CUBIC PSEUDOMORPHS OF QUARTZ AFTER HALITE IN PETRIFIED WOOD

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ABSTRACT. A portion of the Sweet Home, Linn County, Oregon, petrified forest east of the town of Holley has yielded petrified wood which is unique because of its inclusions. These inclusions are white or gray cubes, some more than six millimeters in size, consisting of a mosaic of quartz. They are found in *Platanus*, the sycamore, and more commonly in large concentric tubers which lack the cross grain due to wood rays. Many quartz cubes have hollow centers which are square in cross section. Some of the cubes are modified by the octahedron.

A study of the replacement leads to the conclusion that the quartz is pseudomorphous after skeletal halite crystals. The presence of high concentrations of sodium chloride, necessarily prior to the petrifaction of the wood, indicates the probable existence of a marine lagoon, in this case most likely during the Oligocene epoch. The generally accepted conclusion that hopper-shaped or skeletal halite develops only on an evaporating surface is refuted by this occurrence because the halite is distributed all through the wood.

INTRODUCTION

IN the region adjacent to the town of Sweet Home in Linn County, Oregon, there is a large area containing petrified wood. The exact size of the area is not known, but the largest concentrations of petrified wood are distributed over some 20 square miles. Petrified wood is common in the Willamette Valley but in the Sweet Home area there is an occurrence which is unique in that some of the specimens contain inclusions of quartz which are cubic in shape (pl. 1, fig. 1). The best specimens are to be found in a small area about 1½ miles east of Holley. A study of the inclusions, which are pseudomorphs, was made in order to determine their genesis and to throw some light on the geological conditions existing at the time of their formation.

The presence of inclusions in petrified wood has been noted by several investigators. Probably the most unusual inclusions previously described are the small elongate objects with hexagonal cross-sections found in opalized wood from Santa Maria, California, which Rogers (1938) explained as excreta of termites. Another type of inclusion, common in many Oregon localities, consists of tube-like bodies of chalcedony formed by filling of borings left by a species of *Teredo*. Material with nicely banded chalcedony in the borings, such as that found east of Roseburg, Oregon, on the North Umpqua river, is in demand by mineral collectors. The pseudomorphs described in this paper are of neither of the above-mentioned types and are quite certainly inorganic in origin.

ACKNOWLEDGMENTS

The writer is indebted to Mrs. Ted Gordon of Salem, Oregon, for first calling his attention to the material described in this paper. Professor George Beck of the Central Washington College of Education kindly sectioned and identified several specimens of the petrified wood. Permission to collect material on his property was granted by C. C. Swigart. Finally, the writer wishes to acknowledge financial assistance in the preparation of the paper from the Graduate School of the University of Oregon.

SWEET HOME PETRIFIED FOREST

The Sweet Home petrified forest has received very little attention. Dake (1940) noted the occurrence and described some of the best spots for observing the trees. Beck (1944) studied some of the wood and reported the probable presence of oak, sycamore, alder, beech, and a conifer which apparently was *Trochodendron*. Beck was amazed at the large number of hardwoods present and he was convinced that many of the trees must have become extinct and left no living counterparts.

All of the fossil woods studied from the Sweet Home area are silicified, quartz and chalcedony being the replacing minerals. Opal seems to be almost entirely lacking. In most specimens, the original wood structure is beautifully preserved. All of the wood containing the inclusions to be discussed was found as float, although in several areas petrified trees up to six feet in diameter are found in place. All of the observed trees were embedded in tuff or agglomerate. No pre-Tertiary formations are known in the area and it is safe to assume that all of the woods are of Tertiary age. Recent finds of excellently preserved leaves, closely associated with the petrified trees, make this an unusually good locality for a study of Tertiary flora. Work of this type is now underway.

No attempt was made to study the generic distribution of the petrified wood devoid of quartz pseudomorphs; the following discussion is concerned only with those relatively rare specimens which contain the cubic inclusions.

The term "petrified wood" used throughout this paper requires some qualification. Most of the specimens, some up to 20 cm. in diameter and containing quartz pseudomorphs, show no evidence of longitudinal grain (long fibers) or cross grain due to wood rays. From study of sections of this material, Beck[1] concluded that it was not true wood but the petrifaction of some type of concentric tuber. In general, geologists in using the term "petrified wood" do not attempt to draw a fine distinction between true woods and pith-like or tuberous plants. In this case, further search yielded some material, with quartz pseudomorphs, which permits proper use of the term "wood." A specimen from a tree which was probably about 15 cm. in diameter showed distinct rays. According to Beck,[1] the wood is a "diffuse porous hardwood with compound rays" and most likely is that of *Platanus*, the sycamore. *Platanus* has been found before in the area, although this is the first time that it has been seen to contain quartz pseudomorphs. Petrifaction of the wood has also taken place by replacement of the wood with quartz.

DESCRIPTION OF QUARTZ PSEUDOMORPHS

As shown in the illustration (pl. 1, fig. 2), the quartz pseudomorphs are square or nearly square in cross section and in three dimensions are usually equidimensional or cubic. The frequency with which true cubes, rather than malformed ones, are found leaves little doubt that the replaced mineral was cubic. In the specimen of *Platanus* mentioned above it was found that some of the square cross-sections had truncated corners. Because this might have been produced by modification of a cube by either a dodecahedron or an octahedron, search was made for complete crystals in order to determine the correct interpretation. Several complete crystals were found, and on these the modification was observed only at the cube vertices, indicating that it was due to the octahedron. This accounted for the fact that many of the sections of the cubes failed to show the modification. The presence of the octahedron is significant in increasing the evidence that the modified form was isometric.

[1] Personal communication.

Many of the crystals are skeletal, the cubes having hollow centers. The cavities usually appear as square holes on a cube face and many of them are partly filled with euhedral quartz growing inward from the walls of the skeletal cube.

The arrangement and orientation of the quartz pseudomorphs are striking. The crystals are massed along the outer edge of the wood, often making it difficult to see the original structure of the bark, if any were present. Closer to the heart of the wood the cubes are more widely dispersed and consequently can be studied better. The annular rings spread around the cubes, indicating that the original cubic mineral had sufficient crystallizing force to induce the spreading (pl. 2, fig. 4). In sections of the wood cut either transversely or longitudinally, almost all of the sections of the cubes are square or rectangular, and only occasionally are triangular sections found. This indicates that most of the cubes in these sections are cut perpendicular to a 4-fold axis rather than perpendicular to a 3-fold or 2-fold axis and shows a preferred orientation of the cubes. This orientation may well be governed chiefly by the annular rings. Also of interest, but not easily explained, is the fact that the cavities in the skeletal crystals are parallel to the longitudinal axis of the wood.

DETERMINATION OF REPLACED MINERAL

The cubic crystal form implies that quartz replaced an isometric or pseudo-isometric mineral. Although there is some malformation of a few cubes it is not sufficient to cause one to think that the original crystals could have been rhombohedrons, such as those described by Adams (1920) where dolomite replaced wood.

Some of the most common minerals to be found in cubes are pyrite, fluorite, galena, and halite. In addition, anhydrite and quartz are sometimes found pseudo-cubic. The possibility of the original mineral being quartz with a large development of the rhombohedron ($rr' = 85° 46'$) giving a pseudo-cubic appearance can be disregarded, since aside from the fact that modification by the octahedron has been observed, it is unlikely that the original quartz crystal would be replaced by finer grained quartz. Fluorite in distinct separate crystals would not be expected to occur in petrified wood and there is no known source for the fluorine in this area. Likewise there is no evidence of lead minerals in the area, and there is no reason to believe that the quartz is pseudomorphous after galena as described by Emerson (1896, p. 139) from Massachusetts where hollow cubes were found with the quartz in parallel ridges due to penetration into the cleavage planes of the galena. Limonitic stains are generally absent and there is no evidence to indicate the former presence of pyrite in the wood. Also, as will be shown, the quartz definitely is a replacement and not merely a cast due to filling of the impression left by the removal of original material. Consequently it cannot be assumed that pyrite was removed and quartz later filled the void.

The two most likely minerals to be replaced to yield the quartz pseudomorphs are anhydrite and halite. Only occasionally does anhydrite occur in euhedral crystals, but it may do so and assume a pseudo-cubic habit when the pinacoids are the dominant faces. Rarely, also, anhydrite is pseudomorphous after halite and therefore in cubes, but there is no evidence of this replacement. From a physical-chemical standpoint it would be possible for anhydrite to form under the conditions which probably existed at the time of the formation of the cubic crystals. Although usually anhydrite crystallizes above 66°C, with gypsum forming below this temperature in pure solutions, it is known that if considerable NaCl is present in the solution the critical temperature for the crystallization of anhydrite may be as low as 25°C. In spite of the fact that it would have been possible for anhydrite to form, there is no positive evidence to indicate that this mineral ever existed in the wood.

All of the evidence obtained from a study of the pseudomorphs leads to the conclusion that the quartz is pseudomorphous after halite. The strongest confirmation of this is the fact that the original mineral often occurred in skeletal or hopper-shaped crystals, a habit which is typical and common only in halite, among the minerals considered above.

The term 'hopper-shaped" as applied to skeletal crystals of halite has attained very general usage, but as a result of

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EXPLANATION OF PLATE I

Fig. 1. Quartz pseudomorphs standing in bold relief on surface of petrified wood.

Fig. 2. Quartz pseudomorphs after skeletal halite exhibiting square central cavities, X 1.

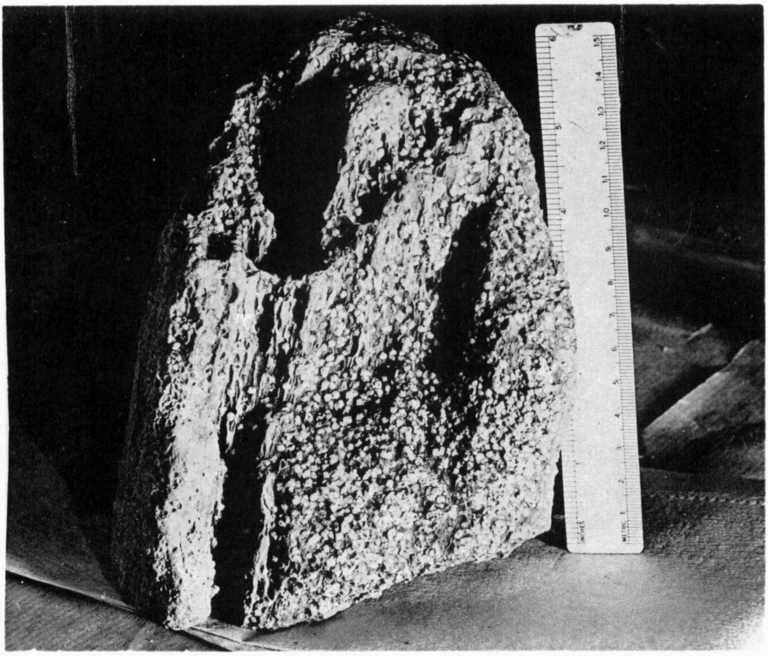

FIGURE 1

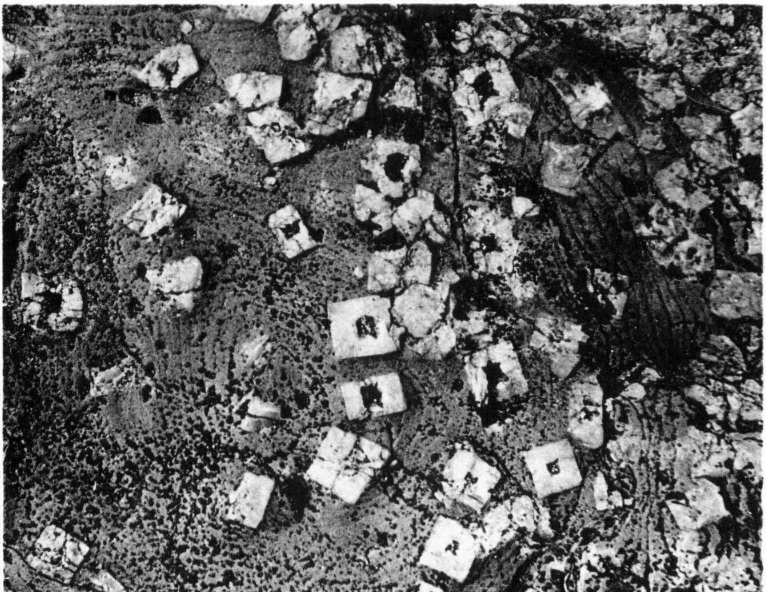

FIGURE 2

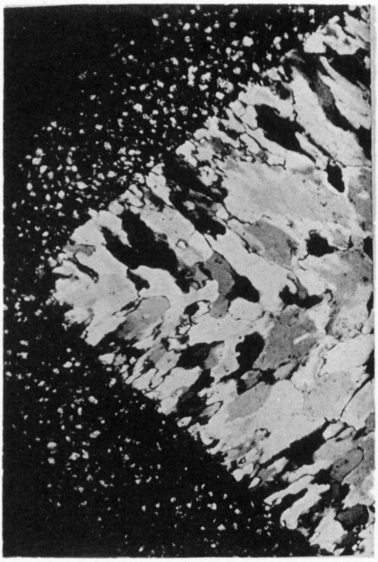

FIGURE 1

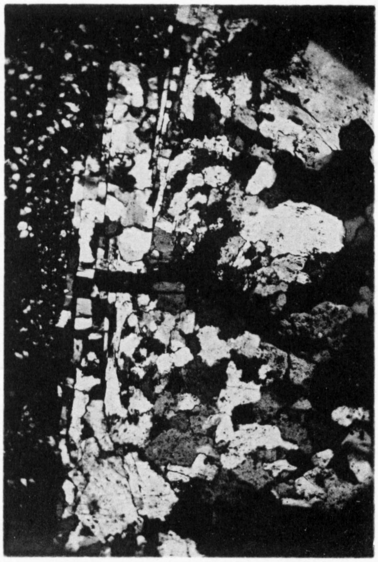

FIGURE 2

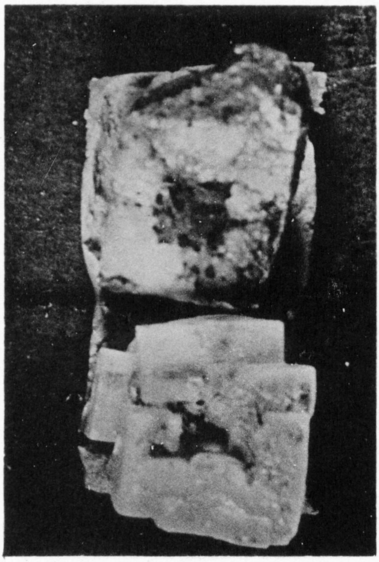

FIGURE 3

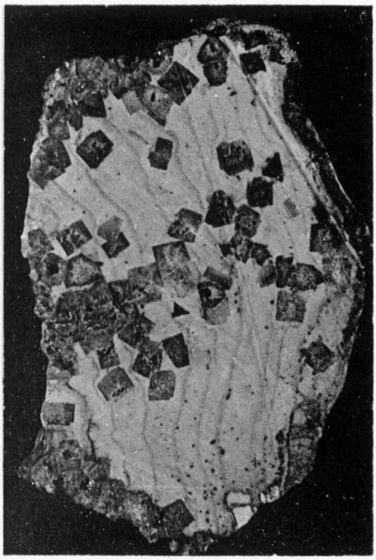

FIGURE 4

never having been carefully defined, many different skeletal types are included. The word "hopper" usually refers to a funnel-shaped container and consequently it would seem logical to confine the term "hopper-shaped" to those skeletal crystals which have funnel-shaped cavities. There are two general types that fulfill this requirement. The type which is usually pictured in mineralogy textbooks (Dana, 1892, p. 154) is a cube with an inverted pyramidal depression which descends by steps on each cube face. Another type consists of a single "hopper" presenting a V-shaped cross section and is due to the offsetting of the cube units during growth. This is the type described by Mendeleeff (1891, p. 416), "the salt often separates out on the surface as cubes, which grow on to each other in the form of pyramidal square funnels." In many cases it is difficult to determine whether the internal cavity is funnel-shaped and the general term "skeletal" is preferable under these circumstances. In the case of the quartz pseudomorphs described here, the original halite was of the single cavity type with a square surface opening and a cavity that closed at the bottom. Any step-like character of the walls of this cavity is now hidden by a coating of small euhedral quartz crystals. However, there is little doubt but that the halite was of the second type of hopper crystal mentioned above, that is, the single hopper. Further evidence of this is the offset in the crystal walls, so characteristic of this type of crystal grówth.

A comparison of a skeletal crystal of halite with a quartz pseudomorph removed from the petrified wood is shown in plate 2, fig. 3. It is to be noted that the cavity in the center of the quartz pseudomorph produces a square opening on the cube face, just as is the case with the skeletal halite crystal. The presence of the square central hole is evidence that the quartz replaced the halite rather than filling the

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EXPLANATION OF PLATE 2

Fig. 1. Photomicrograph of quartz pseudomorph showing alignment of quartz normal to edges. Crossed nicols, X 25.

Fig. 2. Quartz pseudomorph with quartz aligned parallel to edge. Arrangement probably determined by original cleavage of halite. Crossed nicols, X 25.

Fig. 3. Comparison of quartz pseudomorph from petrified wood (above) with skeletal halite crystal (below), X 5.

Fig. 4. Section of petrified wood with quartz pseudomorphs showing spreading of annular rings by halite before pertification, X 1½.

cavity as a cast, since in the case of partial cavity filling a circular or irregular void would be expected. A study of many thin sections gave further evidence that the replaced mineral was halite. Plate 2, fig. 2 shows sharp breaks parallel to the cube face, with anhedral quartz crystals arranged in rectangular blocks. This is probably evidence of the cubic cleavage of the halite. In other examples (pl. 2, fig. 1) the quartz is aligned normal to the cube face and produces a striking orientation.

Burt (1929) described some petrified wood from Brazos County, Texas, in which silica was pseudomorphous after either pyrite or halite. Dr. H. B. Stenzel, University of Texas, kindly made a specimen of this material available for study. Unlike the Holley petrified wood, the pseudomorphs occur only on the surface of the wood, occupying the position of the bark. Moreover, as pointed out by Burt, the evidence is inconclusive as to what the replaced mineral might have been. Not only pyrite or halite suggest themselves, but even fluorite is a possibility.

The literature contains numerous references to pseudomorphs after halite by minerals other than quartz. Obenauer (1930) describes pseudomorphs of gypsum after large distorted cubes of halite (15 x 12 x 8 cm.) in a clay pit at Saarbrucken. Emerson (1896, p. 144) mentions calcite pseudomorphs after halite in the Triassic shales of Massachusetts, at one time mistaken for chiastolite. Hopper-shaped cavities have been described by Hawkins (1928) from the red Triassic shales of New Jersey, and both Dropsy (1938) and Merritt (1936) described hopper-shaped casts of dolomite after halite, from France and Oklahoma respectively. Shrock (1948, pp. 146-149) cites several other references to pseudomorphs after halite in sediments and discusses their value in determining the top and bottom of beds. Although quartz pseudomorphs after halite in wood are rare, it is evident that pseudomorphs after euhedral and hopper-shaped halite are relatively common in nature.

CONDITIONS FAVORING FORMATION OF HALITE

As there can be little doubt that the replaced mineral was halite, the question arises as to the unusual conditions which existed prior to the petrifaction. The portion of the forest in which the trees lived must have been covered to some extent by water with a high NaCl content. Such saline bodies might have been salt lakes or salt pans due to evaporation under conditions of internal drainage, saline crater lakes, salt springs, or they might have been arms of the sea cut off and forming lagoons or saline estuaries. There are no known saline strata in the Holley area that might produce local salt springs so this method of bringing in the salt is unlikely. Nor is there evidence of saline volcanic craters in the area although extrusive and pyroclastic rocks are common. The most probable environment for burial of the trees was either in a salt lake or marine lagoon. Direct evidence confirming either of these latter conclusions is lacking.

As has been mentioned, the Sweet Home forest has many petrified trees in situ, but unfortunately none of these examined contains the quartz pseudomorphs. The exact source of the wood containing the pseudomorphs although not known is probably not far away, because the occurrence is limited to a small area. This locality at Holley is just east of the line which marked the eastern edge of the Oligocene sea according to Lowry (1947). Vokes and Snavely (1948) in studying the fossils in a quarry 12 miles due west of Holley found in the fine tuff along with abundant marine Oligocene fossils, well preserved imprints of what they interpreted as halite crystals. They considered the presence of the fossils and halite imprints in the same deposit as evidence of shoreline conditions. These observations strengthen the possibility of the wood at Holley having undergone inundation in an arm or lagoon of the Oligocene sea.

Dunbar (1924) described an association of halite and petrified wood in Kansas, which, although not strictly analogous because the halite and wood are not together, indicates an environment that might have been similar in some respects to that at Holley. According to Dunbar, the Permian Wellington shales at Insect Hill near Elmo, Kansas, contain a bottom zone of shale with calcareous bands that had salt "hoppers" in them, up to 10 inches across the face. Over this is a black shale with scores of silicified stumps, and above this a marly limestone containing well-preserved insects. Dunbar interprets this occurrence as due to first, a marine body of water surcharged with NaCl, second, temporary emergence permitting the growth of trees in a swamp, and third, submergence again. This took place along the eastern margin of the Kansas sea, and gave rise to "dead sea" and lagoonal conditions.

At Holley, the occurrence of considerable tuff and basalt indicates volcanic activity along with the marginal sea conditions. Assuming that the wood with pseudomorphs was originally enclosed in tuff, similar to the wood in place, it seems probable that the trees grew in swamps not far from the Oligocene coast, and that they were submerged in a shallow lagoon in which NaCl became concentrated. During this stage the trees were killed and the halite crystallized in them. Volcanic ash was then deposited in the lagoon, completely enveloping the trees.

The presence of pyroclastic material closely associated with the petrified wood indicates the possibility of hot water being important in the silicification of the wood. The fact that silicification is entirely by crystalline or cryptocrystalline silica rather than opal also tends to indicate a higher temperature for the silica-bearing solutions. In this connection it is interesting to note that NaCl is one of those rare salts whose solubility in hot water is not appreciably greater than in cold water and consequently removal of the NaCl would not be greatly hastened under these optimum conditions for the transportation of silica.

The mechanics of the formation of the halite crystals in the wood is interesting. Without doubt the crystals formed before petrifaction started, as indicated by the spreading apart of the wood fibers and by the replacement both of the wood and the halite by silica.

It seems probable that the halite crystallized after the plant died, even though there is ample evidence in nature of living plants taking salts from the soil and concentrating them. Grabau (1920, p. 247) gives as examples of the latter the Argentine jume or saltwort, the ashes of which yield 19% NaCl. In the Nebraska Sand Hill region the NaCl content of some lakes is up to 40% NaCl and this has been explained as due to leaching of burned plants (Grabau 1920, p. 259). Although salts may form as a crust on the plant, actual crystallization of larger NaCl crystals within the plant such as occurs in the Holley wood is not known.

An excellent example of dried wood absorbing salt solutions is seen at present on the Bonneville Salt Flats on the western shore of Great Salt Lake, Utah. Here according to Dr. Orlo Childs[2] salt water moves up into the bases of telephone poles and crystallization expands the poles until they burst. The mechanics of the movement of the salt solutions up the poles is not known but the fact that the poles are dry and strong above 3 or 4 feet indicates a limiting factor such as the force of capillarity. Capillarity can satisfactorily account for a rise of this magnitude.

In the case of the Holley petrified wood, the concentration of the halite crystals near the bark indicates that the salt solutions were absorbed from the periphery rather than rising through the center. The even distribution of the crystals around the periphery proves that the trees were completely covered at the time of halite crystallization and solutions had access from all sides.

There can be little doubt that the crystallizing halite had sufficient strength to force the plant tissue apart as shown in the specimens here described. Becker and Day (1905) concluded from a study on crystallization of alum that its crystallizing force is of the same magnitude as the resistance which the crystals offer to crushing stresses. Harris (1909, p. 23) in applying these observations to halite determined that a 4-inch cube withstood a confined pressure of 50,000 pounds without even cracking. It might be assumed that a hopper-shaped crystal would not have great crystallizing force, but in the experiments of Becker and Day the face of the crystal in contact with the lower surface of the vessel was found to be a terraced cup form and the pressure exerted by the crystal was distributed along a thin edge throughout its growth. It is evident then, that a pulpy or rotten condition of the wood was not necessary to explain the forcing apart of the annular rings because ample strength of crystallization of halite could account for the phenomenon. This, of course, does not preclude the possibility that some softening had occurred, but the retention of delicate radial and growth structures in some of the specimens indicates that decay had not advanced far.

The formation of hopper-shaped crystals of halite was explained by Mendeleeff (1891, p. 416) as occurring in the upper

[2] Personal communication.

layer of a brine with subsequent sinking and continued growth at the surface of the brine. Mellor (1922, p. 529) states "When the crystals form on the surface of evaporating brine, distinctive hopper-shaped crystals resembling hollow quadrilateral pyramids are developed; the inner surface appears to be arranged in a series of steps." Hopper-shaped halite crystals have generally been assumed to indicate that evaporation of the NaCl solution took place at the surface of the solution in contact with air, or in the case of halite in clay, the solutions evaporated on mud surfaces. The occurrence described here is interesting in that it indicates skeletal or hopper-shaped crystals can form under very different conditions, with complete confinement.

Considerable work has been done on the subject of habit variation in crystals, and halite has been used in these studies probably more often than any other mineral. It has long been known that halite grown from solutions containing urea exhibits a preferential growth of the octahedron rather than the usual cube. The importance of impurities in the solution has been demonstrated by Egli (1949, p. 272) who found that small amounts of impurities actually produce larger and better crystals of halite than pure solutions, while larger concentrations of impurities frequently modify the crystal habit. Retgers (1892, p. 270) showed that if a solution is thickened by the addition of gelatine, dextrine, or glycerine, the growth of skeletal crystals of NaCl is promoted. In the case of skeletal crystals of NaF, Frondel (1940, p. 346) found that a low OH ion concentration aided their formation. Experiments which may have a bearing on the Holley occurrence were performed by Royer (1930, p. 190) who found that modifications of crystals, especially to forms of lower symmetry, were produced by brown solutions from peat which were rich in humic materials. Although we cannot be certain of the chemical composition of the solutions from which the halite crystals formed at Holley, it seems probable that impurities in the form of humic acids might readily account for the anomalous occurrence of skeletal halite crystals within the wood.

CONCLUSIONS

A study of petrified wood with cubic inclusions from Holley, Oregon, has established the fact that the inclusions are quartz pseudomorphs after halite. The presence of halite crystals in wood, which later underwent petrifaction, permits interesting speculation concerning the conditions at the time of growth and later preservation of the trees. Probably during Oligocene time the trees were inundated by a shallow marine lagoon and enclosed by a fall of volcanic ash. High salinity of the lagoon caused crystallization of NaCl in the tree stumps and silicification of both the halite and the wood took place, beautifully retaining the structure of both.

The NaCl solutions were probably carried into the wood by capillarity and there was some orientation of the halite, governed by the annular rings. The formation of skeletal halite crystals usually takes place at evaporation surfaces and their presence deep within the wood requires special explanation. There is a possibility that organic compounds within the wood were responsible for the unusual habit.

This occurrence is of interest because of the fine preservation of the halite crystal habit in the quartz pseudomorphs and because the data obtained from studying the material aid in reconstructing a picture of the environment of petrification.

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