940, p. 25), and others, between sideromelane, the translucent glass in the outermost rim of the pillow, tachylyte, the brown turbid glass farther in, and the plagioclase and pyroxene phenocrysts. Plate 3, *A*, shows the rim of a typical isolated pillow with the outside layers strongly fractured, but not disaggregated or spalled off as they are on many pillows. Intermediate plagioclase as microlites, laths, and occasional glomerocrysts up to 4 mm. across and augite as phenocrysts up to 1 mm. across—both altered in about the same way and to about the same degree as elsewhere in the pillow—constitute about 35 per cent of the original vitrophyre. They show no evidence of resorption or remelting of the crystal rims.

The "glass" of the outermost centimeter or so of the vitrophyre is translucent pale yellowish-green to olive buff in thin section and almost isotropic. Under high power and strong illumination, most of this "glass" is seen to consist of minute intergrowths or spherules showing the anomalous blue or brown interference colors of chlorite—confirmed as prochlorite by X-ray powder photograph. Some of it, however, shows no birefringence even under the strongest illumination used. This layer of "glass" is taken to be devitrified sideromelane in the sense that Peacock used this term: "clear, pale-colored basaltic glass produced by drastic chilling of basalt magma (subglacial extrusion in Iceland, and submarine eruption in the case of the shell-bearing tuffs of Sicily and the non-pumiceous deep-sea examples), as distinct from the less rapidly chilled vitreous selvages of basaltic intrusions which are typically deep-brown or nearly opaque in thin sections due to incipient or advanced separation of turgid or opaque bodies consisting mainly of magnetite" (Peacock and Fuller, 1928, p. 373).

In addition to the very-fine-grained chlorite, plentiful epidote, minor tremolite, and other alteration minerals common to the pillows, the "sideromelane" contains abundant minute aggregates each about .005 mm. in diameter of a high index, highly birefringent brownish mineral, possibly sphene or anatase.

The transition from "sideromelane" to "tachylyte" begins with the appearance within the chloritized sideromelane of scattered rusty brown spherules up to 0.1 mm. in diameter containing goethite, and with coronas of this same material around plagioclase and pyroxene crystals. The goethite was determined by X-ray powder photograph. Progressively inward, the goethite-bearing spherules increase at the expense of the "sideromelane" until at about 2 cm. or so below the surface of the pillow, the groundmass is entirely radiating brown clusters each a fraction of a millimeter across. Except for the alteration of the outer glass to chlorite, the whole sequence agrees precisely with descriptions by Fuller and Noe-Nygard of the transition from sideromelane to tachylyte. Peacock's opinion that sideromelane—as a result of its drastic quenching—retains iron in solution, whereas tachylyte—having chilled more slowly—contains the iron as segregated minerals, appears to apply to these occurrences.

Amygdules are moderately abundant in the chilled rims and in general are more perfectly spherical than those in the interior of the pillows. They are filled most commonly with chalcedony and chlorite with or without epidote. In some slides, a channelway clearly connects a chlorite-filled amygdule in the rim of the pillow with an apparent source in the matrix outside the pillow. Scattered minute fibers of tremolite replace the chlorite in the channelways and amygdules and are noticeably abundant in the altered sideromelane adjacent to the channelways.

VI. THE TUFFACEOUS MATRIX

1. *Globules, granules, and shards.*—Macroscopically, the matrix between isolated pillows is usually a fairly even-grained, compact, coarsely tuffaceous rock. Its color is brown or gray, commonly reddish where the pillows are gray, and grayish where the pillows are brown. A sawn or moistened fresh surface shows irregular light and dark mottles of medium grain size. Occasional amygdule-like areas may be occupied by quartz. Filling and replacement by fine-grained quartz between fragments in the matrix as well as along fractures in the pillows is very noticeable in some outcrops. Rock fragments over 0.5 cm. are not abundant where the pillows are 1 foot or more apart, but are increasingly common where the pillows are less isolated, especially in the transition to broken-pillow breccia.

Microscopically, the matrix is extremely interesting, for although much of it has vitroclastic texture it is neither an ordinary water-lain subaerial tuff nor does it consist merely of fragments broken from pillow rims. Instead, the greater part of it—60–80 per cent—is made of distinct globules and granules of chloritized sideromelane or sideromelane vitrophyre and of shards, many of which are visibly formed by cracking and splitting apart of the globules and granules *in situ*. These fragments along with some crystals are enclosed in an extremely fine-grained chloritic mesostasis, some of which shows flowage around the particles. There is no suggestion of aqueous bedding, grain gradation, or current structures, and nothing that requires an explosive origin for the shards.

The globules are discrete ellipsoidal bodies of altered vitrophyre from 0.25 mm. to 1 cm. in longest dimension. The occasional one is vaguely teardrop-, or spindle-, shaped; still fewer are recurved. Some appear to have been squashed. Nearly all have convex and concave portions and tiny fractures or irregularities along their surface, but none show abrasion or corrosion of these irregularities. They suggest more than anything else moderately viscous droplets caught haphazardly in a slow-moving pasty stream. Some globules are whole and unfractured; others are so granulated as to be hardly recognizable as once-coherent masses (pl. 3, *B*, *C*). They are completely unsorted as to size but show some preferred orientation of the long axes, and this is what gives the rock much of its slight foliation. The material of the globules, and of the granules and shards, has the same appearance and contains the same phenocrysts as the outer rims of the pillows. The bulk of it is chloritized sideromelane, pale greenish-tan in color, with varying amounts of brown ferruginous stain, and of minute ferruginous aggregates—some closely resembling the sphene or anatase (?) in the pillow rims, others about the same size and shape as the sphene or anatase (?) but without birefringence. Many of the globules contain a single great phenocryst or glomerocryst of plagioclase or subophitic plagioclase and pyroxene. Others contain crystals or clusters of plagioclase and pyroxene throughout. The outermost 0.1 mm. of the globules is commonly free of iron stain and of the minute ferruginous aggregates, the adjacent mesostasis usually being deep brown in color, suggesting that the iron has migrated out from the glass on the rim of the globules. In some fractured globules, the chloritized sideromelane is almost completely bleached of iron stain or of minute aggregates, and a thin, dark brown ferruginous layer has developed along the outer edge of the shard fragments. Amygdules up to 1 mm. or so are present in globules, granules, and shards but are not noticeably abundant.

Granules differ from globules only in that they are bounded in part by conchoidal fractures. Generally, the corners are subrounded and some show plastic deformation. Apparently there is a gradation from granules to globules. Some granules probably are chunks from larger globules, and some may be spalls from outer pillow rims.

Tachylyte is found in the breccia matrix only in the cores of tiny pillows or as angular to subangular particles apparently broken from pillows, since they are generally more abundant near pillows. These are the rock fragments that one sees megascopically. Globules formed completely of tachylyte have not been found. Unlike the globules, moreover, the tachylyte fragments observed do not show iron-depleted borders.

Typically the globules and granules of chloritized sideromelane vitrophyre are divided into a mass of chunky shards from

PLATE 3

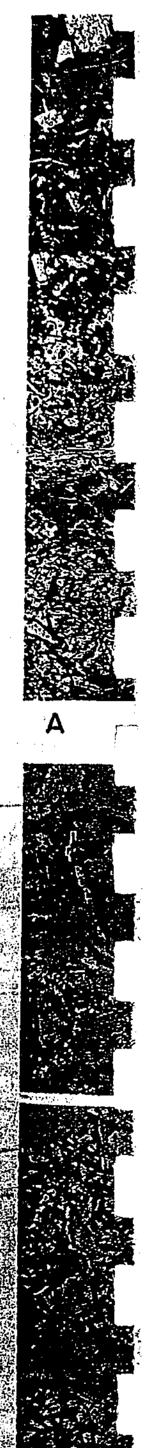
A, Rim of isolated pillow showing transition from fractured chloritized sideromelane vitrophyre of outside rim (*bottom*) to dark-brown tachylyte vitrophyre in inner rim. Amygdules and veinlets are filled with chlorite and epidote. From the same locality as pl. 2, *D* (ts. C57*b*).

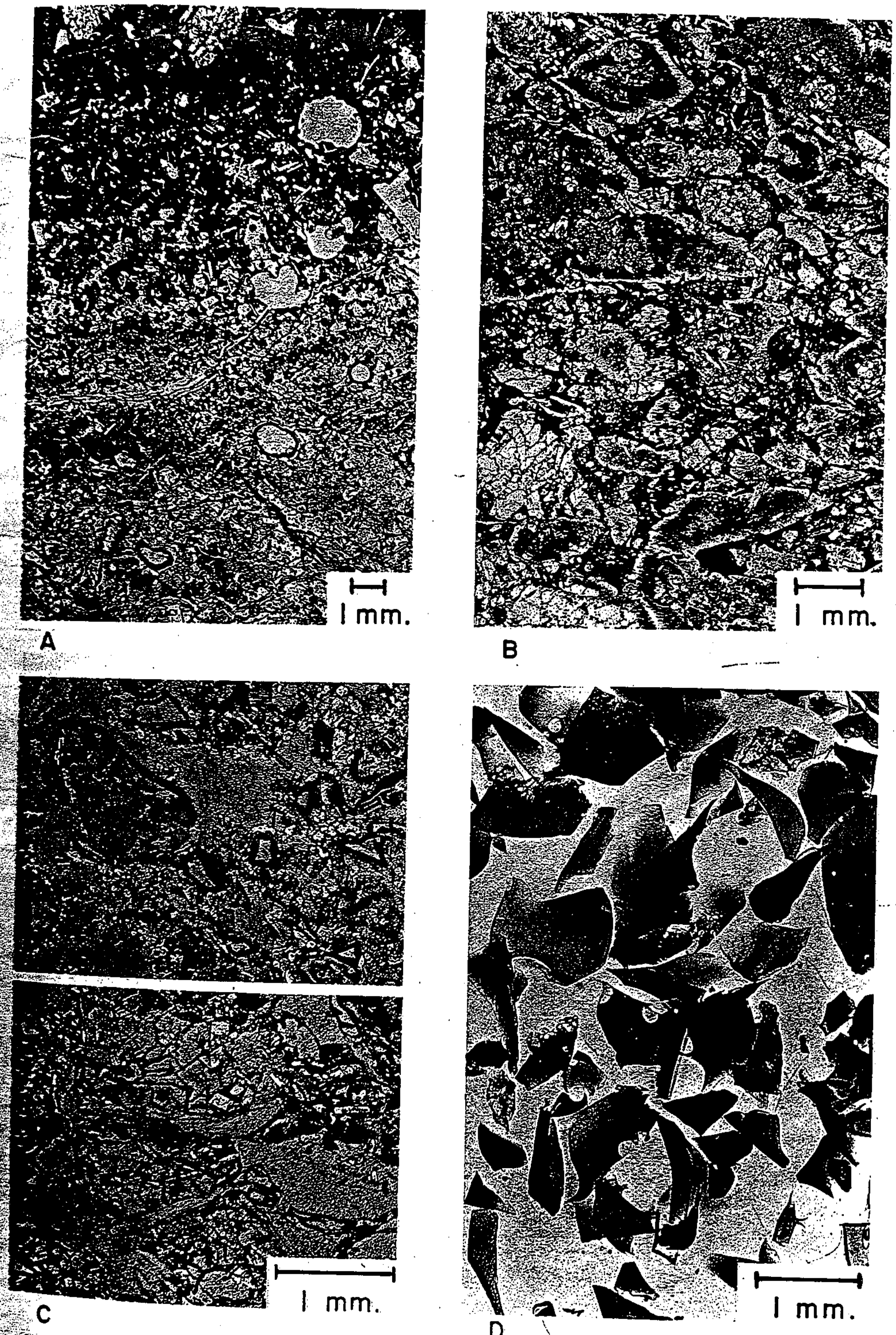
B, Isolated-pillow breccia matrix 1 foot away from any pillow consisting of whole globules of chloritized sideromelane vitrophyre with bleached rims set in an extremely fine-grained chloritic mesostasis. Same locality as pl. 1, *A* (ts. C48*b*). This is an aquagene tuff.

C, Isolated-pillow breccia matrix, also an aquagene tuff, with sideromelane globules and granules fractured and moderately to strongly disaggregated into shards, all in a chloritic mesostasis. "Bleaching" and segregation of iron along rims of granules or shards can be seen (ts. C15, C48*a*).

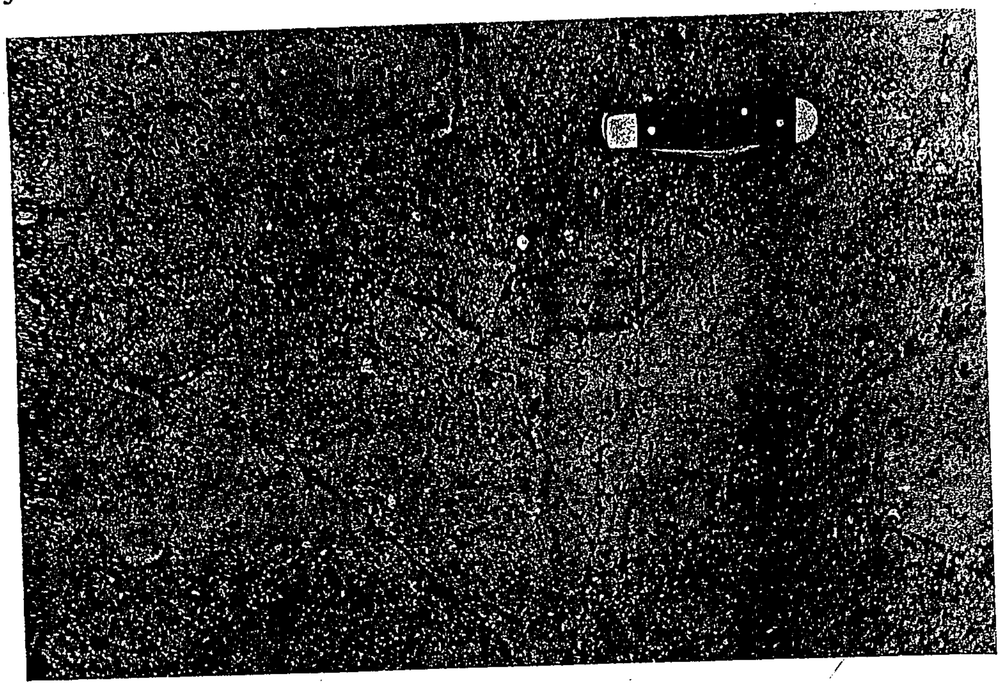
D, Artificial "aquagene" shards produced by dropping beads of melted pillow basalt into cold water. Beads remained whole until steam envelope had dissipated and then shattered, as illustrated.

Thin-section numbers in parentheses. (*For* Vol. 70 *read* Vol. 71.)





Isolated-Pillow Breccia and Matrix of Aquagene Tuff



A

B

Broken-Pillow Breccia, Quadra Island, B. C.

0.05 to 4.0 mm. in length (pl. 3, *C*). Some are merely fractured or only partly split apart. Some are broken into clusters of separate shards each of which, nevertheless, can be matched with a neighbor. Others are so completely disrupted and disoriented that they cannot be fitted together at all. The therefore, does not appear to have caused the fracturing. Furthermore, none of the globules show onion-skin fractures, and the shards are not shaped like concentric flakes so that drastic chilling of a thin rind is likewise not the cause of the disintegration.

2. *Conditions of globulation and shard for-*

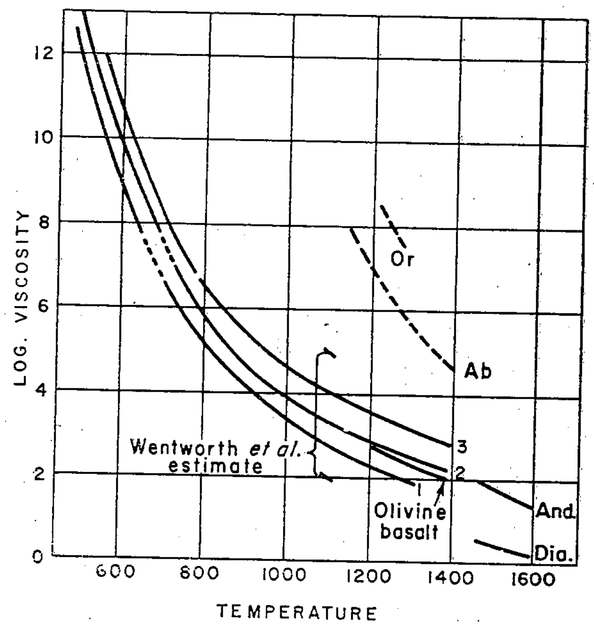


FIG. 3.—Viscosity-temperature relations for some synthetic glasses and natural materials. Modified from Bowen, 1934, fig. 2, by the graphical addition of estimate of Wentworth *et al.* (1945) based on visual field observations and approximated as to temperature.

fractures, like those on the outer rims of pillows, are conchoidal, and they extend through the globules without systematic orientation. A radial arrangement of cracks —as though around a center of expansion, explosion, or impact—has never been observed. Though some cracks in the glass break though to amygdules, the great majority do not; and amygdules are commonly isolated within the shards. Vesiculating gas,

mation—aquagene tuff.—As a melt is cooled rapidly to form a glass, its viscosity rises continuously—at first slowly, then almost exponentially as it approaches and falls through the liquidus (fig. 3). Viscosity reaches extremely high values at the vitrifaction temperature whereupon the glass becomes a rigid body easily subjected to brittle fracture. Melted minerals and rocks typically have viscosities between 10 and 10^3

PLATE 4

A, Broken-pillow breccia from small island north of Heriot Island. Segment of a pillow with part of original chilled rim and amygdule zones appears beneath knife. Matrix from this outcrop shown in thin section in pl. 6, *A*.

B, Broken-pillow breccia north-central Quadra Island, a very typical occurrence. Strike of volcanics is about in plane of photograph. (*For* Vol. 70 *read* Vol. 71.)

poises at 1,400° C. (diabase, basalt, and andesite 15 to 1,500 poises; Birch, 1942, p. 135). Most glasses vitrify at a viscosity between 10^{13} and 10^{14} poises. To give some indication of the range of stiffness involved, commercial glass is generally "gathered" from the furnace at a viscosity of 10^3 poises (about like syrup) and shaping and working ceases at a viscosity of 10^8 poises (about like pitch). Viscosities greater than 10^8 poises are measured by observing the rate of deformation of a glass rod under a given force. It seems highly unlikely, therefore, that the globules in the pillow-breccia matrix could have formed at viscosities greater than 10^8 poises. A range of temperatures that interests us here is that which glass technologists call the "softening range." It lies between temperatures at which a glass body deforms under its own weight under certain standard conditions, and temperatures at which glass can be annealed without deformation and without the creation of new strains upon cooling. This is the range, then, in which glass gradually changes in its response to short-time stresses from a viscous material to a rigid body. Data on juvenile magmas are inadequate, but for several synthetic glasses which agree in their viscosity with melted basalt at high temperatures (Na-Ca, Na-Mg, Na-Al, Na-B silicates; Morey, 1954, p. 145–149; Bowen, 1934, p. 253) the "flow point" (viscosity 10^5 poises) is at about 825° to 950° C. The "softening point" (viscosity 4.5×10^7 poises) is at about 650° to 750° C. The "upper annealing point" at which a standard glass anneals in 15 minutes (viscosity 2.5×10^{13} poises) and the "strain point" below which the viscous yield is almost negligible (viscosity 4.0×10^{14} poises) would lie between 475° and 575° C. Some dry crystal-free melts of basalts studied by Volarovich (1936) and Kani (1934) between 1,150° to 1,400° C. have viscosities in the same range as the synthetic glasses at those temperatures. In juvenile lavas, the contained gas should decrease the viscosity and crystals should increase it. Wentworth *et al.* (1945) conclude that the best that can be said from field observations is that the viscosity of basalt in active lava-channel streams appears to fall in the range from 10^2 to 10^5 poises. The viscosity-temperature relations given for the glasses above are thought to be reasonably indicative, therefore, and since we are dealing with submarine effusives, the rates of cooling and of deformation should be of the same order of magnitude as those encountered in glass manufacture or laboratory investigation; and similar temperature-strength characteristics should apply (viscosity would be increased slightly by the hydrostatic pressure). On the basis of viscosity data, therefore, and judging from their shapes, the globules most likely were formed at temperatures well in excess of 900° C.

The globules, granules, and shards contain scattered phenocrysts and glomerocrysts of plagioclase and pyroxene of the same general size, composition, and appearance as those in the pillows and flows. Some of these crystals terminate with a fracture surface at the edge of a globule. Without doubt, these minerals crystallized before the globules, granules, or shards formed. Yoder and Tilley (1955), in laboratory studies of a tholeiite basalt from Kilauea, found upon cooling the melt at atmospheric pressure that pyroxene began to crystallize at 1,190° C. and plagioclase at 1,170° C. The basalt was almost entirely crystalline at 1,090° C. In view of these data, it seems reasonable to conclude that the globules in the pillow breccia matrix formed at a temperature less than 1,200° C. The maximum initial rate of crystal formation from synthetic glasses has been found to occur at a temperature a few degrees below the liquidus, but not so far below that the impeding effect of rising viscosity upon crystallization is felt. The abundance of tachylyte-free glass in the vitrophyre of the globules, granules, and shards in question and also in the outer pillow rims, in contrast with the abundance of crystals in the pillow cores, suggests that the temperature in the vitrophyre remained in the vicinity of 1,100 to 1,200° C. long enough to permit phenocrysts to grow, but fell rapidly thereafter. It seems reasonable to conclude, therefore, that the globules were extruded into the water as globules at a temperature not greatly above 1,100° C. The viscosity at this point would be in the vicinity of 10^3 to 10^4 poises. Even violent explosion at this viscosity would produce droplets rather than shards. Droplets thus produced under water could continue to deform viscously for a short time in the water in the manner indicated by some of the recurved globules. One can demonstrate this possibility by heating a glass rod to the temperature of flowage, immersing it quickly in cold water, and drawing it apart plastically before it cracks.

Turning now to the brittle fractures, particularly in the shards, viscosity-temperature relations indicate that all of these must have occurred at temperatures well below 700° C. unless one appeals to extremely rapid stress application from violent explosion attendant upon vesiculation. Even then, shards formed at much higher temperatures should have had an opportunity to round their corners. Vesiculation can begin at temperatures well above the liquidus and can be particularly active during crystallization. Vesiculation diminishes drastically with increasing viscosity, however, and becomes exceedingly slow before the vitrifaction temperature is reached. Explosive vesiculation—if it is to take place at all—therefore is most likely to occur in a basalt at a temperature where the viscosities are too low to permit brittle fracture. The relative scarcity of amygdules in the pillow rims, in the globules, and in the shards, indicates that very little vesiculation occurred after formation of the globules. Moreover, the fracture pattern, as noted above, does not support explosive vesiculation as the cause of shattering.

If, as is contended here, all the shards in these submarine volcanics result from autocomminution upon quenching, why can so many of them be fitted together into globules? Why are they not all completely scattered by the steam explosions and the very violence of the process? The answer is easily demonstrated. If droplets of molten glass are allowed to fall into cold water, a few of them will shatter explosively upon contacting the water; but most of them, surrounded at first by an envelope of steam, will fall to the bottom and remain whole until chilled practically to the temperature of the water. Then they may shatter. It is well known that chilling itself does not produce permanent strain in a glass body provided that the chilling occurs while the body is so hot and fluid that stress is relieved by viscous flow as quickly as it develops. Thereafter, a temperature gradient is set up within the body, diminishing only gradually throughout the whole cooling period. As the body reaches the temperature of its surroundings, however, the temperature gradient is destroyed, the central part of the body contracts more than the exterior and, according to the theory, if viscous relief is not possible at that temperature, the body shatters. If the temperature of the surroundings is high, of course, or if the viscosity of the glass is low at surrounding temperature, the body may not shatter at all.

One can easily perform this experiment with melted volcanics, not only of basaltic but of intermediate composition as well, and produce typical "vitroclastic shapes," curved splinters, pointed chips bounded partly by vesicle walls, and so on (pl. 3, *D*). One can also produce vitroclastic structure occasionally by quenching in air, though usually since heat is not dissipated in producing steam, the initial temperature gradient is not severe enough to create much permanent strain at room temperatures. The mechanism is certainly capable of producing true volcanic tuffs entirely beneath water, and under some conditions it may play an important role in the production of subaerial tuffs as well.

To contrast with ordinary subaerial or pyroclastic tuff, the term "aquagene tuff" is proposed here for a tuff, such as that associated with pillow breccias, which has been produced by globulation or granulation through quenching, or both, or by a similar process entirely beneath water or when lava has flowed into water or beneath ice (the sideromelane-tuff and palagonitic-tuff in the palagonite formation of Iceland is an example of this latter). "Aquagene" is preferable to "subaqueous" since that term has been applied to water-lain subaerial tuffs. Aquagene tuffs are not necessarily palagonite tuffs.

As for the over-all change in extrusive conditions responsible for the great increase in tuffaceous matrix and the consequent transition from close-packed to isolated pillows on Quadra Island, there is nothing in the microscopic evidence indicating a systematic change in composition of the lava. Most likely the change represents an increase in the violence of extrusion, perhaps the initiation of submarine lava fountains, while at the same time quiet volcanism continued to form pillows in the same area.

3. *Palagonite.*—Except for the alteration of the glass to chlorite, the similarity of the globules and shards in the pillow breccia matrix to those described by Peacock from the Palagonite formation of Iceland is quite obvious (Peacock, 1926, p. 394; 1928, p. 60 ff.; see also Peacock and Fuller, 1928, and Noe-Nygard, 1940, p. 29 ff.). In these young Icelandic rocks, the fresh sideromelane—which has an index of refraction slightly greater than 1.60—has been altered in varying degrees to the mineraloid palagonite, which has an index of refraction in the range of 1.48–1.52. Two varieties of palagonite were recognized by Peacock: (1) gel-palagonite, a yellow clear isotropic material bordering the unaltered sideromelane or entirely replacing it, (2) fibro-palagonite, obscurely fibrous, weakly birefringent, yellow-brownish to greenish material as a second narrow irregular border around the outside of some of the gel-palagonite. Fibro-palagonite, commonly in more than one layer, also cements sideromelane grains or lines amygdules. Peacock considered it likely that the alteration to palagonite resulted simply from hydration of the sideromelane, but that this hydration was accompanied by some separation of dissolved iron from the sideromelane as oxide since he found lines and zones of ferruginous globulites along the margins of the relict sideromelane and also as a first lining in amygdule fillings. Apparently as a result of this separation of iron, the palagonitized borders of the sideromelane shards appear bleached in contrast with the light-brownish, unaltered sideromelane. Palagonitization and concomitant bleaching did not affect the tachylyte grains nor the plagioclase or pyroxene phenocrysts. Peacock proposed that palagonite alters to chlorite and zeolites, and he suggested that some of the obscurely fibrous material may represent incipient separation of limonite and chlorite. Raw (1943), reporting on some altered Cretaceous and Eocene palagonite tuffs from Jamaica, however, concluded after examination of Peacock's sections that much of the chlorite and zeolite deposition preceded alteration of sideromelane to palagonite in the Icelandic rocks and that palagonite, in fact, is "essentially chlorite."

Whatever the true nature of palagonite, no such isotropic low index material is to be found now in the Triassic pillow breccias of Quadra Island. Nevertheless, the pattern of bleaching and segregation of iron from the chloritized sideromelane and the fact that this bleaching has not affected tachylyte or the plagioclase and pyroxene phenocrysts are in such accord with the character of palagonitization in Iceland that it is concluded that this process affected the Quadra Island rocks also.

4. *Mesostasis.*—From 10 to 40 per cent of the isolated-pillow breccia matrix is a very fine-grained mesostasis of foliate, fibrous, and concentrically layered chlorite plus lesser epidote, tremolite, and impalpable ferruginous matter. It lies between the globules and the shards, and it fills amygdules in the vitrophyre or fractures through the whole. In its original state this was transportable material. It has been squeezed and has flowed between the fragments in such a way that foliation in the mesostasis mimics foliation in the whole pillow-breccia matrix. Some of the chlorite has been carried along tiny fractures after granulation of the vitrophyre and reprecipitated concentrically in amygdules. As mentioned earlier, the same

thing can be seen along through-going fractures in the chloritized sideromelane of the pillow rims leading to chlorite-filled amygdules (pl. 3, *A*). An interesting feature of these fractures is that the altered sideromelane adjacent to them is depleted in iron—just as are the rims of the altered sideromelane fragments in the matrix—whereas the fracture fillings are enriched with lenses and streaks of deep iron stain. This transfer of iron has resulted in removal of the minute, high-index ferruginous aggregates adjacent to the fractures, but it has not affected the goethite microspherules of the tachylyte. Apparently this is another manifestation of palagonitization.

Scattered throughout the mesostasis are occasional crystals or clusters of plagioclase and pyroxene, well formed but commonly broken. They have no authigenic overgrowths. Probably these were merely set free during granulation of the sideromelane. An intimate part of the mesostasis in some sections and showing deformation around the ends of shards or larger fragments are wispy masses of semi-translucent, light-brownish material, 0.1–0.2 mm. across, with abundant epidote crystals and poorly formed chlorite spherules. Isolated crystals and clusters of tiny plagioclase laths and pyroxene occur within these masses. Possibly this material is vitrophyre altered to soft palagonite so early during deposition that it was especially vulnerable to deformation.

The mesostasis is apparently what remains of dissolved substances and colloidal and clay-sized debris that accumulated during reaction between lava and water plus substances derived from sideromelane during palagonitization and chloritization. It has been particularly vulnerable to replacement, in some sections being almost completely replaced by spherulitic chalcedony.

VII. BROKEN-PILLOW BRECCIA

1. *Fracturing of the isolated pillows.*—The transition from isolated-pillow breccia—or in some instances from close-packed pillows—to broken-pillow breccia takes place over only a few feet. It consists mainly of the sudden appearance and increasing abundance of large fragments of pillows and of angular blocks of the same composition but not obviously pillow-derived. The matrix is macroscopically similar to that just described, though its foliation is generally better developed. In some occurrences, too, the gradation in size from clasts a foot or more across down to particles in the matrix is almost continuous.

It is expedient at this point to look back at the whole pillows in the upper part of the isolated-pillow breccia. In addition to the obviously epigenetic or regional fractures mentioned earlier, the pillows are cut by (*a*) crudely radial cooling cracks, (*b*) concentric rim fractures, and (*c*) occasional irregular fractures transecting glass, amygdule zones, and crystalline lava. The first two are commonly not well developed in isolated pillows presumably because of the warm covering of tuffaceous matrix and the consequent long cooling period. The third type, located at random or perhaps in a re-entrant in a folded pillow (fig. 4, *A*), is usually well developed only in the upper part of an isolated-pillow section but is not really abundant even there. A few pillows have split apart along these fractures, and the fragments lie close together separated by matrix. The walls of the fractures are not chilled or different in any way from the main body of the pillows. The matrix, moreover, has flowed into the more open of them and between separated fragments; and its foliation, accentuated in some places by chalcedonic replacement, conforms partly with the fracture surfaces. These fractures formed, therefore, after vesiculation had ceased and after the pillows had settled into place and solidified, but before final compaction and consolidation of the entire pillow-tuff mixture. The fracturing appears to have been the result of vigorous motion in the upper part of the isolated-pillow breccia more than of explosion. Steam explosions may have played a role, but if they were a principal cause of fracturing they should have affected pillows at the bottom, as well as the top, of the section, and they should have shattered them prior to their settling into place.

In broken-pillow breccia, the disaggregation of pillows has gone much further. Typically one can recognize individual parts of a pillow—perhaps a pyramidal segment with a convexly curved and chilled base or occasionally an onionskin-like piece cleaved from the outer rim of a pillow—but one can rarely see that any of them could fit together to make a pillow (pl. 4, *A*, *B*). Nevertheless, there are enough recognizable pillow fragments to justify the belief that a large part—if not all—of the large clasts could be of this origin. And in some sections there are a few large and small, unbroken or only partly broken pillows in the rock. All the clasts are in the compositional range of the pillowed volcanics as a whole, but the variety of color and texture indicates that a good deal of mixing has taken place. Bedding and sorting are completely lacking. There is no imbrication or other evidence of current action. The longer axes of the pillow fragments, however, show a quite definite preferred orientation in the stratigraphic plane which is of about the same degree as that observed for the globules and granules in the matrix of the isolated-pillow breccia. There is a marked tendency also for brecciation to increase and for the size of the clasts and of the occasional unbroken pillows to decrease upward while at the same time the proportion of matrix increases slightly. This, however, is not invariably true and there are local reversals.

2. *Glass clots and partly rimmed pillows.*—Plate 5 shows sawn surfaces through a typical broken-pillow breccia. "Clasts" of two quite different kinds can be seen. The predominant clasts in the occurrence from which these specimens were taken are fine-grained basalt of pillow composition, some of them being fairly clearly derived from pillows as just described, but many of them being subrounded to angular and without chilled rims, suggesting that they are from an inner part of a pillow or perhaps not pillow-derived at all. They range from a fraction of an inch to several inches across. Much of this basalt is tachylytic or has a very fine groundmass in thin section. The fragments are not deformed, but have caused globules, shards, and mesostasis to deform around them.

The second kind of "clast" in plate 5, found abundantly in some occurrences and very sparsely in others, consists of irregular, nodular, and amoebiform clots of altered vitrophyre. These range from about two inches in length down to the size of globules in the matrix. Indeed they are entirely similar to the altered sideromelane globules previously described, except that these are less regular in shape and some are enormously larger. Most of them obviously have undergone a large amount of viscous deformation. Their long axes tend to lie along the foliation of the matrix. Phenocrysts of intermediate plagioclase (An_{55-60}) and subcalcic augite suggest no change in the composition of the original lava. Again the glass has altered to very-fine-grained chlorite, abundant epidote, tremolite, minute high index aggregates, carbonate, and ferruginous stain. Bleached rims around the clots shown in plates 5 and 6, *A–D*, are evident even on a weathered surface and recall the presumed palagonitized rims in the isolated-pillow breccia matrix. Amygdules, mostly spheroi-

PLATE 5

A, Light-colored masses with bleached rims are clots of chloritized sideromelane vitrophyre, essentially very large globules. Dark subangular masses are basalt, two of them having a large deformed partial rim of altered sideromelane identical with clots. Shapes and orientation of clots and partial rims may indicate sense of movement.

B, Partial rim of altered sideromelane vitrophyre with a lobe almost torn away. Both sawn slabs are from the westerly occurrence 1½ miles north of Hyacinthe Bay. For thin section see pl. 6, *D*. Photographs by Takeo Susuki. (*For* Vol. 70 *read* Vol. 71.)

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everal inches across
achylytic or has a
thin section. The
leformed, but have
s. and mesostasis to

"clast" in plate 5,
ome occurrences and
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that these are less
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sts of intermediate
d subcalcic augite
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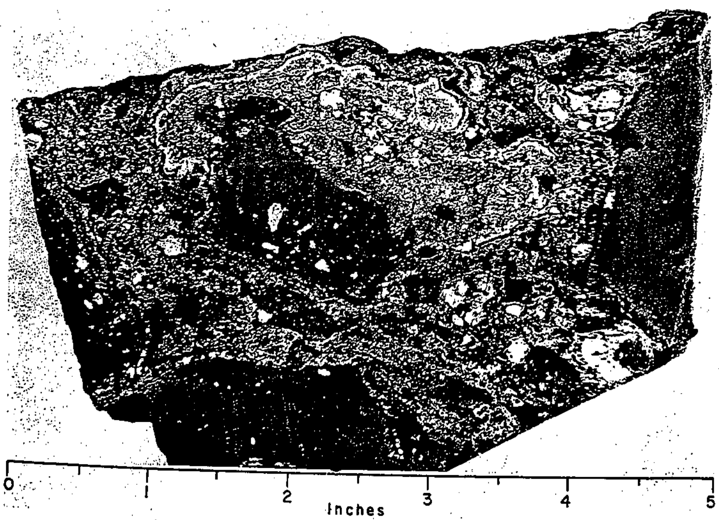
e glass has altered to
e, abundant epi-
high index aggre-
d ferruginous stain
the clots shown in
evident even on a
ecall the presumed
the isolated-pillow
les, mostly spheroi

vitrophyre, essentially
rge deformed partial rim
partial rims may indicate

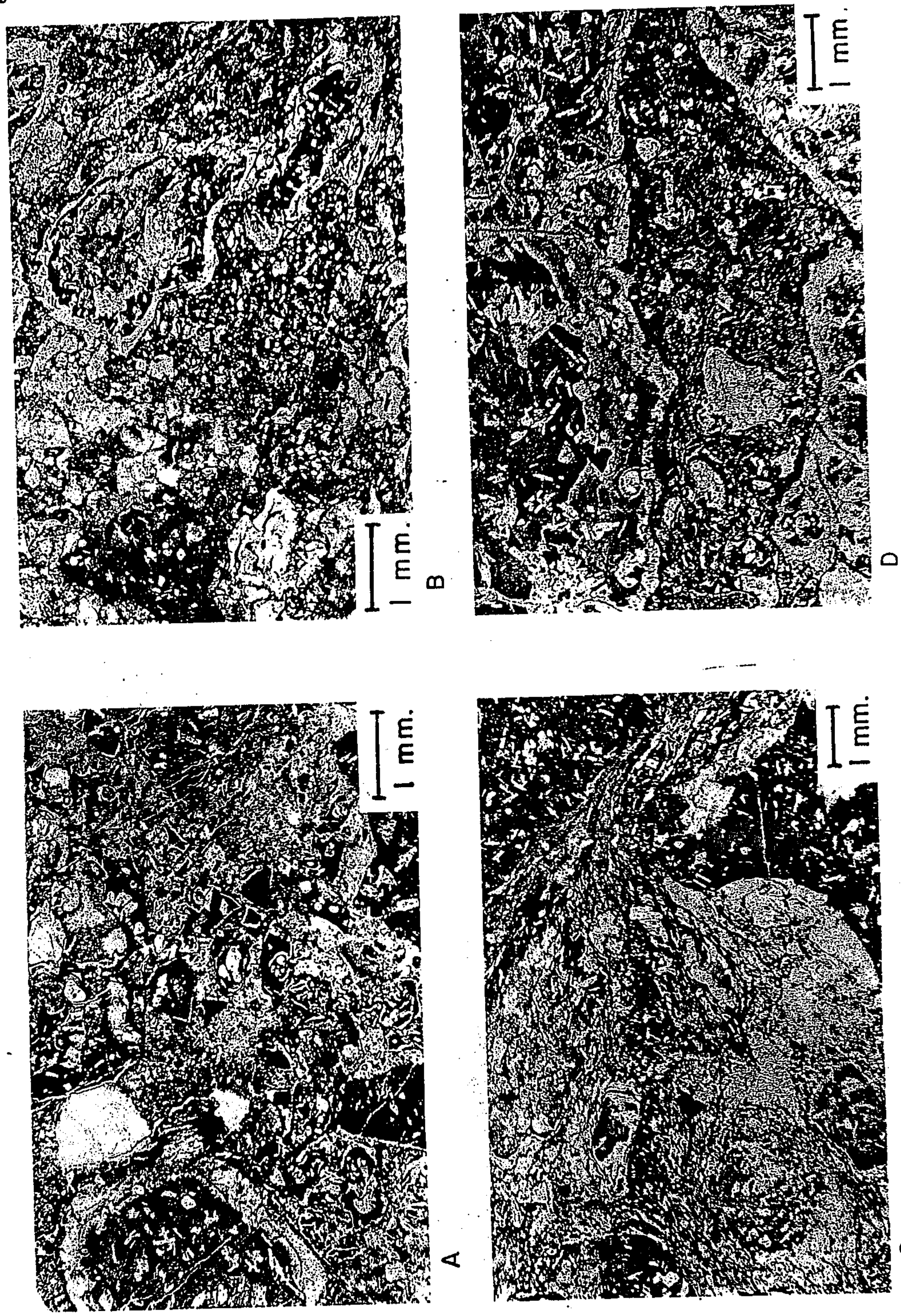
. Both sawn slabs are
pl. 6, *D*. Photograph

A



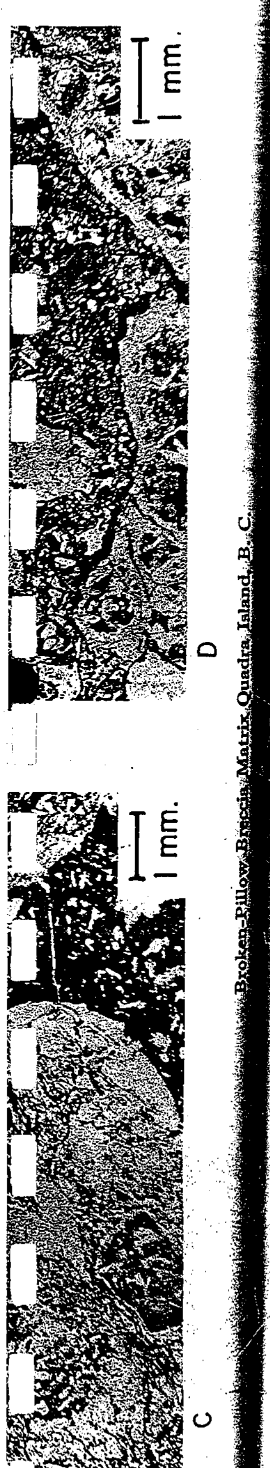
B

Glass Clots and Partly Rimmed Pillow Fragments



Broken-Pillow Breccia Matrix, Quadra Island, B. C.

CARLISLE, PLATE 6



dal to ellipsoidal but some lenticular in shape and filled with chlorite, chalcedony, or any of the other alteration minerals make up about 5 per cent of the volume of the vitrophyre. Locally there are clots more vesicular than this, and even in these the filled vesicles are not collapsed but still spheroidal streaming out in the plane of foliation but without any of the twisting or random orientation found with aerial lapilli. The fact that many of the clots, as seen in a hand specimen or in a thin section, were pliable enough to be bent with the plane of foliation where it swings around basalt clasts suggests that

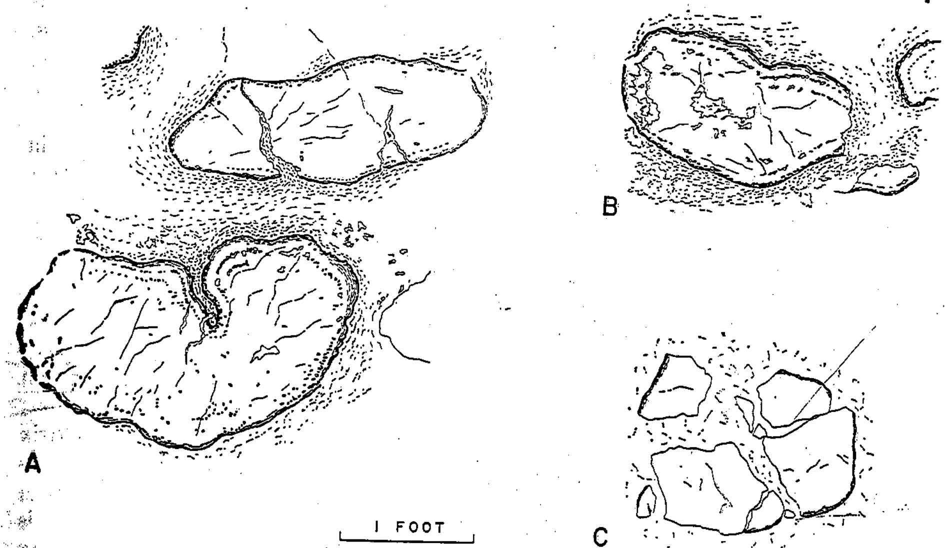


FIG. 4.—Isolated pillows fractured after accumulation in matrix but before consolidation of pillow-matrix mass. *A*, typical folded pillow and also truncation of chilled rims and concentric amygdule zones at fracture surfaces. Slight foliation of matrix in *A* and *B* follows pillow surface across fracture surfaces and into larger fracture openings. Amygdules and smaller fractures are filled and matrix is partly replaced by quartz.

to ellipsoidal. Internal fracturing of the clots is somewhat less than in the globules in isolated-pillow breccia.

These clots are not collapsed pumice but lumps of vitrophyre extruded with relatively little vesiculating gas at a temperature slightly below the liquidus into an environment in which they were simultaneously deformed and quenched. Some clots have tails all of the materials accumulated so rapidly that even in this quenching environment streamlike foliation and deformation could occur at a temperature at which viscosity of the sideromelane was low.

Still another feature seen in plate 5 distinguishes these submarine breccias. Two of the basalt clasts have an uneven, partial mantle of altered sideromelane vitrophyre.

PLATE 6

A, Broken-pillow breccia matrix from small island north of Heriot Island (pl. 4, *A*) showing clot (*left*) with bleached rim, granule (*right*), globules and shards of altered sideromelane vitrophyre; two fragments of tachylytic basalt (*bottom*) and an unusually vesicular and pasty-looking clot (*top*). Chloritic mesostasis is partly silicified (ts. C55*c*).

B, *C*, Flow-deformed clots, globules, and shards of altered sideromelane vitrophyre in chloritic mesostasis. Note how tachylytic basalt fragments in *C* resist bleaching (palagonitization?) and deformation. Broken-pillow breccia occurrence north-central Quadra Island same as pl. 4, *B* (ts. C5*a*, C4*b*, C4*a*).

D, Shards between partial rim and lobe of altered sideromelane vitrophyre shown in pl. 5, *B* (ts. C202*b*).

(*For* Vol. 70 *read* Vol. 71.)

The material in the mantles is identical with that in the clots, and yet it grades uniformly into the body of the basalt fragment in exactly the same way that the glass rim on an ordinary pillow grades into basalt. In one sawn surface, a pendulous lobe of sideromelane can be seen stretched out along the foliation in the matrix, yet remaining connected to the mantle on a basalt fragment by a narrow neck. Apparently these partial mantles are what remains of a once-continuous glass rim around a pillow. Much of the original rim must have been pulled from the pillow, as hot candy can be pulled from a spoon, through vigorous flow of the whole broken-pillow-tuff mass essentially during emplacement. Clearly many, if not all, of the glass clots described above could have been formed by this very process—the unrimming of pillows. The fractures that split the pillow fragments apart must have also formed during that same period of movement, though after partial unrimming of the particular pillow, since the clots are deformed and the matrix is foliated around those fractures.

Many pillow fragments in a broken-pillow breccia, therefore, may lack chilled rims and not be obviously pillow-derived because (*a*) they are from the interior of a pillow, or (*b*) they are from a pillow that has been mechanically unrimmed. Furthermore, even the more or less complete pillows are likely to be battered out of shape and quite angular.

3. *Broken-pillow matrix.*—The same components make up this matrix as make up the isolated-pillow breccia matrix—globules (apparently indistinguishable from very small clots), granules, and shards of altered sideromelane vitrophyre, tachylyte fragments, a ferruginous chloritic mesostasis, and plagioclase (An_{55-60}) crystals presumably intratelluric. But in this rock, the globules are much more irregular in shape, much more drawn out along the foliation, and the foliation is more pronounced. Distorted teardrop and spindle shapes are common. Globules which are highly distorted tend to show relatively little internal fracturing or granulation of the glass, suggesting that the environment was hot and the cooling strains commensurately less.

Textural relations indicate that shards in this rock have been produced both by internal granulation, as previously described, and by spalling from the rims of clots and globules. Undoubtedly, vigorous flow enhanced the disrupting effect of quenching. In some specimens, cuspate terminations on the shards are slightly attenuated or bent in the plane of foliation, suggesting that fragmentation occurred while the glass was in the softening range. This is particularly true of one specimen in which an unusual abundance of amygdules indicates that the fluidity of the glass was probably increased by contained gas. At this point, however, it is not clear how much of the visible deformation of the shards and globules might have been made possible by subsequent alteration of the glass to soft palagonite.

Between 10 and 25 per cent of the matrix is a heavily iron-stained, largely indeterminate mesostasis much the same as that in isolated-pillow breccia. A large part of it is turbid and almost isotropic; but locally, chlorite, epidote, tremolite, and chalcedony are abundant. The same material follows tiny cracks and fills amygdules.

A striking feature of the foliation in many thin sections of these submarine breccias is its similarity to the so-called compact or eutaxitic structure of ignimbrites. The similarity is most pronounced in those specimens in which the globules have undergone a large amount of viscous deformation but are not particularly granulated. The deformed globules closely resemble in outline what have been illustrated as deformed and flattened shards in "welded tuff." It should be emphasized, perhaps, that in the present discussion a distinction is being made between globules which separate from the lava as liquid droplets, and shards which result from more or less brittle fracture. The highly deformed particles in broken-pillow breccia appear to be globules. True vitroclastic shards may show some stretching or bending if formed in the softening range of the glass, but they would not be expected to show a large amount of plastic deformation unless some mechanism is available for lowering viscosity after brittle fracture. The same consideration of temperature and viscosity would seem to apply to ignimbrites.

Once again, though, it is not entirely clear to what extent early diagenetic palagonitization might have contributed to softening and weakening of the brittle glass. The next section suggests that it may have contributed a good deal.

4. *The laminated vitric tuff.*—Some of the best clues to the origin of broken-pillow breccia are in the sporadic interbedded tuffs. The tuffs are from 1 to 4 feet thick, usually not more than two or three per breccia section, and continuous along strike for several tens or hundreds of feet. They occur anywhere in the broken-pillow breccia section from a few feet above the base on up. Most typically the breccia simply grades upward into the tuff through loss of clasts. The tuff, however, is a bedded sedimentary rock with uniform and continuous rhythmic laminations up to 1 cm. thick and excellent graded bedding—coarse at the base—within these. The grains are from clay size to 4 mm.—very rarely up to 1 cm.—in diameter. No cross bedding or current structures have been seen as yet.

The tuff is overlain directly and abruptly by more broken-pillow breccia, usually without appreciable erosion of the tuff but commonly with excellent load casts produced by fragments of the overlying breccia. Usually the upper surface of the tuff has become undulatory beneath the uneven load and in some places the tuff has been squeezed upward into the breccia.

The sole components of the tuff, apart from a few admixed breccia clasts, are the same altered sideromelane vitrophyre (deformed globules, granules, and shards) and occasional tachylyte fragments in an extremely fine-grained ferruginous groundmass. Again the plagioclase is intermediate (An_{55-60}) and the sparse pyroxene is subcalcic augite. Alteration of the sideromelane—particularly to chlorite, epidote, and tremolite in the specimens examined—is of the same character as in all the other rocks described, but more completely developed. The rims of the particles have been bleached and differentially altered, and iron has segregated in the manner of the presumed palagonitization. Minute high-index aggregates (sphene or anatase?) occur in the central parts of the particles but not in the rims. There can be no doubt that the tuff is cogenetic with all the other pillow rocks or that it settled through an aqueous medium.

The evidence seems to be conclusive that broken-pillow breccia was formed from a juvenile mixture of pillows and aquagene tuff by what must be the submarine equivalent of a hot lahar, or perhaps it should be called a volcanic turbidity flow since it was buoyant enough—at least locally—to place the breccia directly upon unconsolidated tuff without appreciable erosion. Such a flow by its turbulence would set a cloud of fine-grained shards, globules, and clay-sized debris in suspension. The tuff would be the rhythmic condensate from such a cloud or perhaps several clouds from neighboring flows. Alternatively, one might hypothesize that the tuff resulted from continued explosive vulcanism during a hiatus in pillow formation. It is possible, too, that the tuff was air-borne to start with, but the thorough similarity in form and composition between these tuff particles and those in the broken-pillow breccia matrix, including the clots torn from pillow rims, renders this possibility highly unlikely.

An amazing thing about some of the laminated tuff is that the altered sideromelane, globules, and shards, in spite of having settled in water, are molded against each other and drawn out in a flowlike foliation parallel to the bedding. Some appear to be "welded" (pl. 7, *D*). Surely the vitrophyre fragments could not have been reheated to the softening range of the glass after sedimentation. The texture must have resulted from the diagenetic alteration of the glass to soft palagonite (or chlorite) and compaction. One can observe that the more highly the particles are deformed the more perfectly are they oriented in the plane of the bedding. The occasional tachylyte fragments, however, are not so oriented and are not deformed, which is consistent with the fact that tachylyte is known to resist palagonitization.

It will be recalled that the shards in isolated-pillow breccia show no such collapse in spite of complete alteration to chlorite; those in broken-pillow breccia show some postfracture deformation, thought possibly to be a result of palagonitization; and those in the laminated tuff have lost their brittleness altogether. Since these three differ in the length of time over which they traveled through sea water prior to sedimentation, a resultant difference in the intensity of very early palagonitization might account for the differences observed in compaction deformation. Raw (1943, p. 228) observed collapsed palagonite grains in the Icelandic rocks.

The "welding," however, is probably an illusion. If one will refer to plate 3, *C*, showing undeformed, partly granulated sideromelane globules, he will see many shard fractures which have failed to break completely through to another surface. Consequently, many potentially separate shards remain joined to one or more sibling shards by unbroken sideromelane. Diagnetic deformation could readily lead to the textures seen in plate 7, *D*. This mechanism makes it possible, also, to explain single devitrification crystals extending from within one shard to another across the "weld." Perhaps the occurrence of such "Siamese" twin or multiplet shards is another criterion for recognizing tuffs, including aquagene tuffs, formed by granulation.

VIII. CONDITIONS AND MECHANISMS OF ORIGIN OF PILLOW BRECCIAS ON QUADRA ISLAND

The obvious fact that pillows settled into soft fossiliferous limey muds at the base, the gradational continuity from one rock type to the next, the abundant evidence of quenching, globulation, and pasty flow, and the laminated and graded tuffs with load casts from overlying breccia at the top of the section leave no doubt whatsoever that all of these rocks are of submarine origin. Moreover, apart from the vulcanism itself and the processes that caused brecciation, the environment was one in which sedimentation could take place quietly and rapidly. There is no evidence whatsoever in the subpillow sediments, in the isolated-pillow breccia, or in the laminated tuffs of appreciable aqueous currents. Foreset bedding is not found in the isolated-pillow or the broken-pillow breccia. Nor is there evidence or need for any source of syngenetic material beyond the vulcanism itself and the ocean, including the organisms living in it. All the rocks could well have been deposited at depths of several hundred feet and scores of miles from the nearest exposed land. Precipitation of the limestone, though in considerable part organic, might well have been augmented by the heating and stirring of the sea during vulcanism. Kania (1929) has suggested such a mechanism. The chert and other colloidal materials are probably mainly from reaction of sea water with the erupting volcanics. All of the remaining identifiable syngenetic materials are volcanic of a remarkably uniform composition, and there are no admixtures of terrigenous debris or accidental fragments.

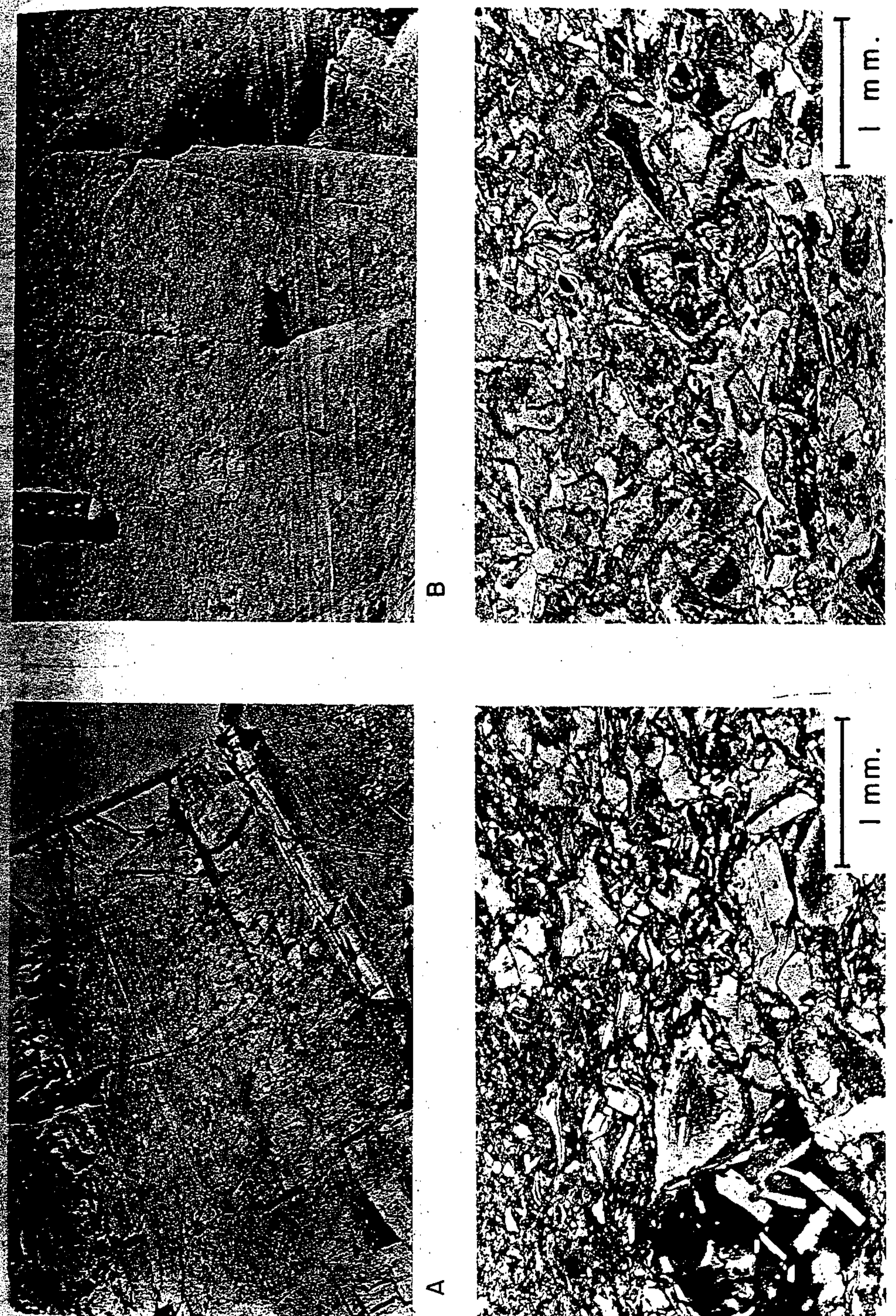
PLATE 7

A, Laminated tuff beds within broken-pillow breccia. A few feet of pillow lava and very minor isolated-pillow breccia occurs beneath photograph. All subjects on this plate are from north-central Quadra Island 50–500 feet north of outcrop shown on pl. 4, *B*.

B, Laminated tuff within broken-pillow breccia.

C, Globules, granules, and shards of chloritized sideromelane vitrophyre in tuff bleached, flattened, and molded against each other. Tachylyte grain on the left, however, is neither bleached nor deformed (ts. $C5_2$).

D, Twinned (pseudo-welded) shards, granules, and globules strongly deformed and molded against each other after sedimentation (ts. $C5_1$). (*For* Vol. 70 *read* Vol. 71.)



Laminated Aquagene Tuff Within Broken-Pillow Breccia

Although the exact process of pillow formation is not understood, it must involve the uneven advance of hot lava into a medium in which a tough but plastic chilled envelope is caused to form without permitting solidification of the lava within. Irregularities in the advance permit large or small masses of skin-toughened lava to globulate or to bud into separate ellipsoids, globes, or pillows. If, because of its composition and its temperature, the lava were already highly viscous when it reached the chilling medium, or if it chilled slowly, or if its internal pressure were not great, it might form ropy or pahoehoe structure but not good pillows. If, on the other hand, it were highly fluid and under considerable internal pressure when chilled, it would seem to be in a condition to globulate promiscously and vigorously. Probably in this situation, the globules would be relatively small but numerous. If gas pressure were very high, the globules would explode.

Pillow formation is commonly preceded by a period in which volcanic deposition had ceased in the local area and the ocean had become clear and cool. From the fossil accumulation, one might guess this to be a period of at least several months.

The close-packed pillows apparently accumulated in this relatively clear water. Very little fine-grained matrix accumulated between them, and much of this is the already settled limey mud which squeezed up between and around them. They would settle rapidly and thus remain sufficiently plastic to adjust to the shape of the underlying surface. Nevertheless, they solidified rapidly enough that successive pillows became deformed against them while those that had already settled retained their shape. These conditions might be expected to prevail during the early stages of renewed submarine extrusion. The outpouring lava would be under sufficient pressure to cause effective globulation while being skin-chilled, but not under so great a pressure that tiny globules would be blasted in all directions.

As the volcanic episode developed—perhaps modestly in one area, vigorously in another—the tendency to produce small globules would have increased. Numerous observers of subaerial basaltic eruptions report roughly contemporaneous or proximate quiet eruptions and violent outbreaks and firefalls. Much the same thing could be expected subaqueously. Here the relatively violent outpourings would yield minute globules of glass or vitrophyre, the quieter ones would yield pillows, and an isolated-pillow breccia would form. The usual upward increase in the ratio of matrix to pillow and in the proportion of small pillows might be explained by an increase in the amount of violent globulation with time or it may only reflect the lower settling rate of small particles in comparison with large pillows. Considerable flow of the pillow-matrix mixture must certainly have occurred, but there is no evidence that it was violent or turbulent at this stage. Any one part of the isolated-pillow breccia appears to be a random accumulation of pillows of any size or shape but of a single composition in an equally unsorted matrix of the same bulk composition. Pillows seem to have been dumped into the mixture over its whole thickness.

Isolated pillows, buoyed up by the increasing accumulation of globules, granules, spalled pillow fragments, and colloidal debris in the water, were unable to settle into contact with previously deposited pillows. They cooled in a medium of hot water and hot granulating glass; and, therefore, they cooled slowly—deforming appreciably during even relatively gentle flowage of the pillow-matrix mass. Many became bent over or recurved, a condition practically never seen in close-packed pillows. Toward the top of an isolated-pillow breccia section, one can fairly readily find broken or disaggregated pillows; but one practically never finds disaggregated pillows at the base of a section of isolated pillows.

Disaggregation appears to have resulted from slump or flow of pillows and matrix essentially during extrusion; and its fullest development produced broken-pillow breccia. The flow was violent enough—aided probably by steam explosions—to strip pillows partly of their viscous glass rim and to break them apart. The fragments are completely unsorted. What triggered the flow is not clear. It might well have been the simple accumulation of a sufficient thickness of unconsolidated pillow-matrix-water mixture to create instability even on a gentle slope. Quakes accompanying the volcanism could start the mass moving. Relations with the tuff indicate that such flows are turbulent or at least buoyant enough that they can ride over newly deposited ash without eroding it. Continuous evolution of nascent steam would have contributed to the buoyancy. The tuff itself is apparently the condensate from a remnant cloud of fine particles dispersed through a considerable depth of water during the flow. One can imagine that broken-pillow flows might have spread from several sources and at different times, so that in some places, they might have settled upon close-packed pillows; at others, upon isolated-pillow or broken-pillow accumulations; and at still others, upon bedded ash. Explosive extrusion is not by any means eliminated as a source of breccia clasts, but it may have been much less important than a first impression of the breccia would lead one to think. Though more than one cycle of pillow lava and breccia may form, finally—in every occurrence on Quadra Island—the breccias were succeeded by massive flows. The outpouring of lava became so overwhelming that neither pillows nor tuff could form and be preserved. It is not unlikely that in some places true pillows or pillow fragments might have been engulfed in liquid lava.

The environments and mechanisms suggested are not the only ones under which pillow breccias may form. Rocks closely similar to those described are reported in the literature to have formed under glacially controlled, lacustrine, and various marine conditions. It is quite likely, moreover, that under shallow-water conditions some of the components may come to the surface. Van Padang and Richards (1959) concluded that eruption in water shallower than 500 meters characteristically yields ejecta and steam expelled to considerable heights above sea level; abundant floating pumice; and the appearance of ephemeral islands usually composed of pumice and other ejecta. Washington (1909, p. 141) has summarized a report on the eruption of 1891 near Pantelleria in which "vast numbers of subspherical bombs rose to the surface, the largest having a diameter of more than one meter. Some were thrown to a height of 20 meters, and many ran hissing over the water, discharging steam, and being kept afloat by the gases contained in their vesicles. The bombs were hot, some when recovered sufficiently so to melt zinc (420° C.), and a few were red-hot in daylight. After floating for a time, most of the bombs exploded, the explosions succeeding each other so rapidly as to resemble the noise of a battle, and the fragments sank to the bottom." Such a mechanism might well contribute to the clasts in a broken-pillow breccia. It should be easy, however, to recognize fragments of bombs (or pillows?) that were vesicular enough to float. None have been found in the Quadra Island breccias.

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