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ABOUT DEEP-SEA VOLCANISM

Zusmmenfassung

Die Hyaloclastiten entstehen hauptsächlich durch submarines Zerspratzen von Lava, die bei vulkanischen Explosionen im Meer ausgeworfen wurde.

Zahlreiche „sea-monts" waren wahrscheinlich niemals vulkanische Inseln, die später abgestumpft und überschwemmt wurden, wie es allgemein angenommen wird. Wir sind überzeugt, daß ein großer Teil der Vulkane sich unter Wasser gebildet hat aus Laven, die aus einem langlebigen Zufuhrkanal gefördert wurden und die allmählich nach oben wuchsen.

Die Bildungsart der Hyaloclastiten, die hier beschrieben wird, erklärt die Tafelformen und die aus Palagonit bestehenden zackigen Berggrate, die Islands Unter-Eis-Vulkanismus kennzeichnen.

Abstract

Hyoclastites mainly result from underwater comminution of molten basalts initially explosively erupted out of the sea-floor and instantaneously pulverized by closely succeeding phreatic explosion (s).

Many sea-mounts probably never were the alleged volcanic islands, later sea-level eroded into truncated cones and eventually drowned several km down, they are claimed to be. They are here considered as submarine polygenic volcanoes, the shape of which is congenital. Their building up probably started by accumulation of numberless flows of basalt, quietly poured out from a long-lived central vent; when this lava-volcano's crater, so progressively carried higher and higher, reached depths where explosive phenomena became possible because of lowered hydrostatic pressure, magmatic explosions occurred due to violent release of primitively dissolved (or combined) gases. Shattering of lava, 1°) increases by several orders of magnitude lava's surface to volume ratios, so allowing huge quantities of super-heated steam to be engendered; 2°) this super-heated steam trapped below the lava-lumps, as well as in their numberless holes, immediately explodes and comminutes the primary lava-lumps; 3°) so other super-heated steam is produced and further steam explosions are resumed in confined room until almost all the primitive heat content of the magma is transformed into kinetic energy and the lava is comminuted into glassy, ashy, hyaloclastites.

This process also works above fissural eruptions. The difference is that fissural volcanoes, contrarily to large central ones, are usually monogenic (i. e. delivering one eruption only through the same vent instead of numberless ones for polygenic volcanoes). Linear effusive eruptions also produce quietly flowing basaltic flows but — because being monogenic — they cannot build up big, and eventually steep, reliefs as polygenic volcanoes do. When not poured over steep slopes where pillow-lavas develop, submarine flows are characterized by 1°) the lack of any scoriaceous, more or less thick, upper part (or jacket), and 2°) a regular pavingstone-like surface, each polygon of which being the upper face of short prisms similar to ordinary columnar prismation, but one or two orders of magnitude shorter. As for central volcanoes,

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explosive activity along submarine fissures produces huge quantities of hyaloclastites, but these cannot be heaped up into steep ridges, as happens for subglacial eruptions, because sea-currents spread them far and wide.

Résumé

Les hyaloclastites (palagonites) sont formées essentiellement par la fragmentation en milieu aqueux des lambeaux de lave lancés par explosions volcaniques sous-marines (ou sous-lacustres ou sous-glaciaires). Cette fragmentation résulte de l'explosion de la vapeur prisonnière dans et sous les dits lambeaux.

Beaucoup de guyots (sea-mounts) n'ont probablement jamais été, comme on le croit généralement, des îles volcaniques ultérieurement tronquées par érosion et englouties. Nous sommes convaincus qu'une forte proportion de guyots sont des volcans sous-marins, faits de coulées interstratifiées avec des hyaloclastites, et que leur forme tronconique est congénitale.

Le processus de formation des hyaloclastites que nous décrivons rend compte également des montagnes tabulaires et des crêtes dentelées, constituées de palagonites, caractéristiques du volcanisme sous-glaciaire d'Islande.

Les coulées subaquatiques subhorizontales offrent une surface polygonale de « basaltes en pavés ».

Краткое содержание

Гиалокласты возникают, главным образом, в результате распрыскивания лав, выброшенных в моря при подводном извержении вулканов. — Многочисленные „морские-**monts**“, вероятно, никогда не были вулканическими островами, которые, как обычно считают, были затем срезаны и покрыты водой. Мы предполагаем, что большая часть вулканов образовалась под водой из лав, которые выносились по существующим долгое время каналам, и постепенно росли вверх. — Описанная здесь схема образования гиалокластитов объясняет появление „столовых форм“ и состоящих из палагонита остроконечных горных хребтов, характерных для исландского вулканизма. — Если действительно, многие **Guyots** не являются никакими затопленными островами, то, как важное следствие этого, распространенное мнение о колебаниях уровня моря в несколько тысяч метров, становятся спорными.

In a recent paper, Bonatti (1970) stressed that 1°) wide expanses of oceanic ridges are covered by a basalt pavement, most probably resulting from quiet fissural outpourings of fluid lavas, and 2°) central-type volcanoes, known as seamounts (or guyots), widespread over the ridge flanks and abyssal plains, are on the contrary mainly made of breccia — and ash-like hyaloclastites (hyaloclastites — or "broken glass" — also known as "palagonitic tuffs", are accumulations of basaltic pyroclastic debris of small size engendered below water or ice).

He supposes this difference being due to difference in lavas viscosities: while fluid ones would flow freely on the sea-floor, more viscous ones would be comminuted when poured out into the cold deep sea-water. Together with other authors (Cucuzza-Silvestri, 1963; Honnorez, 1963; Nayudu, 1964) Bonatti believes that hyalo-clastites, when not resulting from brecciation of outer pillow-lava's crust (Rittmann, 1958, 1962; McBirney, 1963), are produced by the granulation of lava-flows brutally water-tempered.

Now the first question is: what physical rules can be called to account for basalts reacting so drastically differently to water-quenching as to give massive hard rock for highly fluid fissural ones, but finely grained hyaloclastites for slightly less fluid shield-volcanic ones?

Secondly, I'm questioning the very comminuting process called upon. This point, nevertheless, asks for some longer comments.

To begin with, it should be stressed that this comminuted facies makes up an important proportion of world's basaltic rocks: not only they are widespread over the whole ocean floor but also they are a major constituent of many formerly submarine or lacustrine (Sicily, Oregon, Ethiopia, etc.) or subglacial (Iceland) volcanic provinces.

Four processes have been called upon to account for their production, viz. a) desquamation of pillow-lavas, b) granulation of lava flows, c) quenching brecciation of an ascending magma in a newly opened gaping submarine fissure, d) explosions.

a) Desquamation. RITTMANN (1958, 1962) has shown that lavas flowing down a steep submarine slope, and so developing into pillows, engender hyaloclastites by the continuous breaking down of the thin vitreous shell formed by cooling at the surface of each pillow; these broken fragments fall down, exposing new red-hot surfaces to the same process: quick tempering, hard-shell formation and mechanical comminution; this process lasts as long as the pillow rolls or creeps downslopes. Through this kinematic process, pillows may be completely reduced into small vitreous bits, but remnants usually remain, attesting the origin of this very type of hyaloclastites. This mechanism allows the production of hyaloclastites only on slopes sufficiently steep to provide pillow-lavas. The relative volume of such hyaloclastites is small, as compared with other ones, in which no signs of formerly existing pillows exist. This process most probably works an important role on the flanks of submarine volcanoes where slopes reach the minimum angle for pillow-lavas formation (MOORE, 1970). And BONATTI (1970) is right when he considers it as taking part in sea-mounts building up. But I disagree with the following one he claims being preponderant.

b) Granulation. BONATTI (1970) describes this alleged process as follows: "hot lavas, when suddenly chilled by cold water may, under certain conditions, undergo thermal shattering. The rapid drop in temperature and the instantaneous vitrification of the melt create within the cooling material stresses which can be released by granulation and pulverization of lava." According to me, such a process, if actually existing, could account for only a millimetric or centimetric outer layer of hyaloclastites. Outcrops are actually 3 to 5 orders of magnitude thicker indeed.

On the other hand, BONATTI writes: "while fissural eruptions of very fluid basaltic magmas (f. i. along active ridges) appear to take place 'quietly' with no formation of hyaloclastites, the latter are produced extensively on sea-mounts. The reasons why magmas of similar composition follow two different mechanisms of eruption in the deep sea have not been completely clarified. It has been suggested that the viscosity of the magma at the time of eruption is the main factor which determines whether one or the other type of eruption will be followed".

I can't agree with BONATTI on the hypothesis he proposes for the following reasons:

1°) The viscosity differences seem having, if any, a quite trifle importance in the comminution process; the most viscous lavas, such as dacites and rhyolites, when erupting below water-level (f. i. Bogosloff in the Aleutians or Kaimeni in

Santorini Caldera) do not give any appreciable proportion of hyaloclastites; artificial molten glass likewise, when poured into cold water, produces less than 0,01% in volume of finely comminuted ash, with no hyaloclastites at all, as the author was recently able to observe during the casting of a big glass-furnace of the St-Gobain Co. in Cognac.

2°) Even admitting some supposed viscosity increase, why should granulation occur when a more viscous (though petrographically identical) hot basalt be suddenly chilled when poured out a central volcanic vent, and no granulation happen when an identically hot, if not hotter, but very fluid, basalt flows out? "The rapid drop of temperature and the instantaneous vitrification" which, according to BONATTI, account for the creation of "stresses which can be released by granulation and pulverization of lava" should occur, if any, in very fluid lavas as well. Like many other volcanologists I have got several opportunities to observe hot basalts, fluid as well as viscous, flowing below water: granulation never occurred in any of these occasions. And, as said before, if it happened, it would account for only a thin superficial layer on top of the lava-flow.

3°) Last, but not least, the "serrated ridges" of Iceland, entirely built of hyaloclastites result from subglacial fissural eruptions, which usually deliver the most fluid basalts ever erupted (see below).

c) Quenching brecciation of an ascending magma-column's top, as proposed by CUCUZZA-SILVESTRI (1963) is but a variation of the above-mentioned mechanism: if plausible enough, it could produce only a trifle proportion of breccia, which should moreover be ultimately covered by the subsequent lava-flows and cannot account for the huge amounts of hyaloclastites observed all over the world.

d) Explosions. Contrasting with all these allegedly "granulated-lava" hyaloclastites, actual hyaloclastites have been really witnessed, just shattered, being hurled high into the air. For months, and even years on, large quantities of comminuted basalt have been observed to be ejected from under the sea over submarine exploding basaltic vents, f. i. at Capelinhos in the Azores and at Surtsey, Iceland. During these two important eruptions, volumes of hyaloclastites produced that way widely transcended those of lava flows poured out during the same time; in fact, the lava to pyroclastic ratiois actually reversed in submarine, as compared with subaerial, explosive basaltic eruptions.

The author (TAZIEFF, 1968), after close observations of these eruptions, arrived at the conclusion that no explosive phenomena occur when lava-flows, whether fluid or viscous, simply pour under water. On the contrary, explosive submarine activity is obviously characterized by initial magmatic explosions instantly followed by short series of steam ones, the result of which is the eventual shattering of the lava into a millimetric granulometry and a quite obvious increase of kinetic energy, as measured by heights reached by the ejecta: 600 to 1200 m. as compared with 100 to 300 m in similar (or even the same) eruptions when occurring in the open air.

Recent discussions with Dr. P. ZETTWOOG, thermophysicist, convinced me that the surface to volume ratio hypothesis I had imagined (TAZIEFF, 1968) to account for this behaviour difference between quenched lavaflows and lava-lumps does not suffice to explain the phenomenon. For steam explosions to happen, steam should be emprisoned in a confined room. Now, fluid lava-lumps, as hurled up by magmatic explosions, are good steam-traps indeed: first, they are scoriaceous, i. e. holes pierced, and each hole may thus constitute a small explosion spot; secondly, the many flat-shaped red-hot lava-pancakes, when hurled upwards through water, should more or less take an umbrella shape; these umbrellas act as bigger traps for superheated steam.

These "phreatic", secundary, explosions shatter the first generation lava-lumps; so, new smaller fragments of red-hot lava are put into contact with water, generating a second series of steam explosions. The process may be reproduced until ALMOST ALL THE THERMAL ENERGY CONTAINED IN THE ORIGINAL LAVA BODY BE CONVERTED, by way of produced superheated steam, INTO KINETIC ENERGY. This accounts for the well observed phenomena characterizing these submarine eruptions: 1) close successions of several explosions grouped together, 2) comparatively high altitudes (up to one order of magnitude higher than in similar subaerial eruptions) reached by ejecta, and 3) producing of huge volume of ashes (hyaloclastites) constrasting with the small proportion of pyroclasts characterizing basaltic subaerial eruptions.

Now, this mechanism accounts fairly well for the building up of a series of characteristic physiographic features: ash-rings, table-mountains, serrated-ridges and sea-mounts.

1) Ash-rings are shallow-water subaquatic monogenic volcanoes. They are formed during one single explosive event by hyaloclastites hurled up above the surface of the sea; the higher the reached altitude, the wider the parabolic trajectories, and the larger the ring's diameter. This accounts for the well known fact that diameter to height ratio of ash-rings is several times larger (frequently up to 10 : 1) than that of scoriae mounds born from an identical but subaerial activity (about 1 : 1) (Figs. 1 and 2). The shallower the vent, the higher are the pyroclasts hurled up; this gives a clue to the depth of the sea (or lake) at the time of the eruption (Fig. 3). It should be noted that a large proportion of produced ash is carried far away by prevailing winds (TAZIEFF, 1969).

2) Table-mountains, so typical of Icelandic volcanism (Fig. 4), result from subglacial central eruptions. The lava, pulverized in the melt-water, was not thrown into the air, because of the glaciers which capped the erupting craters; the hyaloclastites consequently settled down after somewhat short subvertical up and down (and not parabolic) trajectories; they were therefore heaped more or less on the spot, accumulating into piles the volume of which was not depleted as for wind-drifted ashes. The flat top and abrupt flanks of the table-mountains is well accounted for by the glacier rigid frame.

3) Serrated-ridges, similarly typical of Icelandic quaternary volcanism, also result from subglacial basaltic explosive activity; but these eruptions were fissural, thus most probably monogenic. The long fire curtains of mighty lava-fountains (together with outpouring of highly fluid flows) typical of linear eruptions (Fig. 5) produced big quantities of hyaloclastites. Contrarily to similar submarine outbreaks, where much of the glassy ashes produced that way are carried away in the open seas by currents, hyaloclastites of a subglacial eruption accumulate practically over the mother-fracture itself, thanks to the frame of hard ice.

It could be questioned why no deep-sea crests, similar to subglacial serrated ridges, apparently no not exist? On the oceanic floor, fissural eruptions occur

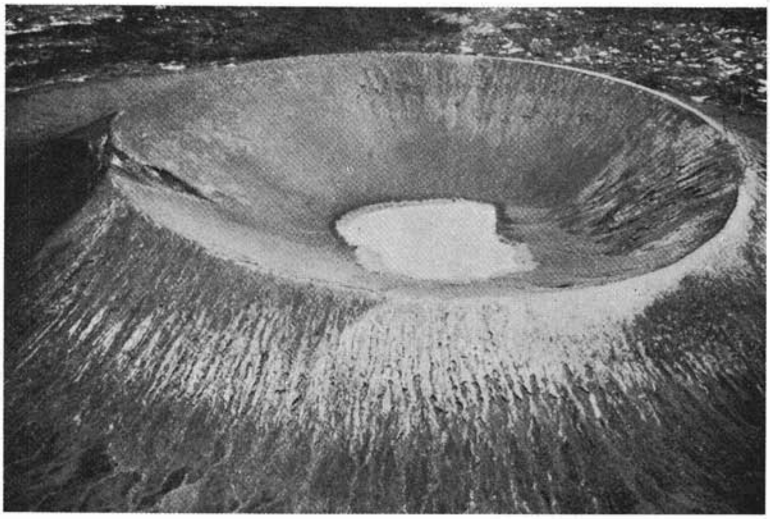

Fig. 1. Geologically very young ash-ring, composed by explosively engendered hyaloclastites, in the northern part of the Erta'Ale range, Afar, Ethiopia. Note the regularity of the underwater deposited circular rampart and the large diameter to height ratio. Also observe the impermeability of the hyaloclastites, notwithstanding the present aridity of this desertic area.

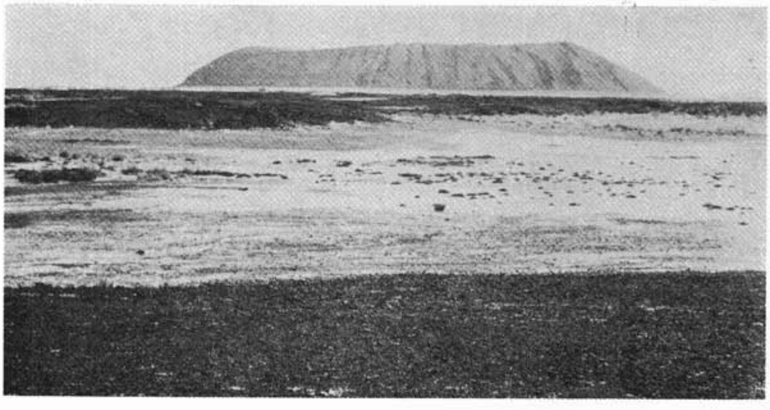

Fig. 2. Kokmaraea, to the SW of Erta'Ale range, ash-ring, similar to, but somewhat older than the Fig. 1, clearly showing the large D/H ratio.

either above the critical depth, f. i. on the crest of sub-oceanic ridges, or below this depth. In the first case, hyaloclastites are produced in huge quantities but are not piled up into steep ridges as in subglacial eruptions because of the lack of rigid lateral brace of ice armature. Shattered bits of glassy lava are on the

Fig. 3. Afar (Ethiopia). The subaquatically built Arrale volcano (12° 45′ N—41° 05′ E), south of Lake Giulietti (N. Afar). A terminal lava flow, later collapsed and (or) eroded away had capped the ash-ring.

Fig. 4. Hlodufell (Iceland — Typical table-mountain, made of hyaloclastites engendered by basaltic explosive eruption(s) below a sufficiently thick glacier: debris were prevented from being hurled into the air and fell back to form an ash-ring, but they were heaped up in the comparatively narrow space of meltwater; the glacier, around and above, worked as a rigid brace which prevented pyroclasts to be widespread by sea-currents before being cimented together into hard "palagonitic tuff".

contrary spread by sea currents over *comparatively* wide areas. On the other hand, fissural eruptions giving birth to monogenic volcanoes, big lava accumulations from numberless eruptions delivered by one same volcano do not happen.

4) Seamounts (guyots). When comparatively small (some hundreds of

meters high), they probably are monogenic volcanoes similar to ash-rings, but generated at depths too great to allow the ejecta being sent into the air, though shallow enough — say less than two to two and a half Km, which corresponds to the critical pressure for water — to allow phreatic explosions to occur. Mutadis mutandis, it's a process similar to the table-mountains producing one, the glassy fragments following more or less vertical up and down trajectories; they accumulate close to the vent and eventually over it. This, most probably, accounts for the emersed sea-mount, Mt. Asmara, recently discovered in Afar (Bonatti & Tazieff, 1970) (Fig. 6).

When large (kilometers high and tens of km across at the base), many sea-mounts most probably represent polygenic volcanoes, whose manifold eruptions, both effusive (pillow-lavas and associated desquamation hyaloclastites) and explosive ("phreatic" hyaloclastites), heap their products into huge piles; the crater is eventually filled up by ashes which both fell back during the final eruptive phase and were washed down from the crater walls by turbidity currents. The typical flat top of sea-mounts results from this last process as well as from the capping effects of water. Consequently, no erosion of hypothetical volcanic islands (Hess, 1946; Hamilton, 1956; Menard, 1964) is needed to explain this morphology. Furthermore, if this classically admitted hypothesis had to be accepted, a fair number of islands in the process of being leveled as well as submerged truncated cones at levels varying from zero to several Km, should exist; which is not the case.

When the eruption boosts out far below the critical pressure depth, no explosions are supposed to occur and lavas are poured quietly out. They spread out laterally from the monogenic fissural volcano, and only hard rocks result from these eruptions. On steep slopes, pillowing develops, with associated desquamation-type hyaloclastites. On gentle slopes and over flat expanses, the basaltic surface most probably usually shows that peculiar morphology we have recently discovered to characterize recent (holocene) lava fields, now in the open air at altitudes ranging from — 150 m. b. s. l. to + 1000 m ca., in the Afar depression (Bonatti & Tazieff, 1970).

They consist in regular sheets of basaltic rocks, the surface of which offers a typical polygonal pattern, the polygons being usually tetragonal to hexagonal and frequently about 10 cm across (Fig. 7). These polygons are the upper base of short vertical prisms which differ from classical columnar prismation in that their height and their diameter usually are of the same order of magnitude; when longer than wider, it's only by a factor 2 to 4, while differences several orders of magnitude large exist between lengths and cross-sections of subaerial flows' columns.

Another feature by which these exposed "paving-stone" lava flows differ from subaerial ones is the absence of any upper scoriaceous part, neither of aa, pahoehoe, not blocky type: the prismation, in the numberless places where these flows have been observed so far, reaches the very surface. It can of course be supposed that a hypothetical scoriaceous jacket originally existed but was later eroded away; examination as long carried out induces to dismiss such an hypothesis.

The microscopic texture of paving-stone lavas is quite different from the

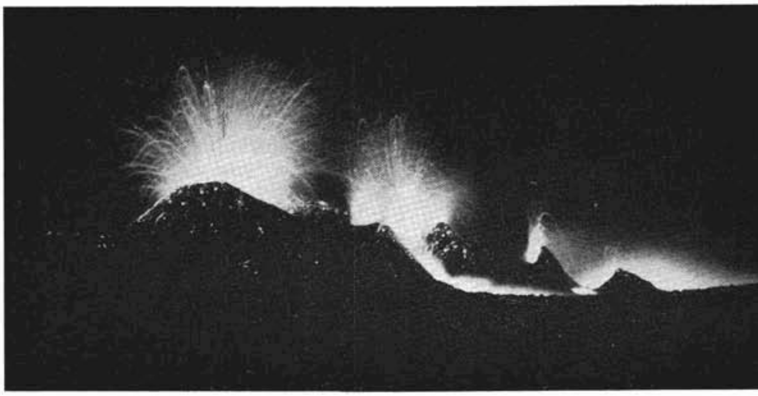

Fig. 5. Fissural fountaining, Mt. Etna, 6 April 1971; the same type of eruption below an ice-cap should provide the building-up of a hyaloclastic "serrated ridge" (Photo: Prof. F. BARBERI, Pisa).

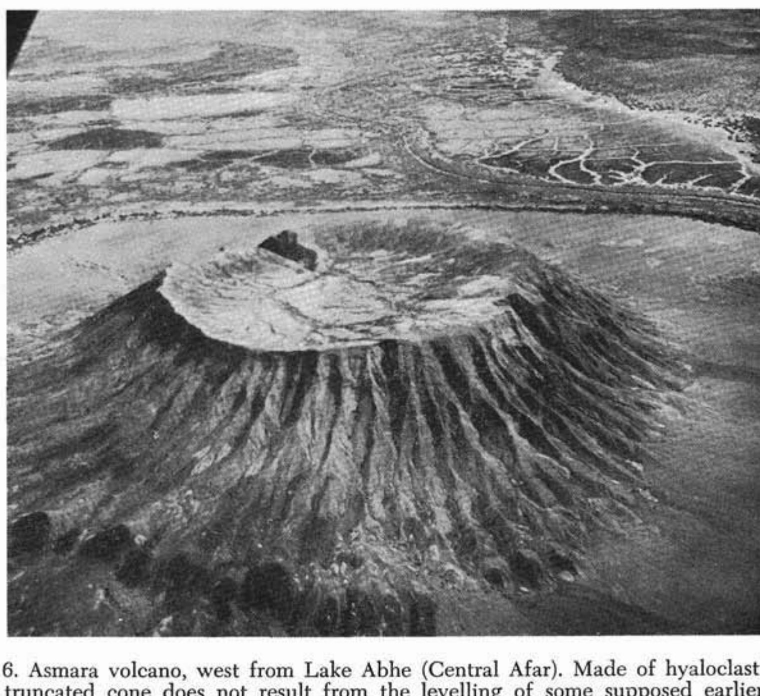

Fig. 6. Asmara volcano, west from Lake Abhe (Central Afar). Made of hyaloclastitites, this truncated cone does not result from the levelling of some supposed earlier and more pointed cone but is actually congenital. This morphology most probably originates from submarine volcanic explosive activity having occurred at a depth great enough to prevent ejecta being hurled into the atmosphere; they have accordingly followed an up-and-down approximately vertical path (instead of usual parabolas, as described in the air), so being heaped up as a pile instead of a ring

Fig. 7. "Paving-stone" surface, presumably typical of subaquatic lava flows. Afar Depression, Ethiopia.

usual texture of subaerial basaltic lavas. It's characterized by the presence in the groundmass of small circular crystals of plagioclase set out in a fan-shaped motif, like in the groundmass of some pillow lavas. Clinopyroxene and olivine in the groundmass also appear in small elongated crystals, the former often dusted with opaque minerals (BARBERI & VARET, 1970).

BARBERI & VARET (1970, p. 49—51, Fig. 38 & 39) describe the somewhat aenigmatic "lava cumulus" we have observed in Northern Afar. Further investigations have convinced the present author they represent a typically subacqueous morphological structure made up by *pillow-lavas at their very initial stage*. These submarine "Ühornitos" are built up by *successive quite small outflows of short duration each*. They get their cylindrical shape because of the rapid outer cooling and the steepness of the slope. Within the cylindrical crust of each of these elongated and steeply inclined pillows the molten basalt, not replenished from the eruptive vent, was drained down, so eventually leaving a central hollow.

Conclusion — Submarine volcanism is a highly important phenomenon, both by its building-up the oceanic floor, so accounting for about 2/3 of the earth's outer crust, and because it probably being the working agent of tectonic plates movements. Therefore its mechanisms should be taken into serious consideration and investigations carried on on a somewhat larger scale.

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