The origin of honeycomb weathering

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ABSTRACT

Honeycomb weathering occurs throughout the world, but the origin remains a matter of controversy. Wind erosion, exfoliation, frost shattering, and salt weathering have been proposed as explanations, although few attempts have been made to substantiate these hypotheses with chemical or mineralogical studies.

Chemical analyses and field observations indicate that honeycomb weathering in coastal exposures of arkosic sandstone near Bellingham, Washington, results from evaporation of salt water deposited by wave splash. Microscopic examination of weathered surfaces show that erosion results from disaggregation of mineral grains rather than from chemical decomposition. Thin walls separating adjacent cavities seem to be due to protective effects of organic coatings produced by microscopic algae inhabiting the rock surface. Cavity walls are not reinforced by precipitation of elements released by weathering, as has often been suggested at other locations. Honeycomb weathering develops rapidly and can be observed on surfaces that were planar less than a century ago.

INTRODUCTION

Honeycomb weathering is found throughout the world, from Antarctic valleys to temperate, arid, and tropical environments. The delicate structures resulting from honeycomb weathering are sometimes quite spectacular, but although many scientists have noted these features, only a few have attempted to explain their origin; most published reports consist largely of descriptions of their physical appearance. The nomenclature has not been standardized, and authors have variously described this type of erosion as "alveolar weathering," "stone lattice," and "stone lace." "Alveolar weathering" has been preferred among French geomorphologists, while publications in English often describe these textures as "honeycomb weathering" or "fretting." Commonly weathering features of this type are described as miniature tafoni, although this usage is unfortunate since it implies that honeycomb is genetically related to large-scale cavernous features (tafoni). Although tafoni and honeycomb weathering frequently occur together, numerous locations exist where each occurs independently, suggesting possible differences in their modes of origin.

Honeycomb weathering occurs in many populated regions and must have been noted in ancient times. Early descriptions of

TABLE 1. OCCURRENCES OF HONEYCOMB WEATHERING

Location	Rock type	Reference
Europe:		
San Sebastian, Spain	sandstone	Rondeau, 1965
Livorno, Italy	sandstone	Scherber, 1927
Heidelberg, West Germany	sandstone	Bourcart, 1930
Fountainbleau forest, France	siliceous sandstone	Rondeau, 1965
Gourmalon beach, near Clion-sur-Mer, Loire-Atlantique, France	schist	Grisez, 1960
Saint Cheron, near Paris, France	siliceous sandstone	Cailleux, 1953
Carteret, Normandy	schist	Bourcart, 1930
Agay, Normandy	porphyry, sandstone	Bourcart, 1930
Neiderbronn, Alsace	sandstone	Haug, 1907
Vosge mountains, France	sandstone	Bryan, 1928
Baux en Provence, France	limestone	Bourcart, 1930
Coast of Bretagne, France	not listed	Bourcart, 1930
West coast, Caspian Sea, near Baku, U.S.S.R.	sandstone	Mustoe, 1981
Saxon-Bohemian Alps	sandstone	Novak, 1924
Isle of Delos	granite, gneiss	Cayeux, 1911
Corsica	granite, gneiss, schist, sandstone	Penck, 1894; Bourcart, 1930; Popoff and Kvelberg, 1937; Ligus, 1952; Cailleux, 1953; Klaer, 1956; Rondeau, 1965
Elba	granite	Wilhelmy, 1964
Middle East and Africa:		
Ma'aza plateau, east of the Nile, Egypt	nodular limestone	Hume, 1925
Tabarka, Tunisia	sandstone	Rondeau, 1965
Morocco, in gorges of the El Kansera that cross the Oued Beht	argillaceous limestone	Rondeau, 1965
South America:		
Atacama Desert, Chile and Peru	agglomerate	Segerstrom and Henriquez, 1964; Grenier, 1968
Coast near Cabo Frio, Brazil	mica schist	Tricart, 1972
Australia and New Zealand:		
King George's Sound, western Australia	eolianite	Darwin, 1839
Western Australia interior	granite	Jutson, 1918
San Remo & Lorne, near Melbourne	feldspathic sandstone and mudstone	Bartrum, 1936
Newcastle, New South Wales	massive sandstone	Bartrum, 1936
Murchison River, western Australia	sandstone	Jennings, 1968
Otway coast, Victoria	sandstone	Jennings, 1968
Waiheke Island, near Auckland, New Zealand	greywacke	Cotton, 1922; Bartrum, 1936
Auckland City, New Zealand	argillaceous sandstone	Bartrum, 1936
Smugglers Bay, Whangerei Heads, Auckland, New Zealand	dacitic lava	Bartrum, 1936
Wellington, New Zealand	greywacke	Cotton, 1922

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occurrences in Australia were made by Darwin (1839) and Dana (1849). Other investigators later noted honeycomb weathering from sites throughout the world; these localities are summarized in Table 1.

THEORIES OF ORIGIN

The processes of differential erosion that give rise to honeycomb structures have been a matter of great controversy. Numerous hypotheses have been advanced. Early reports of tafoni and honeycomb weathering in the granitic rocks of Corsica assumed that cavities result from wind erosin (Futterer, 1897, 1899), but Popoff and Kvelberg (1937) examined this location and concluded that weathering occurred as a result of microclimatic temperature variation, as rising currents of warm air displaced cold air in shady areas of the rock surface. Cailleux (1953) believed that honeycomb-weathered surfaces in Corsica were preserved from the Pleistocene epoch, when they were formed by localized frost shattering.

Examples of honeycomb weathering were reported in rocks ranging from sediments to volcanics and crystalline igneous rocks, distributed from polar latitudes to the equator. These discoveries were accompanied by an equally diverse variety of hypotheses advanced to explain their origin. Some examples represent rocks that weather at different rates because of internal variations in structure or composition. Cotton (1922) described honeycomb weathering developed in greywacke at Waiheke Island near Auckland, New Zealand, where limonitic material has impregnated joint planes. Other examples of honeycomb cavities in rocks containing iron oxide cements have been reported from San Sebastian, Spain, and Tabarka, Tunisia (Rondeau, 1965). Bartrum (1936) described honeycomb weathering in fragmental andesitic rocks near Auckland, New Zealand, resulting from dissolution of calcium carbonate cement surrounding volcanic clasts. Palmer and Powers (1935) observed honeycomb cavities developed in pahoehoe lava of Hawaii, where erosion has enlarged vesicles within the lava.

TABLE 1. *(Continued)*

Location	Rock type	Reference
Antarctica:		
West coast, Antarctic Peninsula	gabbro	Nichols, 1960
Queen Maud Land	granite, gneiss	Bardin, 1963; Markov and others, 1970
South Victoria Land:		
Cape Evans	granite, gneiss, dolerite	Treves, 1962
Cape Royds	alkaline lavas	Treves, 1962
Taylor Valley, McMurdo Oasis	gneiss	Prebble, 1967
Wilkes Land:		
Bunger Oasis, Schirmacher Oasis	granite, gneiss, schist	Avsyuk and others, 1956; Voronov, 1960; Bardin, 1963, 1964; Evteev, 1964; Simonov, 1967; Markov and others, 1970
Bunger and Freedom Hills, Freedom Archipelago	dolerite, granite, quartz, pegmatite	Rikhter, 1960
United States:		
Rogers Dry Lake, Mojave Desert, California	granite	Blackwelder, 1929
Chaco Canyon National Monument, New Mexico	sandstone	Bryan, 1928
Douglas County, Wisconsin	sandstone	Bryan, 1928
Northern Puget Sound, Washington	arkose	This report
"Semi-arid and desert areas of western U.S."	rhyolitic tuff, agglomerate, "most igneous rocks," sandstone, shale, conglomerate	Blackwelder, 1929
Kalina and Hookena, Hawaii	pahoehoe lava	Palmer and Powers, 1935
Big Sur Coast, California	sandstone	Brower, 1965
Mesa Verde, Colorado	sandstone	Chronic, 1980
Reports that do not discriminate between tafoni and honeycomb weathering:		
Washington County, Arkansas	sandstone	Bryan, 1928; Bourcart, 1930
Isle of Aruba, Dutch West Indies	diorite	Wilhelmy, 1964
Hong Kong; Mt. Abu, Aravelli mountains, northwest India; Sierra Mahoma, Uruguay	not listed	Wilhelmy, 1964
Western desert, Argentina; northern Portugal; Tanganyika; Korfdofan, Sudan; Saharan Hoggar	not listed	Jennings, 1968

Most examples of honeycomb weathering occur in homogeneous rocks, particularly sandstone and granite. Noting that honeycomb textures are common throughout deserts of the western United States, Blackwelder (1929) believed that cavities develop through a process of exfoliation related to hydration reactions of feldspars in moist sites on the rock surface, with removal of resulting debris by the action of wind, rain, and animal movements. After examining well-developed honeycomb weathering in sandstone of the Fountainbleau forest of France, Rondeau (1965) could find no satisfactory explanation of the phenomenon, and concluded that erosion may have occurred under weathering conditions that no longer exist today. His speculation that erosion resulted from rain water dissolving the siliceous cement rests upon the assumption that at some earlier time rain water had an unusually high pH, and Rondeau admits there is no actual evidence to support this possibility.

The concept that honeycomb weathering results from physical action of salt crystallization was first advanced by Hume (1925), who observed masses of fibrous salt crystals associated with honeycomb structures in nodular limestone of the Ma'aza plateau, east of the Nile River in Egypt. Salt weathering has since become the most popular hypothesis for explaining honeycomb weathering in coastal environments (Bartrum, 1936; Cailleux, 1953; Bourcart, 1957). At inland locations it is less easy to explain, but the action of evaporating salt solutions has been cited by several investigators. Salts may be introduced by migrating fluids (Hume, 1925), or from salts contained within the original sediment (Bryan, 1928; Bourcart, 1930, 1957). Among recent investigations, salt weathering is the agent most often mentioned, and evidence favoring this hypothesis has been summarized by Evans (1970); more recent bibliographies appear in articles by Cooke (1979) and Goudie and others (1979). Discovery of tafoni and honeycomb weathering in many areas of Antarctica has led to conflicting interpretations. Wellman and Wilson (1965) and Treves (1962) believed these features are due to salt weathering, but several workers have revived the hypothesis that cavity development is caused by wind erosion (Evteev, 1964; Voronov, 1960; Barden, 1964).

A major limitation of all previous studies is their reliance on visual observation to explain the origin of honeycomb weathering. Visual evidence may be sufficient to explain sites where the rock is obviously heterogenous, but in most cases surface appearance provides too little information to explain physical and chemical changes that occur during weathering. Several factors have emerged from the limited data that have been obtained. First, examination of cavities indicates that weathering primarily results from physical disaggregation of the grains rather than from chemical decomposition. Second, in a given locality the occurrence of honeycomb textures is frequently restricted to a particular set of environmental conditions. Honeycomb weathering is most common along coasts and in hills bordering desert or semiarid regions, and cavities tend to develop along bedding, joint planes, or other areas of structural or compositional weakness. However, abundant evidence demonstrates that the process of formation does not require the existence of such features, and well-developed honeycomb weathering commonly occurs in homogeneous sediments and massive crystalline rocks.

HONEYCOMB WEATHERING IN THE CHUCKANUT FORMATION

The Chuckanut Formation represents a thick series of arkosic sandstone, conglomerate, and siltstone of Late Cretaceous to early Eocene age, and forms a 16 km long sequence of cliffs and headlands bordering Puget Sound. Extensive inland exposures of these rocks also occur on the western flanks of the Cascade Range. The petrology of the Chuckanut Formation has been described in detail by Kelly (1970) and Pongsapich (1970). Arkosic sandstone predominates, consisting primarily of feldspar and quartz grains imbedded in micaceous matrix. Biotite is the most abundant micaceous mineral, constituting up to 6% of the total rock. Siliceous or calcareous cement is usually absent.

Honeycomb weathering is extensively developed on coastal outcrops, although its distribution shows some variation according to local conditions. Honeycomb cavities can be found on boulders dispersed throughout the intertidal zone, where they commonly consist of rather shallow circular depressions inhabited by a variety of marine organisms. The most spectacular occurrences of honeycomb weathering appear above the high tide line. The upper limit of the intertidal zone is marked by disappearance of barnacle encrustation, and occurs approximately 2.5 m above mean tide level. Honeycomb weathering is most prominent in the zone extending up to about 3 m above the high-tide line. Cavities are generally small, with an average width of 5 to 10 cm, although individual cavities sometimes reach diameters of more than 30 cm. In homogeneous rocks, cavities are generally equidimensional, but are sometimes slightly elongate, with the axis of elongation parallel to bedding. The diameter commonly exceeds the depth, which is seldom more than 10 cm. Shallow cavities are generally in the form of simple depressions, while deeper cavities typically widen toward the interior. Cavities generally occur within a very restricted vertical range, and lithologically identical units at higher elevations do not contain honeycomb textures (Fig. 1).

Although the overall pattern of cavity development is along a well-defined horizontal band, the distribution also reflects

Figure 1. Honeycomb weathering in homogeneous arkose at Larrabee State Park. Note smooth areas where erosion has destroyed cavity walls. The lower limit of honeycomb weathering corresponds to the mean high-tide line.

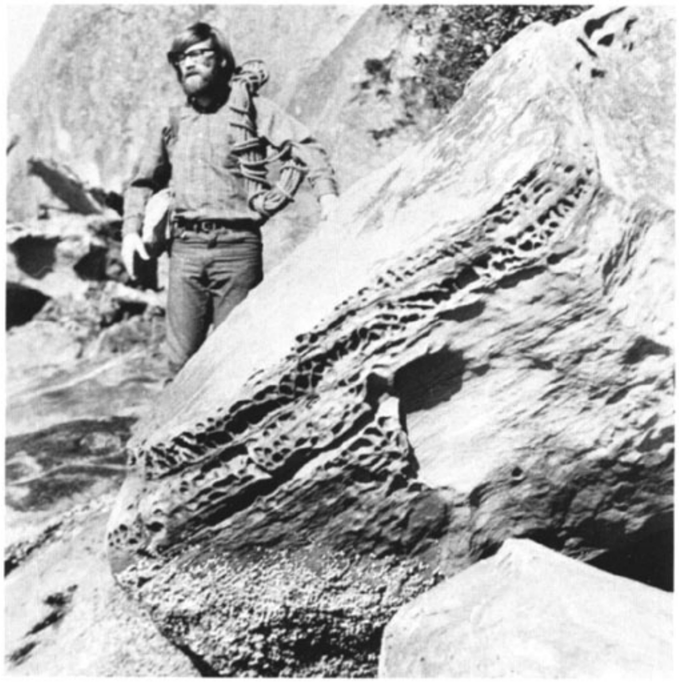

Figure 2. Honeycomb weathering developed along inclined bedding. The well-defined barnacle line marks the upper limit of the intertidal zone.

lithologic varition within the outcrop. Cavities are particularly common in coastal outcrops where bedding edges are exposed, where they tend to occur in linear bands parallel to bedding planes (Fig. 2). Although differential weathering is most likely to occur in rocks that contain such zones of potential weakness, abundant examples can be observed where honeycomb weathering has developed on homogeneous surfaces (Fig. 3).

Cavities often contain small quantities of loose sand released by erosion of the walls. Binocular microscopic examination of this material indicates that excavation of cavities occurs as the result of physical rather than chemical weathering. Sand within the cavities consists of disaggregated grains that show virtually no chemical alteration or dissolution. Feldspars occur as fresh, angular grains, and flakes of unaltered biotite are abundant. Clay particles are not visible, and there are no traces of iron oxide stain on mineral surfaces. Weathered debris collected from fissures, niches, and ledges on the same outcrop 30–100 m inland, or on cliff faces 5 m or more above the high-tide line displays much different characteristics. In these locations, quartz and feldspar grains usually have coatings of clay and silt, and reddish iron oxide stains resulting from decomposition of ferruginous minerals are common.

EVIDENCE FOR SALT WEATHERING

The occurrence of honeycomb weathering only in coastal exposures of the Chuckanut Formation gives credence to the hypothesis that these cavities are excavated by evaporation of salt water deposited as wave splash. The physical characteristics of debris within cavities suggests erosion occurs due to crystallization of salt rather than from chemical alteration related to high local humidity. Certainly the mild local climate eliminates the possiblility of frost action, and cavities can be found in many exposures where the rock is sheltered from wind.

Although thin coatings of salt crystals can be observed within cavities occurring in the intertidal zone, the extensive networks of honeycomb weathering located above the high tide line almost never contain visible amounts of salt, and yet observations at periods of high tide show droplets of sea water do strike these surfaces. The strongest evidence for the effectiveness of salt weathering comes from discoveries of sites where concentration of soluble salts is very high, sometimes to the extent that masses of crystals coat the rock surface. Experimental studies have usually tested the ability of very concentrated salt solutions to attack rocks during repeated evaporation cycles (Evans, 1970; Cooke, 1979; Goudie and others, 1979). The importance of salt weathering under natural conditions may be even greater than these studies indicate if such high salt concentrations are not essential for erosion to occur.

In order to investigate the possibility that salt weathering is involved in formation of honeycomb weathering in the Chuckanut Formation outcrops, chemical analyses were performed to measure the amount of soluble salts present on the rock surface. Samples of weathered debris were collected from a total of 56 honeycomb cavities at four sites along the coast. At each location, samples of weathered rock were also gathered from portions of the outcrop 30–100 m inland or on faces 5 m or more above the high-tide line, yielding 18 samples. Samples were dried at 100°C, and 1.0 g quantities were washed with 100 ml aliquots of distilled water. Resulting solutions were analyzed by atomic absorption spectroscopy to determine amounts of soluble Na^+, K^+, Ca^{++}, and Mg^{++} present in the weathered debris.

Although honeycomb weathering occurs in the upper intertidal zone, cavities at this elevation are swept clean by wave action. Cavities 0.5 m or more above the high-tide line usually contain small quantities of fine sand, and amounts of soluble cations in this material decrease as a function of elevation (Table 2). The distribution of salts is nearly identical at each of the four sites, even though these locations are as much as several kilometres apart. Samples collected in late summer after several weeks of calm weather are similar in cation content to samples collected from the same site during an autumn storm characterized by very strong winds. Thus, deposition of salts by wave splash is a continual process rather than a result of episodes of unusually strong wave action.

Weathered debris from areas not exposed to wave splash have much lower concentrations of soluble Na^+, but other cations are present in amounts similar to samples from honeycomb cavities. Soluble cations from inland sites probably represent elements released by dissolution of constituent minerals, based on the microscopic evidence mentioned earlier. Relative abundances of

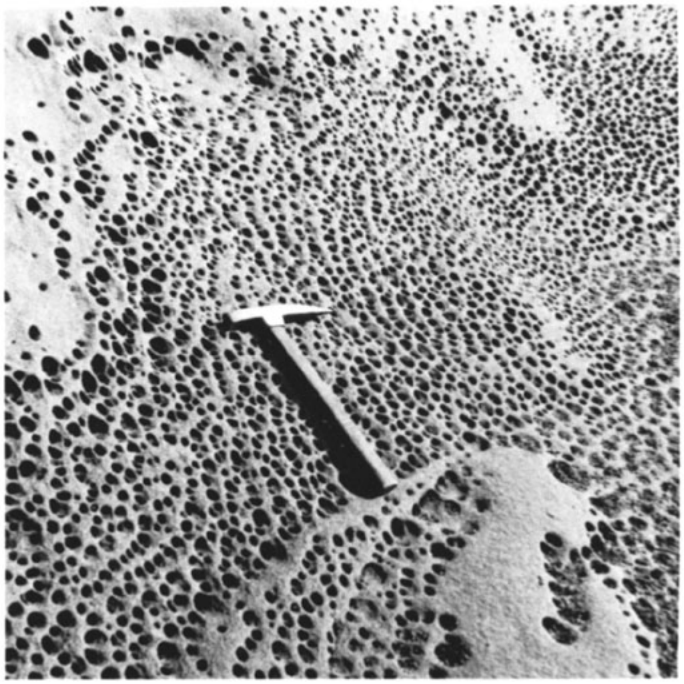

Figure 3. Very uniform miniature cavities are developing on the surface of this bedding plane at Clark Point, near Bellingham.

TABLE 2. SOLUBLE CATION CONTENT OF WEATHERED ARKOSE

Distance above high-tide line (m)	Wt % soluble cations			
	Na^+	K^+	Ca^{++}	Mg^{++}
Weathered debris from honeycomb cavities in beach cliffs at Larrabee State Park				
0.5	0.27	0.035	0.055	0.035
0.6	0.27	0.028	0.061	0.035
0.7	0.26	0.026	0.031	0.028
0.8	0.24	0.027	0.041	0.039
1.0	0.14	0.020	0.030	0.027
1.1	0.18	0.024	0.035	0.021
1.2	0.17	0.025	0.028	0.018
1.3	0.19	0.028	0.029	0.017
1.8	0.13	0.021	0.031	0.013
2.0	0.15	0.027	0.019	0.008
2.3	0.12	0.021	0.015	0.012
2.4	0.14	0.023	0.187	0.054
Weathered arkose from areas of outcrop not exposed to wave splash				
A	0.03	0.020	0.015	0.003
B	0.01	0.007	0.005	0.001
C	0.19	0.032	0.336	0.065
D	0.03	0.030	0.075	0.009
E	0.02	0.012	0.009	0.001
F	0.05	0.008	1.22	0.056
G	0.04	0.023	0.840	0.033
H	0.01	0.010	0.005	0.001
Composition of salt water (ppm):				
	8,040	394	801	1,075

Na^+, K^+, Ca^{++}, and Mg^{++} in samples from honeycomb cavities are somewhat variable, and do not always correspond closely to the ratio of these elements in sea water. To some extent these cations may represent dissolution of minerals, but some cavities contain shreds of seaweed, wood fibers, mollusc shell fragments, and organic debris introduced by wave splash or wind action; this material probably makes a contribution to the cation content.

DEVELOPMENT OF CAVITY WALLS

Although evaporating salt water may attack the rock surface, this mechanism alone is not sufficient to account for development of honeycomb structures. Wind, rain, and storm waves probably all serve to remove loose debris from the interior of cavities, but none of these agents explain the origin of the delicate walls that remain between adjacent holes. As they enlarge, cavities should coalesce to form larger openings, and eventually result in development of a nearly planar surface. Although cavities do occasionally coalesce, far more commonly a thin wall remains, sometimes developing to a spectacular degree (Fig. 4).

Previous investigators have suggested that ions released by weathering within the cavity precipitate on surrounding surfaces, causing the walls to become strengthened

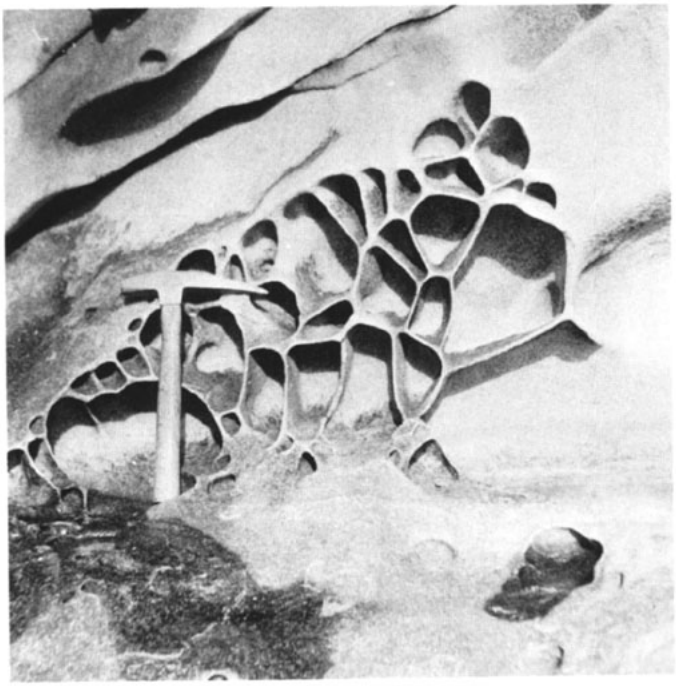

Figure 4. Thin walls separating cavities show no evidence of chemical alteration, and seem resistant to weathering because of the presence of organic coatings from algae that inhabit the rock surface.

TABLE 3. CHEMICAL COMPOSITION OF CHUCKANUT FORMATION ARKOSE FROM COASTAL EXPOSURES: FRESH ROCK, HARDENED SURFACES, AND CAVITY WALLS FROM HONEYCOMB WEATHERING

Oxide	Site 1		Site 2		Site 3		Site 4	
	Fresh rock	Hardened surface	Fresh rock	Hardened surface	Fresh rock	Cavity wall	Fresh rock	Cavity wall
SiO_2	74.72	73.34	73.16	71.94	73.06	74.41	70.23	70.31
Al_2O_3	12.70	13.44	12.42	13.74	12.28	12.55	15.80	16.19
TiO_2	0.25	0.21	0.44	0.59	0.44	0.36	0.40	0.37
Fe_2O_3*	2.41	3.40	3.21	4.39	3.63	3.40	3.80	3.70
MgO	0.93	0.99	1.34	1.53	1.40	1.37	1.48	1.52
Na_2O	3.00	3.13	3.00	3.24	2.93	2.78	3.91	3.84
K_2O	1.84	1.84	1.53	1.42	1.65	1.75	1.92	2.41
CaO	1.68	1.86	1.44	1.97	2.06	1.65	2.48	2.60
MnO	0.04	0.03	0.06	0.07	0.08	0.07	0.06	0.05
Total	97.67	98.24	96.60	98.89	97.53	98.34	100.08	100.99

*Total iron calculated as Fe_2O_3.

(Cotton, 1922; Bartrum, 1936). This "case hardening" hypothesis seems to contradict the widely accepted view that cavities result from physical rather than chemical weathering, and is supported mainly by observations that in some localities honeycomb weathering occurs on outcrops where the rock has been hardened by addition of ferruginous cement derived from surface weathering (Bartrum, 1936; Blackwelder, 1929; Cailleux, 1953).

Exposures of Chuckanut arkose in both coastal and inland environments commonly display a hardened surface layer, ranging in thickness from a few millimetres to several centimetres and dark gray or reddish in contrast to the light-colored unweathered material from which it is derived. Microscopic examination of thin sections and hand specimens indicates the hardened layer results from dissolution of iron minerals, particularly biotite, within the arkose. While unaltered biotite flakes are visible in fresh rock, this mineral is absent in the hardened zone. Instead, ferric oxides or hydroxides are observed as grain coatings and as interstitial cement. In samples where the hardened layer is well developed, chemical analyses show a small enrichment in iron and aluminum content (Table 3), but the increased durability of the rock seems to result mostly from the redistribution of these elements rather than from a high degree of accumulation.

Hardened surfaces occur in environments where erosion has occurred at a relatively slow rate, allowing time for the necessary mineral alteration. Honeycomb weathering sometimes occurs on hardened surfaces, and in these locations penetration of this outer layer is probably an important stage in the development of cavities. Honeycomb structures occur on outcrops where no surface hardening is evident, however.

Walls separating cavities do not show mineral alteration characteristic of hardened outer surfaces. Microscopic examination of freshly broken speciments show that even very thin walls are identical in appearance to unweathered rock. Biotite flakes show no signs of alteration or dissolution, and interior surfaces of cavities are devoid of iron stains of ferruginous cement. Chemical analyses of samples from a number of sites indicate that cavity walls are identical in bulk composition to fresh rock collected from the same outcrop. Some typical reults are shown in Table 3. This evidence demonstrates that while the walls are somehow relatively resistant to the process of erosion that deepened the cavities, their resistance is not related to deposition of additional interstitial cement.

In almost every instance, side walls are darker than rock exposed on the vertical back wall of the cavity (Figs. 1, 4). This discoloration is usually dark gray, although green stains are evident in many locations; streaks of yellow or orange lichens are present on a few outcrops. Microscopic examination reveals dark deposits to be accumulations of organic detritus, and green stains represent photosynthetic microorganisms that inhabit the rock surface. Some surfaces that appear clean and fresh contain a thin bright green horizon 1 to 2 mm below the barren outer surface.

Because oxidation of ferruginous minerals can also lead to dark discoloration of outcrop surfaces, a more selective method was needed to evaluate the abundance of microorganisms in the weathering zone. Determination of chlorophyll content is simple and accurate for assessing the presence of algae on rock surfaces. Chlorophyll is rapidly degraded outside of living cells, and the method is particularly suited for evaluating biologic activity in sediments because results are not affected by organic matter present at the time of deposition. The chlorophyll content measured on walls of nine cavities ranged from 0.35 to 1.84 mg/cm^2, with a mean of 0.88. Rock samples taken from back walls of an equal number of cavities at the same outcrops contain less chlorophyll, averaging only 0.40 mg/cm^2.

The role these organisms play remains uncertain. Perhaps the thin organic coating inhibits the action of salt weathering by causing the rock to remain moist so that evaporation of saline solutions is retarded. Alternatively, this organic coating may act as a physical barrier, filling surface irregularities so that droplets of salt spray are not readily absorbed. The reasons why biotic coatings seldom develop on back walls of cavities are not known, but this may be related to ecologic factors such as differences in humidity or exposure to sunlight. Possibly this portion of the cavity simply erodes at too great a rate to allow large populations of microbes to develop.

The organisms involved cannot be identified by ordinary microscopy, but analysis of extracted pigments by thin-layer chromatography indicates that green algae are the most abundant form of life. Chromatograms of pigments from four sites all contain relatively large amounts of chlorophyll and yellow and orange carotenoids; pigments characteristic of lichens, fungi, and red, brown, or blue-green algae were not detected.

RATE OF FORMATION

The time required for development of honeycomb weathering and the degree of permanence of the resulting features has not been investigated in detail by previous workers. Cailleux (1953) expressed the opinion that honeycomb weathering in Corsica had formed during the Pleistocene, but honeycomb cavities have been reported in a sea wall constructed on the French Atlantic coast in 1898 (Grisez, 1960). Bartrum (1936) noted well-developed honeycomb on boulders of sandstone in an artificial embankment on the coast near Auckland, New Zealand, but did not establish whether these cavities existed prior to use of the rocks for construction purposes.

Several exposures near Bellingham, Washington, provide opportunities for dating the rate of development of honeycomb weathering. Large arkose blocks quarried from inland locations were used in 1902 to construct a railroad causeway extending along Post Point and Chuckanut Bay. Exposed surfaces contain areas of honeycomb weathering, with individual cavities are large as several centimetres in depth and width. Cavities of similar size occur in two boulders of metavolcanic greenstone used to anchor pilings for the Interurban Railway built across the tidelands at Clayton Bay in 1911. These rocks are unusual because they are the only examples of honeycomb weathering in nonsedimentary rocks in this area; serpentinized metavolcanics exposed as beach cliffs at the south end of Chuckanut Drive are devoid of honeycomb textures, as are crystalline mafic and felsic igneous rocks and fine-grained metasediments that form beach cliffs in other areas of Puget Sound.

Additional information regarding the rate of formation was obtained by examining historical photographs from the archive collection of the Whatcom County Museum. Four photographs dating from 1895 to 1905 show beach cliffs containing honeycomb weathering, but only one of the four sites could be located: a cliff at Post Point, photographed in 1903. Detailed comparison of the archive print with a modern photograph taken from the same point of view provides a valuable glimpse into the evolution of honeycomb weathering.

Aside from a large block fallen from the cliff face, the general features of the outcrop remain unchanged. Small-scale features show many signs of change, however, particularly in rock nearest the high tide line. Two areas of well-developed honeycomb weathering occur on rock surfaces that were planar in 1903. Each of these areas now contain 30 to 40 cavities averaging 5 cm in width and depth, and located about 1 m above mean high tide. At higher elevations on the cliff fewer changes have occurred. Near the center of the 3-m-high cliff small remnants of honeycomb visible in 1903 have disappeared, leaving a smooth, concave face. Overhanging this face is a shelf-like projection, located about 2.5 m above the high-tide line. Individual cavities shown in the early photo can still be recognized on this surface, and have undergone only minor enlargement. This photographic evidence suggests that the rate of development of honeycomb cavities is much greater near the tidal zone where surfaces have greatest exposure to salt spray. Although the rate of formation is less at higher elevations, the honeycomb textures are quite similar.

CONCLUSIONS

For the first time, quantitative methods have been used to study the origin of honeycomb weathering, and results support the hypothesis that honeycomb weathering in coastal environments results from crystallization of salt solutions deposited as wave splash. In contrast to previous speculations based on observations at other localities, the Chuckanut Formation arkose shows no evidence of mineral alteration accompanying development of honeycomb cavities. In particular, these features do not seem to require the presence of a hardened surface layer, and thin walls separating cavities do not contain additional cementation. Instead, erosion resistance of these surface appears to be related to the presence of a layer of microscopic algae that offers protection from evaporating salt water.

Field observations and laboratory data from Puget Sound are of limited use when applied to other areas. Reports of honeycomb weathering from diverse environments throughout the world suggest cavities may result from more than one cause. Occurrences in inland locations are particularly difficult to explain, and published reports contain too little information to accurately describe physical and chemical changes that have taken place. My investigations show the importance of microscopy and chemical analysis for studying weathering, and indicate the need to consider the effect of organisms. Although sandstone cliffs of Puget Sound provide little direct information for understanding weathering forces acting on igneous boulders of Antarctica or the Chilean desert, study of the local coast demonstrates the kinds of evidence that must be obtained before the origin of honeycomb weathering in other environments can be fully understood.

ACKNOWLEDGMENTS

Rod Slemmons, curator, provided generous access to the Whatcom County Museum archives and aided in searching through the extensive photo collection.

APPENDIX: ANALYTICAL METHODS

Bulk Chemical Analysis. Rock samples were washed with distilled water, ground to less than 150 mesh, and dried at 110°C. Then 0.100 g rock was fused with 0.6 lithium metaborate for 10 min at 900 °C, and the resulting molten bead dissolved in 50 ml of 5% HCl. This solution was brought to 100 ml, and analyzed by atomic absorption spectroscopy for Si, Al, Ti, and Mn. Dilutions of 1:10 were prepared, adding a 10 ml aliquot of distilled water containing 1.23 g lithium chloride and 0.254 g lanthanum chloride to suppress interferences, followed by determination of Fe, Ca, K, Na, and Mg. International rock standards prepared in this matter were used to construct calibration curves. All samples were analyzed in duplicate, and listed results represent mean values.

Chloropohyll Determination. The surface area of fragments broken from cavity walls was calculated using graphical integration, tracing the outline on paper and weighing the trimmed pieces on an analytical balance. Samples were crushed in a mortar and extracted for 4 hr in darkness at 10 °C in 100 ml of chloroform-methanol (2:1 v/v). After filtration, absorbance of the extract was measured at 652 nm using a Beckman Spectronic 21 spectrophotometer. Chlorophyll concentration was calculated using a standard curve measured from solutions of spinach chlorophyll obtained using the method of Arnon (1949).

Thin-Layer Chromatography of Pigments. Chloroform-methanol extracts were transferred to separatory funnels and extracted with about 200 ml of water to remove the methanol. The chloroform layer was drained, filtered, and evaporated to dryness under vacuum using a rotary evaporator. The resulting residue was dissolved in a small volume of diethyl ether, and aliquots of this solution were applied to 12 x 20 cm glass plates coated with Silica Gel G, and developed in a glass tank containing 200 ml of benzene-methanol (95:5 v/v). A reference sample of pigments extracted from dandelion leaves was analyzed on each plate.

REFERENCES CITED

Arnon, D. I., 1949, Copper enzymes in isolated chloroplasts. Polyphenoloxidase in Beta vulgaris: Plant Physiology, v. 24, p. 1–15.

Avsyuk, G. A., Markov, K. K., and Shumskii, P. A., 1956, Geographical observations in an Antarctic "oasis": Washington, D.C., Israel Program for Scientific Translation, Ltd., National Science Council and Department of Interior, 53 p. Translated from Vesoiuznoe Geograficheske Obshchestvo (Moskva), Isvestia 85 (4), p. 316–356.

Bardin, V. I., 1963, Zonality of periglacial phenomena in the mountains of Queen Maude Land: Soviet Antarctic Expedition Information Bulletin 5, p. 4–6. Translated by American Geophysical Union from Bulletin 43, p. 11–14.

—— 1964, Geographical observations in the Schirmacher Oasis (E. Antarctica), *in* Bugaev, V.A., ed., Izdatel'stvo, Nauka, Moskva. Translated by Israel Program for Scientific Translation, Ltd., Jerusalem, 1966, p. 144–160.

Bartrum, J. D., 1936, Honeycomb weathering near the shore line: New Zealand Journal of Science and Technology, v. 18, p. 593–600.

Blackwelder, E., 1929, Cavernous rock surfaces of the desert: American Journal of Science, v. 17, p. 393–399.

Bourcart, J., 1930, Le probleme des "taffoni" de Corse el l'érosion alvéolaire: Revue de Géographie Physique et de Géologie Dynamique, v. 3, p. 5–18.

—— 1957, L'érosion des continents: Paris, Armand Colin, 129 p.

Brower, D., 1965, Not man apart—Photographs of the Big Sur Coast: New York, Ballantine, 144 p.

Bryan, K., 1928, Niches and other cavities in sandstone at Chaco Canyon, New Mexico: Zeitschrift für Geomorphologie, v. 3 p. 125–140.

Cailleux, A., 1953, Taffonis et érosion álveolaire: Cahier Géologie de Thoiry, v. 16–17, p. 130–133.

Cayeux, L., 1911, Description physique de l'île de Délos, *in* Exploration Archéologique de Delos, v. 4, Paris, Fontemoing et cie, p. 162–186.

Chronic, H., 1980, Roadside geology of Colorado: Missoula, Montana, Mountain Press, 301 p.

Cooke, R. U., 1979, Laboratory simulation of salt weathering processes in arid environments: Earth Surface Processes, v. 4, p. 347–359.

Cotton, C. A., 1922, Geomorphology of New Zealand, Part I: Wellington, Dominion Museum, p. 258–259.

Dana, J. D., 1849, Geology: U.S. Exploring Expedition (1838–1842), v. 10, Philadelphia, C. Sherman, 529 p.

Darwin, C. R., 1839, Journal of researches into the natural history and geology of the countries visited during the voyage of HMS Beagle round the world: New York, D. Appleton, p. 450.

Evans, I. S., 1970, Salt crystallization and rock weathering: A review: Revue de Géomorphologie Dynamique, v. 19, p. 153–177.

Evteev, S. A., 1964, At what speed does wind "erode" stones in Antarctica, *in* Soviet Antarctic Expedition, Volume 2, Amsterdam, Elsevier, 211 p. Translated from Soviet Antarctic Expedition Bulletin 17, 1960.

Futterer, K., 1897, Ein Beispiel für Winderosion am Heidelbert Schlossturm: Mitteilungen der grossherzoglichen badischen geologischen Landesanstalt, v. 3, p. 473–496.

—— 1899, Ueber Windkorrasion am Heidelberg Schlossturm: Mitteilungen der grossherzoglichen badischen geologischen Landesanstalt, v. 5, p. 471–495.

Goudie, A. S., Cooke, R. U., and Doorkamp, J. C., 1979, The formation of silt from dune sand by salt weathering processes in deserts: Journal of Arid Environments, v. 2, p. 105–112.

Grenier, M. P., 1968, Observations sur les taffonis du désert Chilien: Bulletin de l'Association des Géographes Français, v. 364–365, p. 193–211.

Grisez, L., 1960, Alvéolisation littorale de schistes métamorphiques: Revue de Géomorphologie Dynamique, v. 11, p. 164–167.

Haug, E., 1907, Traité de Géologie, v. 1: Paris, Armand Colin, 378 p.

Hume, W. F., 1925, Geology of Egypt, v. 1, Surface features: Cairo, Government Press, p. 214–216.

Jennings, J. N., 1968, Tafoni, *in* Fairbridge, R. W., ed., Encyclopedia of geomorphology: New York, Reinhold, p. 1103–1104.

Jutson, J. T., 1918, The influence of salts in rock weathering in sub-arid western Australia: Proceedings of the Royal Society of Victoria, v. 30, p. 165–172.

Kelly, J. M., 1970, Mineralogy and petrology of the basal Chuckanut Formation in the vicinity of Lake Samish, Washington [M.S. thesis]: Bellingham, Washington, Western Washington State College, 63 p.

Klaer, W., 1956, Verwitterungsformen in Granit auf Korsika: Petermanns Geographische Mitteilungen, v. 261, 146 p.

Ligus, M., 1952, Problèmes géomorphologiques corses: Revue de Gémorphologie Dynamique, v. 3, p. 157–198.

Markov, K. K., Bardin, V. I., Lebedev, V. L., Orlov, A. I., and Suetova, I. A., 1970, The geography of Antarctica: Israel Program for Scientific Translation, Ltd., p. 122–123. Translated from Geografiya Antarktidy, Ixdatel'stvo "Mysl'", Moskva, 1968.

Mustoe, G. E., 1981, Alveolar weathering, *in* Fairbridge, R. W., and Schwartz, M. L., eds., Encyclopedia of beaches and coastal environments: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross (in press).

Nichols, R. L., 1960, Geomorphology of the Marguerite Bay area, Palmer Peninsula, Antarctica: Geological Society of America Bulletin, v. 71, p. 1421–1450.

Novak, V. J., 1924, The forms of the Quandersandstein in Bohemia [abs.]: Revue de Géologie, v. 5, p. 167–168.

Palmer, H. S., and Powers, H. A., 1935, Pits in coastal pahoehoe lavas controlled by gas bubbles: Journal of Geology, v. 43, p. 639–643.

Penck, A., 1894, Morphologie der Erdoberflache, v. 1: Stuttgart, Germany, J. Englehorn, 214 p.

Pongsapich, W., 1970, A petrographic reconnaissance of the Swauk, Chuckanut, and Roslynn Formations, Washington [M.S. thesis]: Seattle, Washington, University of Washington, 63 p.

Popoff, B., and Kvelberg, I., 1937, Die Tafoni-Verwitterungerscheinung: Acta Universitatus Latviensis, Riga-Raksii, Kimijas Fakultate, Series 4, no. 6, p. 129–368.

Prebble, M. M., 1967, Cavernous weathering in the Taylor Dry Valley, Victoria Land, Antarctica: Nature, v. 216, p. 1194–1195.

Rikhter, G. D., 1960, Protessy denundatsii v Antarktide, *in* I. V. Maksimov, ed. Ekspeditsiya ha d/e "Ob", 1956–57 gg Nauchnyye rezul'taty: Leningrad, International Geophysical Year Antarctic Expedition, v. 7, p. 73–84.

Rondeau, M. A., 1965, Formes d'érosion superficielles dan les grès de Fountainbleau: Association de Géographes Français Bulletin, no. 334–335, p. 58–66.

Scherber, R., 1927, Erosionswirkungen an der toskanischen Felsküste: Natur und Museum, v. 62, p. 231–234.

Segerstrom, K., and Henriquez, H., 1964, Cavities or "tafoni" in rock faces of the Atacama Desert, Chile: U.S. Geological Survey Professional Paper 501-C, p. 121–125.

Simonov, I. M., 1967, Eolian weathering in the oasis of East Antarctica: Soviet Antarctic Expedition Information Bulletin 5, p. 347–351. Translated by American Geophysical Union from Bulletin 62, p. 37–43.

Treves, S. B., 1962, The geology of Cape Evans and Cape Royds, Ross Island, Antarctica, *in* Wexler, H., ed., American Geophysical Union Monograph Number 7, p. 40–46.

Tricart, J., 1972, The landforms of the humid tropics, forests, and savannas: New York, St. Martins Press, p. 106–108.

Voronov, P. S., 1960, Nekotovyye cherti geomorfologii Antarktidy: Trudi Nauchono-Issledovate Skogo Instituta Geologii Arktiki, v. 113, p. 183–208.

Wellman, H. W., and Wilson, A. T., 1965, Salt weathering, a neglected geological erosive agent in coastal and arid environmenta: Nature, v. 205, p. 1097–1098.

Wilhelmy, H., 1964, Cavernous rock surfaces (tafoni) in semiarid and arid climates: Pakistan Geographical Review, v. 19, p. 9–13.

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