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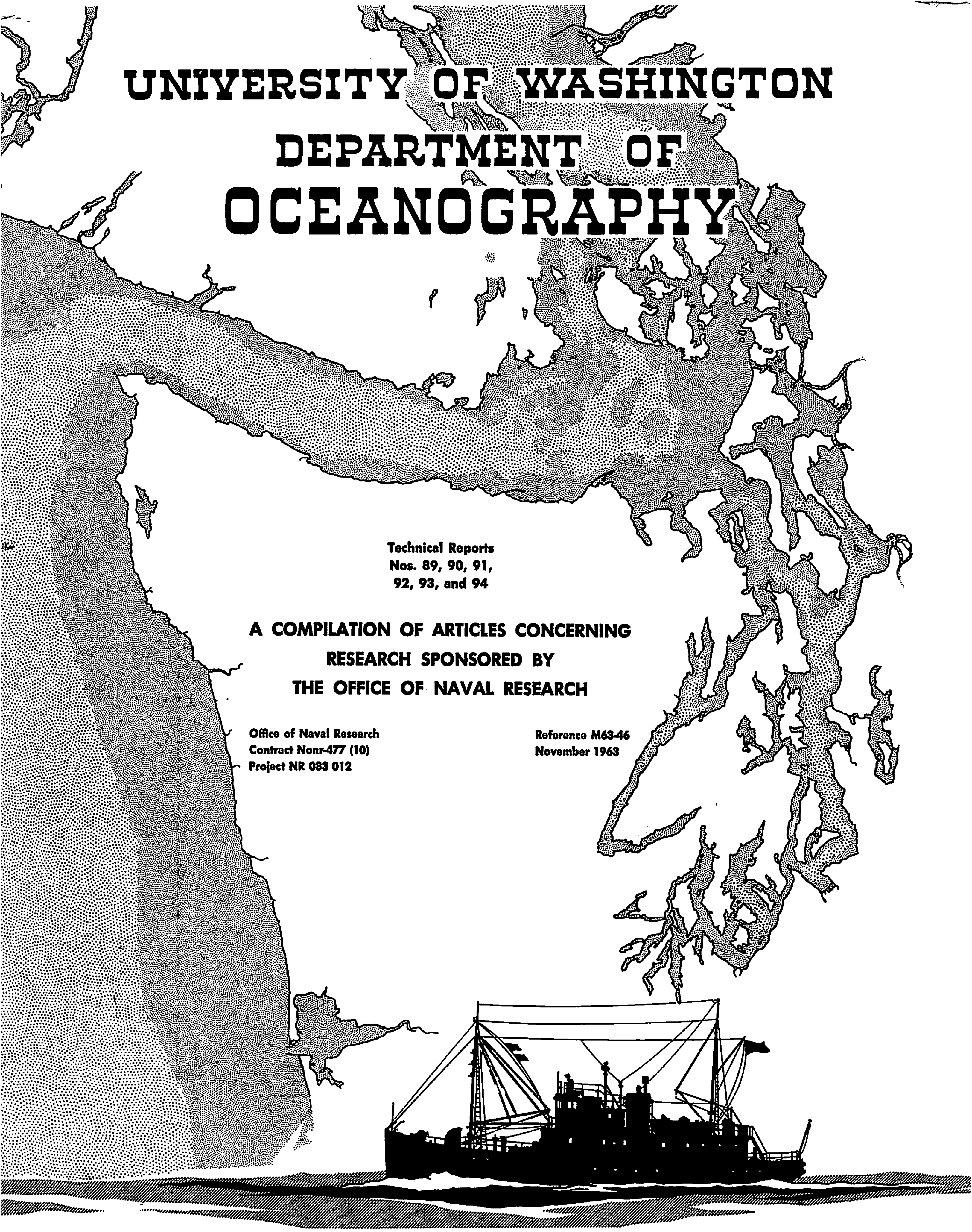

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A New Hypothesis for Origin of Guyots and Seamount Terraces[1]

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Abstract—A number of different volcanic rock types were dredged from the summit terraces of Cobb Seamount off the coast of the State of Washington and Bowie Bank off the coast of British Columbia, Canada. Palagonite tuff is the most common rock type. Fragments of crystals and basaltic glass, angular to rounded, ranging from sand to granule sizes, are set in the palagonite matrix. These rocks closely resemble complexes of pillow lava and bedded palagonite breccia formed where flows of Columbia River basalts entered lakes and therefore are considered to be primary palagonite tuffs. The remainder of the dredged material consists of angular to subrounded boulders which are considered to be unaltered solid parts of the pillow palagonite complex, concentrated locally by the removal of the palagonite matrix by currents. It is concluded that the terraces of Cobb and Bowie Bank are primary volcanic features rather than wave planation surfaces.

Introduction—In the Gulf of Alaska several seamounts have been mapped [*Murray*, 1941; *Menard* and *Dietz*, 1951]. These rise from 3000 to 12,000 ft above the sea floor (Fig. 1). *Hess* [1946] reported some 160 seamounts in the Pacific. *Tolstoy* [1951] described seamounts in the North Atlantic, some of which rise approximately 10,000 ft above the sea floor. *Carsola* and *Dietz* [1952] described two seamounts, Erben and Fieberling, 800 and 600 miles off the coast of Southern California. These are truncated, basaltic volcanoes with summit platforms at 400 and 280 fathoms.

The available information, based on echo soundings, shows that many seamounts are of the flat-topped type known as guyots [*Hess*, 1946]. Dredged rock material is chiefly volcanic, and most previous workers have held that these remarkable ocean-bottom features were wave truncated volcanic islands. However no one has published a detailed hypothesis of the mechanism of submarine eruption which formed these features.

Petrographic study of rock dredged from Cobb Seamount and Bowie Bank in the northeast Pacific (Fig. 1) indicates the presence of palagonite tuffs and breccias. These tuffs and breccias are similar to palagonite tuffs developed by aqueous chilling in the Columbia River basalts and in the Moberg formation of Iceland. The chilling and granulation of basaltic magma to sideromelane on flowing into water, and the mode of origin of palagonite by hydration of sideromelane, have been well described by *Peacock* and *Fuller* [1928] and *Fuller* [1931]. Their terminology is used throughout this paper.

Based on the extensive occurrence of palagonite tuffs a hypothesis is proposed for the building of seamounts, which suggests that the flat tops and terraced slopes may be primary features.

Cobb Seamount—Since the discovery of Cobb Seamount in 1950, several investigations of it have been undertaken aboard the research vessel *M.V. Brown Bear* of the Department of Oceanography at the University of Washington. Cobb Seamount is located 270 nautical miles west of Gray's Harbor, Washington (46°46.4′N, 130°48.8′W). The detailed description of topography, geology, biology and hydrography has been presented by *Budinger* and *Enbysk* [1960]. As shown in Figures 2 and 3, Cobb Seamount has approximately 1500 fathoms relief and is 17 nautical miles wide at the base. The shoalest point on the mountain is 18 fathoms, the top of a pinnacle rising from a terrace which ranges from 45 to 50 fathoms in

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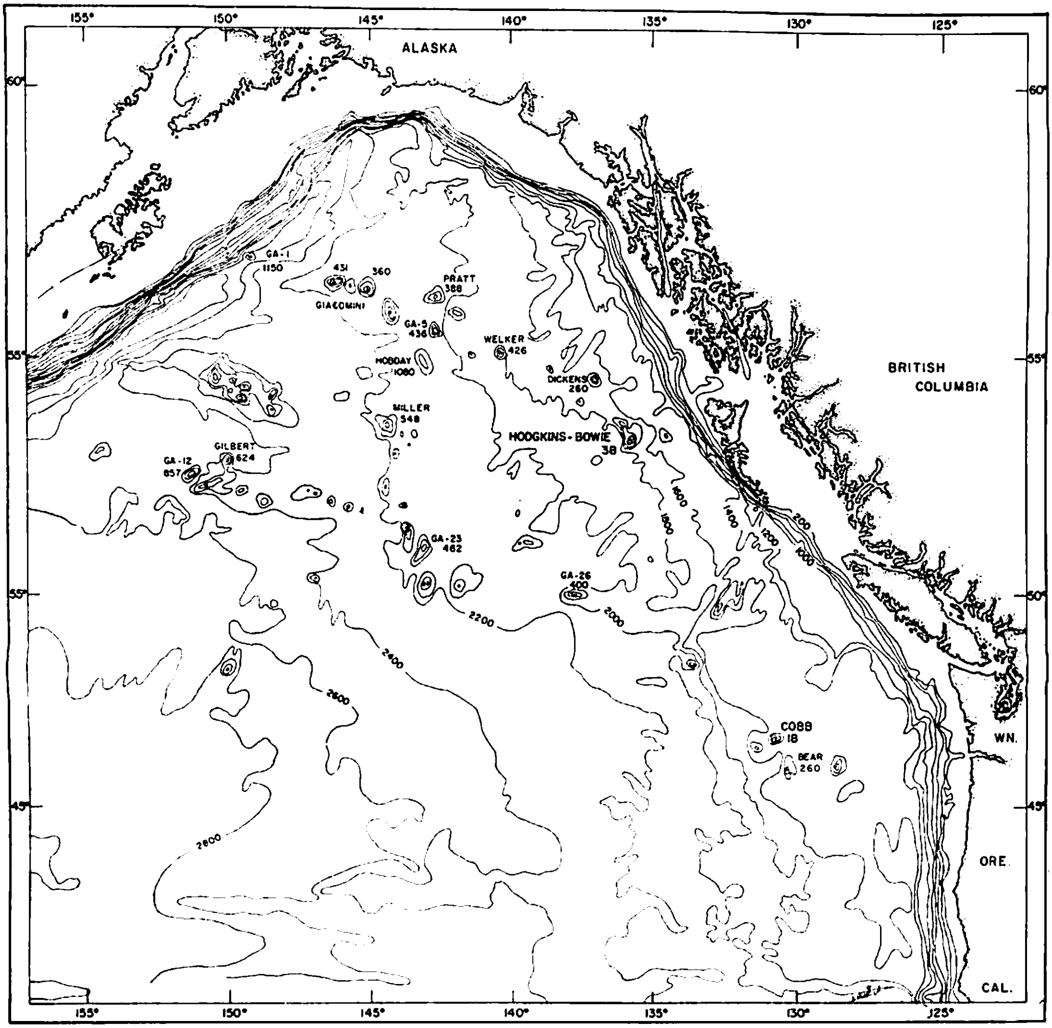

Fig. 1—Distribution of submarine mountains in the northeast Pacific Ocean

depth. A terrace at about 100 fathoms actually varies between 85 and 130 fathoms. Slopes immediately below this terrace are about 22°. The so-called '500-fathom' terrace is not continuous but is a series of levels, varying from 450 to 650 fathoms in depth.

Several dredged samples obtained from the terrace and along slopes contain boulder to gravel size, angular to subrounded solid rocks. In thin sections these rocks vary in composition from olivine-rich to olivine-poor basalts. Some are vesicular and others suggest pillow-structures. The largest portion of most of the samples is a yellowish-orange colored rock consisting of sand- to gravel-size lithic fragments and sand-size mineral fragments (Fig. 4). The rock fragments are mostly sideromelane, to a greater or lesser degree altered to palagonite. The rock is friable and tends to split. This type of rock has often been interpreted as consolidated erosional material of basalts. However, careful megascopic and microscopic studies show that it is palagonite tuff and breccia and not 'normal' weathering products of basalts.

In thin sections the fragments of the orange colored rock are mostly sideromelane, to a greater or lesser degree altered to palagonite. The sideromelane contains euhedral to subhedral crystals of olivine, and plagioclase varying from basic andesine to bytownite. The passage from

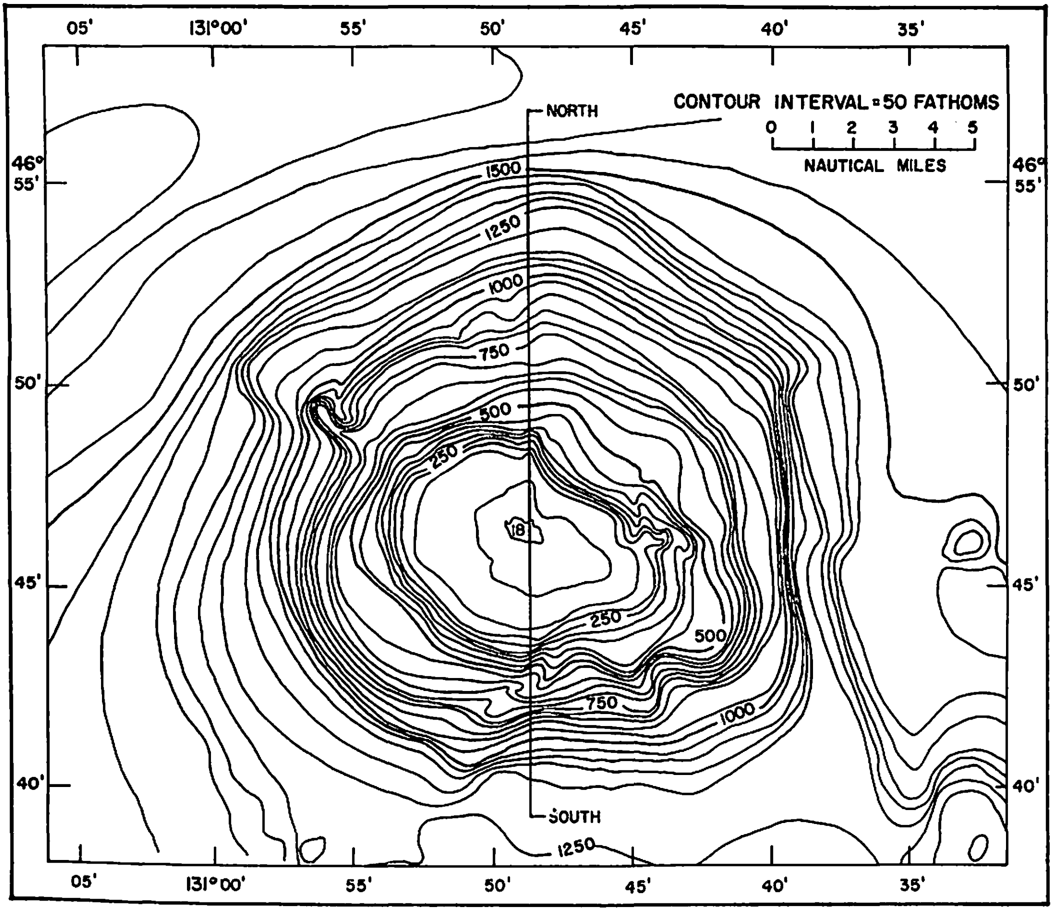

Fig. 2—Bathymetry of Cobb Seamount

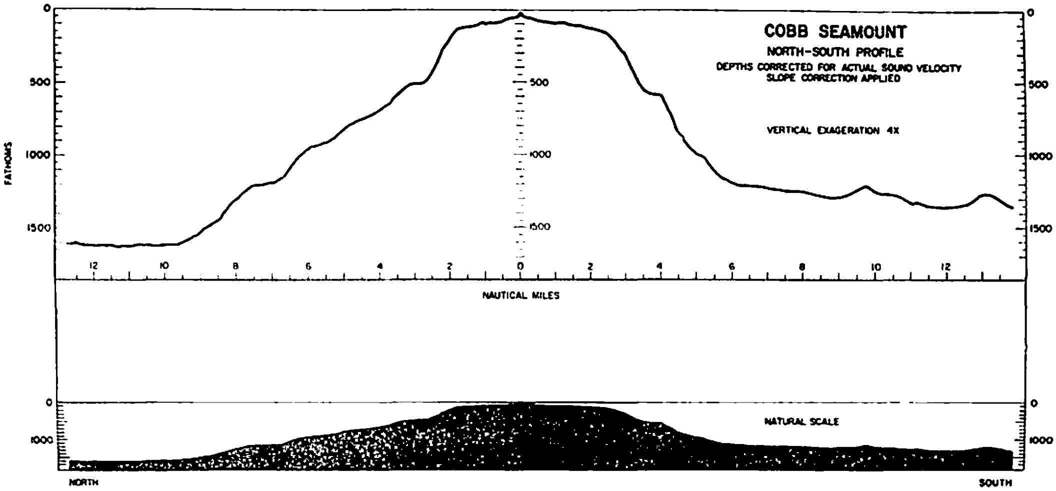

Fig. 3—North-South profile of Cobb Seamount

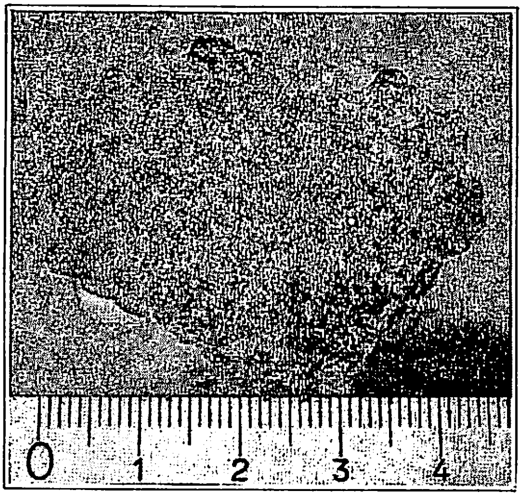

FIG. 4—Palagonite tuff breccia from terraces of Cobb Seamount; scale in cm

vitreous sideromelane interior to the outer margin of the fragment is marked by a change in color of the alteration material from pale yellow through dark yellow to reddish yellow forming bands, shown as dark bands in Figure 5. The alteration product is the palagonite complex forming concentric bands. In some instances it surrounds each sideromelane fragment and in some cases it forms the lining of vesicles. Under high magnification, the bands are resolved into opaque globulites and fibrous structures. These palagonite bands grade into a mostly clear yellowish-brown isotropic variety of palagonite which occupies the greater part of the slide. In all instances, the alteration that affected the sideromelane and led to the various stages of palagonite had absolutely no effect on the marginal microlites of plagioclase and olivine. In some cases the sideromelane fragments have been completely altered leaving islands of unaltered microlites. The other rock fragments are olivine-rich to olivine-poor basalts. Hence these rocks are considered to be palagonite tuff and breccia, not weathering products.

Bowie Bank—Bowie Bank, located in the eastern part of the Gulf of Alaska at about 53°17′N, 135°40 W′ (Fig. 1), has an extensive terrace which varies from 120 to 140 fathoms. Above this terrace steep hills rise to a depth of 25 fathoms or more [*Hurley* and *Nayudu*, 1961]. The writer studied rocks dredged from the terrace and hills, and in his original description suggested the possibility of these rocks being picrite-basalt lapilli tuff breccia. These rocks were then considered to be weathered basaltic material. However, detailed comparative studies of rocks from Cobb Seamount and other occurrences of palagonite tuff indicate that they are palagonite tuff. The Bowie Bank material (Fig. 6) contains more fragments of minerals, chiefly unaltered plagioclase and olivine, than that of Cobb Seamount. The rocks show the same range of alteration of sideromelane as exhibited by the Cobb sections.

If the material dredged from the 100-fathom terrace on Cobb and from the 130-fathom terrace on Bowie is palagonite tuff rather than erosional debris, the terraces may *not* be erosional. The process of palagonitization and forms taken by basalts entering an aqueous environment are discussed below in an attempt to compare the better-observed cases of palagonitization and to understand the morphology of subaqueous lava complexes with the origin and morphology of seamounts.

Palagonitization and aqueous chilling—*Von Waltershausen* [1845] applied the term 'palagonite' to material forming the brown groundmass of a tuff from Palagonia in the Val di Noto in Sicily. He described palagonite as "A fully transparent wine-yellow to resin-brown mineral of vitreous lustre and hackly conchoidal fracture, the external appearance of the substance being very similar to that of gum arabic or brown sugar." In 1846 *Von Waltershausen* [1847] found well developed and widely distributed palagonite in certain tuffs of Iceland and to this rock he gave the name palagonitfels. In Iceland what is commonly known as the Moberg formation or 'palagonite formation' [*Peacock*, 1926a] consists predominantly of palagonite tuff and breccia, which was formed by the palagonitization of basaltic glass (sideromelane). These rocks usually contain fragments, globules, and lumps of more or less crystalline vesicular basalts. *Peacock* [1926b], *Tyrrell* and *Peacock* [1926], *Noe-Nygaard* [1940], *Kjartansson* [1943], and most students of the Moberg formation assume that the basaltic magma was extruded in water-filled chambers under glaciers. *Fuller* [1931] also held that palagonite was formed by entry of basalt flows into lakes.

Peacock and *Fuller* [1928] considered pa-

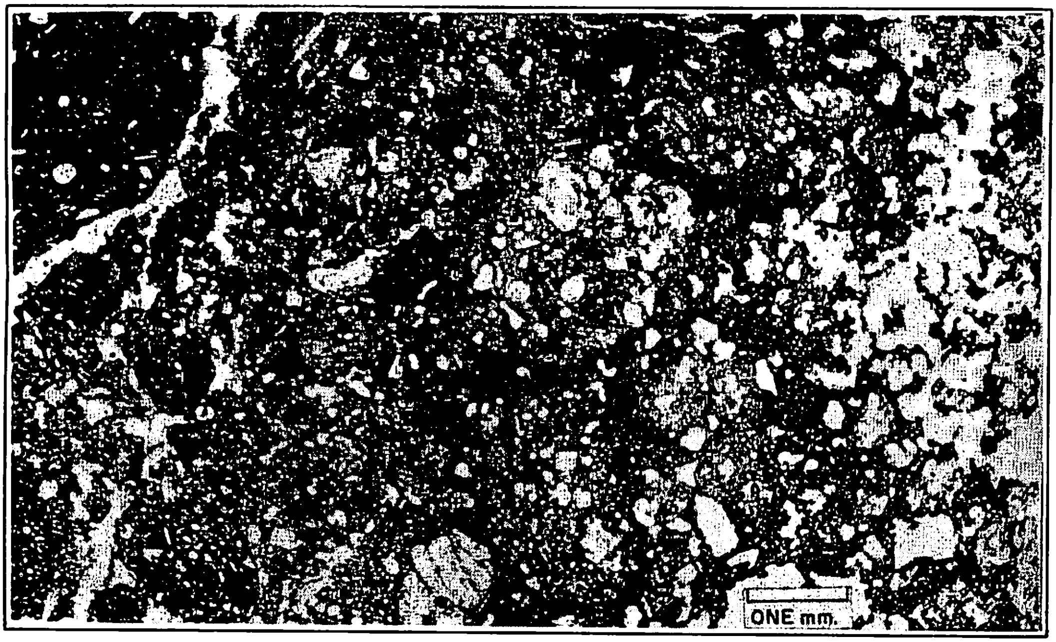

FIG. 5—Photomicrograph showing sideromelane with inclusion of plagioclase and olivine; palagonite, the alteration product of sideromelane forming concentric dark bands, is isotropic

lagonitization as a primary or syngenetic phenomenon brought about by waters associated with phreatomagmatic eruption of basaltic magma in which hot sideromelane glass is altered while in contact with water vapor.

The water content of palagonite from Iceland is 28 per cent and from the Columbia River Plateau is about 32 per cent. The specific gravity of palagonite from Cape Flora, Franz Josef Land, is 2.4, whereas palagonite tuff from the Columbia River Plateau varies from 2.4 to 2.6. The specific gravity of palagonite tuff from the terrace of Cobb Seamount is 2.3.

In thin sections the yellow-brown palagonite tuffs from Cobb Seamount and Bowie Bank show striking similarities to other palagonite tuff occurrences. Because the alteration of basaltic glass (sideromelane) to palagonite is a primary phenomenon, the palagonite tuffs and breccias described from the terraces of Cobb Seamount and Bowie Bank may be primary rocks, rather than erosional debris.

Aqueous chilling—The writer was fortunate to visit many occurrences of palagonite tuffs and breccias in the Columbia River plateau in company with Hoover Mackin and subsequently to study some of these occurrences and material collected from them in detail. The base of the Columbia River flows consists of an accumulation of yellowish tuffaceous-looking material, with pronounced foreset structure, invariably associated with pillow lavas.

Fuller [1931, 1934, 1950], in a classical series of papers, showed that some of these yellowish tuffaceous rocks are primary palagonites in the form of foreset bedded breccias. *Fuller* [1931, p. 284] pictured the origin of the foreset-bedded breccias as follows:

> "A fluid lava on encountering a local body of water would tend to granulate like molten slag and would thus form a fine breccia which would accumulate to a depth approximately equal to that of the water. The fine breccia would settle until its surface attained an angle of repose which owing to the roughness of the fragments, would be relatively steep. If the molten cascade continued to pour into the water, the accumulation of granulated glass would gradually advance like the foreset bedding of a delta. The inclined bedding would be preserved by the thin sheets and the ropy or ellipsoidal masses which failed to granulate. Except for the possible effect of rising steam, the flow would

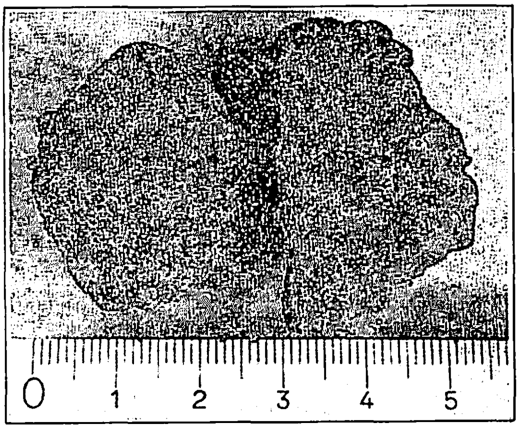

FIG. 6—Palagonite tuff from Bowie Bank; scale in cm

> gradually advance on top of these foreset beds as if on dry land."

A representative sample of bedded palagonite tuff-breccia from one of Fuller's localities of the Columbia River Plateau is shown in Figure 7. This rock bears close resemblance in hand specimen, and even more strikingly in thin section, to the palagonite tuff breccias dredged from Cobb Seamount and Bowie Bank.

Origin of seamounts—The development of the flat tops and terraces on seamounts presents a puzzling problem when we consider the great range of elevation of these features. Most workers explain the flattish surfaces as caused by truncation by wave action at or near sea level. This implies a great lowering of sea level in the geologic past.

Hess [1946] advanced a hypothesis suggesting that the summit surfaces of guyots in Pacific Basin were old and possibly represent marine planation surfaces in Precambrian oceans in which reef-building organism did not exist. He believed that the present depths of the surfaces was largely due to relative rise of sea level since Precambrian time.

Hamilton [1956] gave an excellent review of various aspects of the problem and suggested that some of the guyots in the mid-Pacific were submerged during the Cretaceous time. The submergence was thought to have been brought about mostly by isostatic adjustment. He also demonstrated, by the occurrence of Cretaceous reef corals and other fauna on the guyots, that Hess's idea of relative rise of sea level since Precambrian is no longer tenable.

The mechanism of construction of the volcanic islands which were truncated has been little discussed. *Hamilton* [1956] assumed that the peaks of the main ridge of mid-Pacific mountains were compact cones of lava and pyroclastic material or entirely pyroclastics.

Stearns [1946] following the earlier suggestion of *Bonney* [1902] in discussing the geologic history of the Hawaiian Islands, assumed that in the initial submarine phase the lavas were mainly pillows and ash. *Hoffmeister* and *Ladd* [1944] considered the coral islands of the Pacific to be pyroclastic islands and they believed Falcon and the New Hebrides and other islands in the group consist predominantly of pyroclastic material. *Jaggar* [1930], in discussing Falcon Island, rebuilt of basaltic fragments in 1927, expressed his belief that a submarine lava dome exists under the island: "While such volcanoes exhibit chiefly fragmental material it must be remembered that a pile of solid lava in the form of a dome probably exists beneath. How an outflow of liquid lava like one of the Mauna Loa flows would behave under deep, cold water is a matter of theory, not observation."

Submarine eruptions—Very little is known with certainty about the effects produced by effusive lava when in contact with ocean water. In many cases submarine eruptions where the magma concerned is basaltic is obviously explosive. But the submarine lava flows observed by *Washington* [1926, p. 376], at Santorini in 1925 were not explosive and it has been sug-

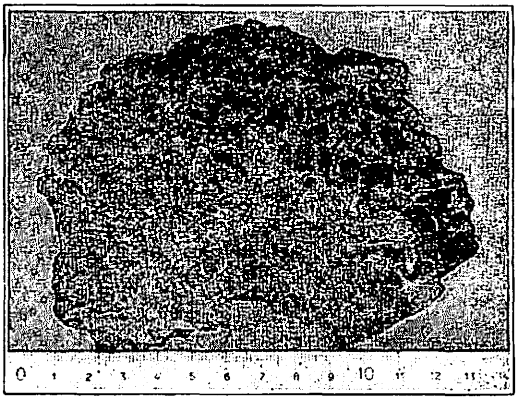

FIG. 7—Palagonite tuff breccia from Columbia River plateau; scale in cm

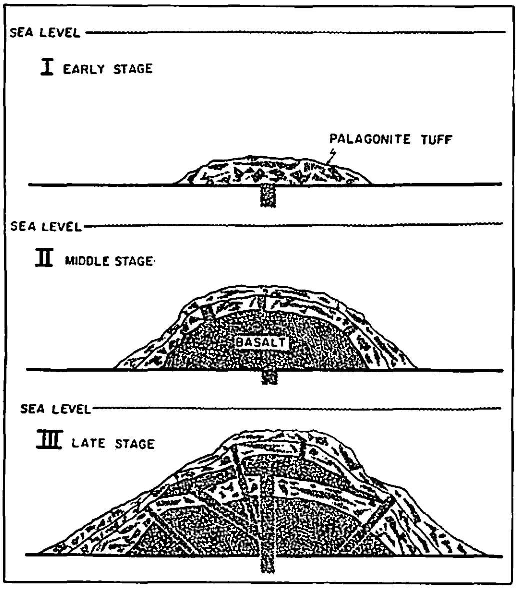

FIG. 8—Successive stages of submarine volcanic eruption leading to construction of a seamount

gested the lack of explosion is because the lava advanced under the protection of a "water cooled and flexible sheath."

Koto [1916], while discussing the great Sakura-Jima eruption, described the explosive nature of lava when entering the sea and the development of 'foamy glass.' According to *Stearns* and *Clark* [1930], when lava from Mauna Loa, Hawaii, entered the sea it was shattered rather violently and large cones of lapilli were built up. 'Globular basalts' and breccias commonly referred to as pillow lava have been described in Iceland by *Peacock* [1926*b*, *Tyrrell* and *Peacock*, 1926], *Nielsen* and *Noe-Nygaard* [1936], and *Noe-Nygaard* [1940]. These resulted from subglacial eruptions of Pleistocene and Recent age.

Peacock and *Fuller* [1928] and *Fuller* [1932] stated that different products will form depending on the depth of water and the temperature and fluidity of the lava. Whether it forms pillow or granulates, the lava that comes in contact with water has invariably been chilled to form a thick shell of sideromelane. Unlike subaerially brecciated tuffs, the aqueous contact material consists of spherical pellets and shell-like fragments formed by perlitic conchoidal fracturing. In addition, large masses of ropy or ellipsoidal forms of basalt are formed. The finer fragments consist largely of sideromelane. This sideromelane is mainly altered to palagonite by the steam generated in quenching the extruded material.

Koto [1916, p. 54], in describing the great eruption of Sakura-Jima in 1914, stated that a shallow bank outlined by the 10-fathom line was formed by the accumulation of submarine ejecta and concluded: "As in normal development of submarine islands, a massive dome or tholoid rose through the aqueo-pyroclastic deposits in the final phase which is typically represented in the form of Iwo-Jima."

Hypothesis—Considering Jaggar's previously-mentioned statement regarding submarine eruptions, that their nature is a matter of theory, not of observation, the writer proposes a working hypothesis for the origin of seamounts based on the development of palagonite in Iceland and the Columbia River plateau and on the occurrence of cumulo-domes or tholoids. A simplified sketch illustrating successive stages of submarine volcanic eruption leading to the building of seamounts is shown in Figure 8.

Stage I—Fluid basaltic lava erupting from fissures on the sea floor granulates like a molten slag and forms a mound of tuff and breccia consisting of sideromelane and rock fragments. The sideromelane alters to palagonite.

Stage II—The magma by its own force intrudes the palagonite mound forming a swarm of dikes, a sill, or a laccolith-like structure. The palagonite layer acts as a carapace protecting the magma from rapid chilling and enables it to crystallize. During protrusion and solidification, apophyses and dikes of lava intrude the carapace and serve as feeders for surface eruption developing successive palagonite mounds. This process causes the carapace to thicken and the volume of the cone to grow. Where erupted on a sloping surface the palagonite tuff might advance seaward in successive foreset beds giving rise to a terrace.

Stage III—The process may end with either stage I or II, but is likely to continue; large seamounts are probably formed by many repeated cycles of the process represented in stage I and II. This process could lead to the building of a steep-sided cone with constructional or primary terraces on the sides and with a somewhat flat top. If there is continuous and/or

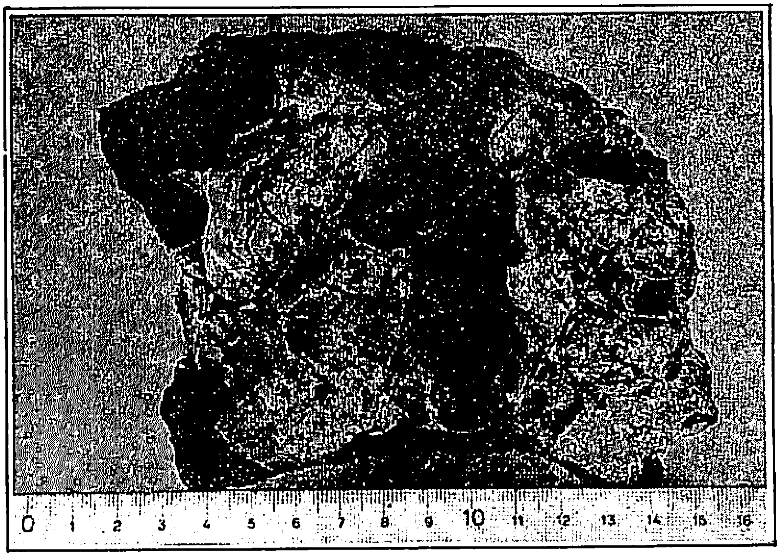

FIG. 9—Palagonite tuff breccia from Columbia River Plateau showing angular to subrounded smooth-surfaced rock fragments; oval and elliptical cavities were formed by removal of similar-shaped rock fragments; scale in cm

repeated eruption within the same locale, seamounts with a greater relief would result.

Discussion—This hypothesis accounts for many geomorphic features of seamounts. The average slope of a typical mid-Pacific guyot is 22° [*Hess*, 1946; *Hamilton*, 1956]. *Carsola* and *Dietz* [1952] described average slopes of 18° for the two guyots. *Kuenen* [1935] discussed the submarine slopes of volcanoes. According to him the slopes are straight and steep and average roughly 25 degrees, with a slight concavity. He assumed these slopes to consist of volcanic debris, and as might be expected these submarine slopes show no relation to subaerial slopes of the adjacent islands.

As stated in stage II of the hypothesis, the marginally erupted palagonite tuff would flow down the slopes developing steep-sided foreset beds on the sides of the seamount. *Fuller* [1931, p. 282] described foreset-bedded palagonite tuff breccias having primary dips of a maximum of 30°.

Finally seismic refraction studies for Bikini atoll group show the occurrence of low velocity pyroclastic material capping the high velocity basaltic material more or less in the form of a dome [*Raitt*, 1954]. The inferred rock type and structure from the seismic studies and the data from drilling records [*Emery, Tracey* and *Ladd* 1954] show a striking similarity to the model of a seamount discussed in this paper.

Truncation and erosional material—The common occurrence of angular to sub-rounded rock fragments of boulder to gravel size on seamounts has been considered to be evidence of truncation by wave action. *Barrell* [1917] estimated a depth of 50 fathoms for the limit of wave abrasion. *Dietz* and *Menard* [1951] believed the effective wave erosion takes place in the surf zone, which is five fathoms deep, and not down to hypothetical wave base. In any case, wave-planed surfaces must be formed at or near sea level. However, a close examination of a representative sample (Fig. 9) of palagonite tuff-breccia from the Columbia River Plateau suggests that angular to sub-rounded fragments are *not* due to abrasion and can be formed primarily. Well-rounded oval-shaped smooth-surfaced fragments of basalt can be seen embedded in the palagonite matrix. In addition, oval and semicircular cavities suggest removal of rock fragments of this shape as the binding palagonite weathers or erodes away. Therefore, it is suggested that mere decomposition, alteration of palagonite material, and its subsequent removal by currents may concentrate originally formed solid fragments as a lag gravel. In the absence of definite biologic criteria of depth, it should not be automatically assumed that rounded to sub-rounded rocks are sure indications of surf-zone activity. It is possible by removal of the palagonite matrix to uncover a 'pebbly gravel' or even solid basalts resulting in a smooth surfaced seamount or guyot.

The writer anticipates extensive occurrence of palagonite tuff breccia with intercalated ellipsoidal and ropy lava, having an average specific gravity of about 2.3, as a significant part of the upper crust of the ocean basins [*Ewing* and *Landisman,* 1961]; the second layer of *Raitt* [1956], and the seismic layer 2 of *Hill* [1957, p. 149]. This layer occurs below the sedimentary layer in the ocean basin and the velocity in it is 4 to 6 km/sec, the average being about 5 km/sec.

Although some of the presently-available facts fully support the suggested hypothesis, it is still speculative and should be considered only as a working hypothesis. In addition, this study is based mainly on only two seamounts. However, it does suggest that some of the existing notions about seamounts must be re-examined. There are many intriguing ramifications which would be worthy of investigation. Research in progress and future work should answer some of these questions.

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