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THE ORIGIN OF COLEMANITE DEPOSITS

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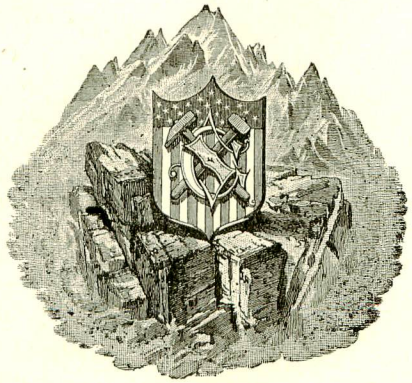

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PREFACE.

The present paper is the first of a new series to be published by the Geological Survey under the title "Contributions to general geology." Of late years Survey authors have become contributors to scientific and technical journals to an extent that suggests the need of an official channel for papers of a certain type. Contribution to these outside journals is a valuable phase of the Survey's activity and will continue; but this method of publication has certain limitations by reason of both the capacity and the circulation of these journals. The time has come for beginning a volume that will afford opportunity for the publication of short papers and preliminary reports of a character not well adapted to publication in any of the forms heretofore used by the Survey.

It is significant that so many of the Survey geologists are making scientific contributions of general interest that represent results incidental to other investigations or that are of the nature of by-products of work whose immediate purpose is economic. This is because the so-called economic work of the Survey is really scientific. It is scientific in method and scientific in results. It represents the application of science to the solution of problems whose main bearing may be utilitarian but which, if successfully solved, will afford by-products in results and principles that will yield greater ultimate possibilities of use to man. In order to encourage greater breadth of observation and investigation among the geologists and to promote the scientific possibilities of their professional work, means should be provided for prompt publication of such papers in a permanent form that will commend itself to both author and reader. Provision has been made since 1902 for the current publication of short papers relating specifically to economic geology, and the new series here established is intended to make similar provision for scientific papers relating to general geology.

In advance of the printing of the full volume, separates, each including one or more papers, will be issued to the number of 10 or 12 a year as the manuscript and illustrations are ready, without waiting for material for the full volume to be in hand or even promised. These separates will be paged continuously, so that the volume will be simply a consolidation of the separates, without change of pagination, a distinct advantage for bibliographic reference. The date of publication will be printed on the title-page of each separate.

The papers included in these "Contributions to general geology" may relate to any phase of geology, provided it possesses general interest—petrology, paleontology, stratigraphy, glaciology, structural geology, etc. This volume is intended not as a catch-all for current odds and ends, but as a dignified collection of scientific contributions, each worthy in importance of subject, value of results, and quality of treatment for separate publication as a bulletin or professional paper if it were of sufficient length.

CONTRIBUTIONS TO GENERAL GEOLOGY, 1913.

THE ORIGIN OF COLEMANITE DEPOSITS.

By Hoyt S. Gale.

INTRODUCTION.

A brief study of several of the more important borate deposits in southern California during 1912 has suggested to the writer some ideas believed to be new regarding the origin of colemanite. The theory presented here has not yet been entirely proved, but as there is much in its favor and as it affords suggestions and a working basis for further observation, which the writer also hopes to have opportunity to make, it seems proper to place the matter briefly on record.

This paper is based chiefly on a short personal study of the borate deposits in Ventura County, Cal., supplemented by more cursory examinations of similar deposits in the vicinity of Death Valley, and includes a review of published data on this subject and of personal communications from those who have visited deposits elsewhere. A report discussing the economic geology of the colemanite deposits of Ventura County and the mining operations on them will appear in another place.[1] It is believed that these deposits afford exceptional opportunities for the study of the relationships of the colemanite ores.

VOLCANIC ORIGIN OF BORIC ACID.

It is generally recognized that boric acid in considerable quantities is an original constituent in the waters and gases given off with volcanic emanations. In fact, the Tuscan fumaroles have been an important commercial source of boric acid in Italy for a long time, and in the past, possibly even to the present time, almost all the boric acid brought into the European market was derived from this source. There is abundant evidence of the presence of boric acid in volcanic emanations in many parts of the world. On the other hand, boron is so rare a constituent of rock-forming minerals that it forms an almost inappreciably small percentage of the earth's rock mass as a whole. It is therefore natural in studying the genesis of boron minerals or deposits to look primarily for evidence of a possible origin in volcanic emanations. Such an origin is believed to be in fact strongly indicated by the relations to be observed in most borate deposits that have been studied.

HYPOTHESES REGARDING ORIGIN OF COLEMANITE.

The immediate origin of the colemanite ores of the southern part of the Great Basin has been discussed by several writers and geologists. W. H. Storms was perhaps the first to provide the explanation which has been more or less fully accepted since. In describing the deposits at Calico, near Daggett, Cal., he says:[2]

> To me it seems that what is now one of the most valuable deposits of mineral in the State was at one time the site of a Tertiary lake of considerable but as yet undetermined size; that although subjected to the same oscillation as the remainder of the region, a basin formed, in which the waters collected, carrying with them the mineral salts derived

[1] Gale, Hoyt S., The borate deposits of Ventura County, Cal.: U. S. Geol. Survey Bull. 540-O, 1913.

[2] Storms, W. H., Mineral resources of San Bernardino County, Cal.: California State Min. Bur. Eleventh Ann. Rept., p. 346, 1893.

from the rocks of the neighboring country; that finally the climatic conditions became such that the supply of water was less than the loss by absorption and evaporation, and the waters of the lake slowly diminished, it finally disappearing entirely, leaving on the floor of the lake a thick deposit of calcium borate of snowy whiteness.

After the deposition of the borax bed a general subsidence of the region occurred, the waters of the great Tertiary lake once more covering the whole country. Again the sands and finer sedimentary material—the erosion of the mountains—were carried down and found a resting place on the floor of the lake, the borax beds being finally covered.

Subsequent deformation of these strata has tilted and erosion exposed the borate beds.

Campbell [1] adopted a similar explanation of the genesis of the deposits at the same locality:

The borax of Death Valley, as well as that near Daggett, occurs in a regular stratum, interbedded with the semi-indurated sands and clays that make up the bulk of the strata. These beds are generally regarded as of Tertiary age, and they are supposed to have been deposited in inclosed bodies of water.

* * * * * * * * *

The principal deposit of boron salts [near Daggett] occurs at Borate, about 12 miles north of Daggett, in the vicinity of the old Calico mining district. The mineral found here is borate of lime, or colemanite, and it occurs as a bedded deposit from 5 to 30 feet in thickness, interstratified in lake sediments.

Spurr,[2] in discussing the character and formation of the Tertiary lake beds, says, with special reference to the borate of lime deposits: "The internal evidence of these beds shows that much of the material was laid down in inclosed lake basins, and that the colemanite beds are probably the result of the evaporation of Tertiary alkaline lakes during periods of aridity."

Later Keyes [3] suggested a modification of the hypothesis by assuming the Tertiary water bodies to have been marine, "a great shallow arm of the Pacific Ocean that had been cut off by the upheaval of the mountain ranges along the coast." As the fossils obtained from the sedimentary beds associated with the borates, at least in the Mohave Desert, indicate a land and fresh-water fauna exclusively, this modification of the hypothesis may probably be dismissed.

Baker [4] discusses at some length the character of the sediments associated with the borate deposits and refers to the genesis of borate ores near Daggett:

The interbedded layers of colemanite, gypsum, and limestone were most probably deposited on the evaporation of a body of water of considerable depth, since the colemanite layer is from 5 to 30 feet in thickness. Layers of pure gypsum several inches thick are found, as well as more considerable thicknesses of what is probably chemically deposited limestone. An alternative hypothesis, that these minerals had their immediate origin in hot springs and solfataras opening directly into shallow lakes, perhaps only of seasonal duration, or in playas, has much to commend it, especially when considered in connection with the numerous evidences of shallow-water deposition. These evidences comprise ripple marks, sun cracks, rain prints, found on the finer as well as the coarser beds, and the layers of fine breccia and conglomerates interbedded with the fine shales and tuffs. Shallow lakes or ponds probably existed at times during the deposition of the fossiliferous tuff member, for they seem to be necessary to account for the presence of the gastropods. The paucity or absence of fossils in the borate and the fine ashy and shaly tuff members (but one specimen of a Planorbis was found in these beds), as well as the presence of the colemanite, limestone, and gypsum layers, apparently indicates the salinity of the waters. * * * Colemanite, gypsum, and limestone were deposited either by hot springs or solfataras in saline lakes, which might have been of shallow depth, or, having leached from the surrounding rocks, were precipitated during a time or times of evaporation of a former fresh-water lake of considerable depth.

Lately Eakle [5] has described the colemanite mined at Lang and summarized the origin of the deposit as follows:

The bedded character of the deposit is evidence that the mineral crystallized from an evaporating solution, and that precipitations of both the borate and some of the silt which formed the shales took place. The solution filled a closed basin as a lake or marsh, probably similar to the alkali marshes of the desert regions. It is generally characteristic of such deposits that salts of various kinds, often in alternating series, especially carbonates and sulphates of lime and soda, make up the deposit, and the well known Searles borax lake in San Bernardino County, with its many associated minerals, is a good illustration of a desert formation. The Lang deposit, however, is an exception, as the neocolemanite is practically unaccompanied by other minerals, except howlite, which is a silico-colemanite, and some calcite. Waters emptying into the basin could not have been charged with mixed alkali salts.

It seems probable that the original site of the deposit was a marsh containing marl and calc tufa with mud and considerable organic growth, and that later waters charged with boracic acid flowed into the basin and converted the

[1] Campbell, M. R., Reconnaissance of the borax deposits of Death Valley and Mohave Desert: U. S. Geol. Survey Bull. 200, pp. 8, 12, 1902.

[2] Spurr, J. E., Ore deposits of the Silver Peak quadrangle, Nevada: U. S. Geol. Survey Prof. Paper 55, p. 21, 1906.

[3] Keyes, C. R., Borax deposits of the United States: Am. Inst. Min. Eng. Bull. 34, 1909.

[4] Baker, C. L., Cenozoic history of the Mohave Desert: Univ. California Dept. Geology Bull., vol. 6, No. 15, 1911.

[5] Eakle, A. S., Neo-colemanite, a variety of colemanite, and howlite from Lang, Los Angeles County, Cal.: Univ. California Dept. Geology Bull. vol. 6, No. 9, 1911, pp. 179–189.

carbonate of lime into the borate. Some and perhaps the greater part of the argillaceous material which forms the shales was precipitated by the decomposition of the impure limestone, together with organic matter. The carbon dioxide set free may not wholly have escaped, but possibly became occluded in the mud and later converted into carbon. Most of the borate is of a blackish-gray color, due to impregnations of carbon along the cleavages and fractures. The conversion of the limestone into the borate in all probability took place before the overlying sandstones were formed. The absence of soda compounds and the presence of abundant plant life indicate that the lake or marsh was fresh, into which springs containing boric acid discharged. The deposit later became submerged and the sandstones were laid down.

The origin of the boric acid is presumably volcanic and the springs probably issued from vents in the immediate vicinity of the basin. The deposit is situated in a hilly district and is partly surrounded by high masses of volcanic tuffs and rhyolites. The subsequent tilting of the deposit was not accompanied by heat or pressure sufficient to modify the borate materially, yet the mineral shows lines of strain and columnar partings due to pressure and shrinkage. The fissile shales owe their solidity to this slight pressure, and carbonization to some extent was also the result. There is, of course, the possibility that all of the carbon in the deposit is from organic matter, the CO_2 of the carbonate escaping, as some of the shales are quite bituminous.

Eakle does not mention any immediate relation of the deposit to lavas, such as are known to be intimately associated with borate-bearing beds elsewhere, although he notes that the Lang district is partly surrounded by high masses of volcanic tuffs and rhyolites.

Study of the colemanite deposits in Ventura County, Cal., and observations on similar deposits near Death Valley have led the writer to the conclusion that these borate minerals and probably also most of the gypsum associated with them are vein deposits and not the product of evaporated lake waters. The evidence supporting this conclusion is set forth briefly below.

COLEMANITE DEPOSITS OF VENTURA COUNTY, CAL.

The Ventura County deposits of colemanite lie on the southern flank of Mount Pinos, near the San Emigdio Range, at the south end of the San Joaquin Valley. The colemanite is found within a series of bedded rock formations, which have been extensively folded and faulted. In general the trend of their outcrop is northeast and southwest, and the dip southeastward, away from the higher elevations of the Mount Pinos Range.

The section of sedimentary beds and lava with which the colemanite is associated is in general terms as follows:

Section of formations in which colemanite occurs in Ventura County, Cal.

Top of section measured.	Feet.
Shale and some sandstone	300
Basaltic lava flows, with intercalated layers or lenses of shale and limestone	600
Shale	600
Conglomerate, bowlders, or cobbles of light granitic rock cemented	600
Other sedimentary rocks below.	

These beds are believed to be of Miocene age. The more extensive stratigraphic section exposed in this general region has not been included here, as its possible relation to the borate ores seems remote and it evidently involves many complex problems. The beds defined above are apparently conformable. The most valuable borate deposits are included within the layers of shale and limestone intercalated within the flows of basalt, but borates occur also in the shales above and below the basaltic flow rock, though invariably in close association with this lava.

The following interpretation may be placed on the section given above. The base of the section is a massive conglomerate made up of bowlders or more or less rounded cobbles, in part very firmly cemented together, and the whole mass constitutes a rather distinct formational unit. This is supposed to be a piedmont alluvial deposit that was originally spread out from the base of the Mount Pinos Range. The core of the range is believed to be mainly granite of the character represented by the bowlders of this formation. The bowlders are coarser near the mountains and seem to grade off to finer material at greater distance, the formation as a whole taking on the character of sandstone, as illustrated at the Ives camp, at the lower end of the Middle Fork canyon. There seems little evidence in this formation to indicate other

than subaerial distribution of very coarse detrital material. However, in the opinion of R. W. Pack, who has studied the areal geology of the north slope of the San Emigdio Range, there may exist some room for doubt that the coarse gravels were deposited subaerially. On the north slope of that range about 10 miles north of the borax mines he has found coarse conglomerate beds containing granitic bowlders several feet in diameter interstratified with fine sandstones and sandy and diatomaceous shales, the latter containing marine fossils of Miocene age. The coarse beds occur at several horizons and are so intimately associated with the fossiliferous strata as to suggest that the whole section is marine.

The shale overlying the bowlder conglomerate and sandstone is light-colored detrital material, thin bedded, and so readily eroded that it does not form conspicuous exposures. It has not been examined in detail, but it is supposed to be made up of muds derived by the more complete comminution of granitic material similar to the granite in composition. It may be a delta plain or alluvial deposit distributed by quieter waters than those which carried out the bowlder wash, or it may have been deposited under water. At present there is no conclusive evidence as to its origin.

Overlying the shale is a massive accumulation of flows of basaltic lava, with vesicular and slaggy layers. Evidently many distinct flows are represented in the thickness of some 600 feet measured on North Fork. These flows include several intercalated layers of shale and limestone, with which the most valuable colemanite deposits of the district are associated.

The basalt is overlain by another mass of shale and sandstone similar to that which underlies it. The history represented by these beds may be much like that which preceded the outpourings of the lava.

The colemanite of Ventura County is evidently typical of the mineral as it occurs elsewhere. It is found in solid crystalline masses of large size but of very irregular form. The mineral itself in its purest form is milky white, even glassy in part, much resembling pure-white calcite in general appearance and cleavage. The crystal forms are, however, quite distinct from those of calcite. The less pure massive ore includes grayish or even black crystalline bodies, the color of which is supposed to be due to included impurity.

The mineral masses as a whole are of very irregular form, but they have been generally described as bedded deposits, for they appear to follow the bedding of the sedimentary strata with which they are associated. When examined in detail, however, the mineral colemanite does not exhibit any bedding structure but only the forms characteristic of the crystallization of the mineral itself. The massive deposits are either crystalline without definite arrangement or show radial structures as well as seams of definitely vein-banded material, included between walls, in places containing open cavities lined with crystal terminations. The irregularity or bunchy character of the deposits alone would prohibit strict parallelism with the distinctly bedded shales in which they are included. Other evidence afforded by the deposits themselves is suggestive of formation in veins, as will be pointed out.

The larger deposits of colemanite, such as those of the Columbus, Russell, and Frazier mines, are associated with shale and limestone lenses included within the section of basalt lava flows. In each of the mines mentioned the colemanite ore appears to have been developed in immediate association with a bed of limestone included within the shale. This limestone is massive or of rough, porous character on the weathered outcrop, suggesting the designation "travertine-like." Basaltic lava occurs stratigraphically above and below the ore bodies and is generally encountered in the mine workings not far from the ore. The shale bands intercalated within the basalt flows much resemble the shales that both overlie and underlie the whole sequence of flows.

The present attitude of the beds that include the ore bodies ranges from nearly flat to steeply dipping. The nearly horizontal ore bodies in the Frazier mine are the development of beds near the crest of an anticlinal fold. In general the rocks dip steeply.

In one large deposit examined underground (in the Russell mine) the main ore body follows a zone of slip faulting, which is also approximately parallel to the bedding, the ore being limited with much distinctness by a wall of slickensided gouge.

The outcrops have rarely shown any colemanite, even in the ore-bearing zone. The one exception noted, that of the original discovery at the Frazier mine, was an exposure near the top of a very steep bluff in which a great amount of slipping had taken place and normal outcrops were not present. Possibly a minor amount of the borate minerals is also present elsewhere in the outcropping strata, but it is very inconspicuous and was not observed. As a rule the outcrop of the borate-bearing beds is either folded and crumpled shale or shale including a massive limestone ledge, the limestone forming the most conspicuous part of the outcrop. These zones are generally indicated by an abundance of gypsum, which is a marker followed in prospecting and occurs in the form of thin stringers included in the opened bedding planes and in cross fractures of the shale. All the gypsum is of the clear crystalline variety selenite, and no massive bedded deposits of gypsum are known in this region. The outcrops of these gypsiferous shales are also characteristically marked by the occurrence of "button" concretions—flattened spheroidal nodules or disks of calcareous composition that have very commonly been mistaken for fossils. The occurrence of these concretions at the outcrop of the basaltic lava, in the immediate vicinity of the ore-bearing zones, usually only a few feet distant, is believed to be significant and is generally noted and referred to by the prospector. As a rule, however, the prospector regards the lava as an intrusive "porphyry," which it clearly is not, as attested by its common vesicular and amygdaloidal character, as well as its distinctly bedded structure, conformable with the sedimentary strata.

Certain specimens collected on the ore dumps and in the mines show that at least a part of the colemanite is a replacement deposit. Irregular portions of the limestone are surrounded by white crystalline colemanite, and minute fractures which traverse the limestone throughout are also filled with this mineral. These veinlets are observed to have been enlarged irregularly within the limestone. Small rounded masses of limestone are also included within the solid portions of the colemanite, indicating that in places the same enlargement of intersecting veinlets has been carried to a further stage and the separated limestone portions are residual within the deposited colemanite.

GENERAL EVIDENCE OF VEIN CHARACTER OF COLEMANITE DEPOSITS.

The direct evidence of the character of the colemanite, of course, lies in the deposits themselves. If the deposits are of vein form, the evidence suggesting it has hitherto been overlooked. In natural outcrops relationships are obscure. The study of the ore in place is not facilitated by conditions at the mines. The old mining entries on the Ventura County deposits were, when visited, either inaccessible or, if open, were heavily timbered, dripping with water, and coated with mud, so that they were not favorable to detailed study of the character of the ore. The facts of observation therefore are not yet to be considered conclusive, and judgment as to whether these deposits originated as veins or through desiccation involves a study of other more general considerations.

Colemanite, the borate of lime, is relatively insoluble in water. A recent determination, made at the writer's suggestion by W. B. Hicks in the Geological Survey laboratory, of the solubility of certain specimens of apparently pure colemanite from the Ventura County deposits has shown that at ordinary temperatures (20° to 25° C.) about 1 part is soluble in about 1,100 parts of water. Van 't Hoff has shown that colemanite may be produced artificially by reactions from other calcium borates in saturated alkali chloride solutions, but the writer knows of no data concerning the possible formation of this mineral by direct reaction of boric acid and limestone. It is natural to assume that free boric acid, which is a common constituent of the later volcanic emanations in this general region, might react with limestone, and that by the substitution of boric for carbonic acid the lime borate would be formed. Thus by a process of metasomatic replacement might have been formed deposits of the typical irregular character of the known colemanite masses, roughly following the bedding of the original calcareous rock or of the interbedded lenticular bodies of limestone. Therefore in so far as the natural reactions are concerned the formation of colemanite as fissure and replacement vein deposits is well within

the limits of possibility. But for other reasons also it seems that these colemanite deposits are not logically to be ascribed to deposition as the principal constituent of a residue derived from the waters of a desiccating saline lake.

Borates have been shown to exist in natural saline waters and desiccation deposits in many parts of the Great Basin and the desert country of the western United States. So far as known to the writer, however, colemanite has nowhere been deposited as a result of desiccation, but rather the boric acid has combined to form the more common surface saline minerals, such as ulexite and tincal. Is it therefore reasonable to suppose that ulexite, tincal, etc., could have been the primary deposits of such Tertiary dry-lake formations, from which colemanite had subsequently formed as a secondary product? If this had been so, would not some evidence of the primary deposit be at hand, either in the composition or in the structure of some parts of the colemanite deposits? Such evidence has not been recorded.

If colemanite were but a part of a natural saline residue deposited by the desiccation of the waters in which these materials had accumulated and become concentrated, it would be most natural to expect other salines that are commonly more abundant than the salts of boric acid in the typical desiccation deposits of the desert region. No appreciable amount of bedded salt, sodium sulphate, or carbonate is to be found with the colemanite deposits known to the writer. The borate-bearing shales of the Ventura County deposits are not even of a character that might be described as "alkaline" in ordinary desert parlance.

Gypsum and limestone, the latter travertine-like, occur in association with the borates, and former writings have already been quoted to the effect that both are chemical residues derived from the same desiccation that crystallized the colemanite. The gypsum associated with the borate-bearing shales is crystalline selenite. All or the greater part of it occurs in thin stringers, which not only follow the bedding joints of the shales but fill transverse fractures. The cross-fiber structure of much of this selenite is evidence of its deposition in veins. No rock gypsum of distinctively sedimentary character was observed in any of these beds. Gypsum is being deposited from ground waters along the walls of the mining entries at the present time. It still remains to be proved, therefore, that any gypsum of original sedimentary character is included with the borate-bearing deposits. All of this mineral present may have been introduced in solution by percolating ground waters. The stringers of gypsum noted so abundantly in the outcrops of the borate-bearing shales have not been shown to persist in like quantity in the few deeper developments of the mining entries.

The limestone strata with which the principal colemanite ore bodies are associated are evidently original in the sedimentary sequence. They are in part at least travertine-like, weathering in rough tufa-like surfaces, and are not compact like more typical limestones. Their character suggests the probability that they are chemical deposits, possibly of local extent, laid down in shallow waters, being similar to the travertine deposits now forming near springs or where ground waters flow into ponds or saline lakes. The limestone masses are believed to be of lenticular form and to occur interbedded with shales at various horizons within the flows of basaltic lava. They are not necessarily the product of desiccation.

In fact, there is little evidence from the stratigraphic section associated with the borate beds of Ventura County that can be taken to indicate the extensive lacustral conditions commonly assumed to have existed during the Miocene epoch in the Tertiary. Some of the associated deposits may have been "lake beds," but the writer believes rather that the submergences were the result of local, temporary, and variable conditions, such as may have occurred during or after periods of shallow flooding in the lower portions of piedmont fluviatile plains.

Lastly, an explanation of the source of the boric acid is to be sought. Naturally, a volcanic origin is suggested, and in Ventura County the association of the colemanite with the basaltic lava is certainly intimate. It is a common saying among prospectors of the district that "borax" will not be found except near a "porphyry contact" and in association with limestone. It is true that the larger ore bodies mined are all in close relation with some part of the basaltic lava flow rock in place, generally within a few feet of it. The borate-bearing beds follow the outcrop

of the basalt flows throughout the district. The question in what way boric acid originating with the extrusion of these flows could have caused reactions and mineral deposition soon or long after the period of the lava extrusion remains for further investigation.

SUMMARY.

The evidence favoring the hypothesis of a desiccated saline lake to explain the origin of the colemanite has little to support it beyond rather general assumptions. The actual character of the deposits themselves indicates rather a vein type of formation. The gypsum which has been pointed to as a desiccation deposit related to the colemanite is also of vein character. Other salines which would naturally be expected in desiccation deposits resulting from natural saline solutions are not found in association with the colemanite. Those who have supported the desiccation hypothesis have offered no explanation of the reaction which might produce colemanite in such massive deposits as a product of water evaporation, while, on the contrary, its formation from limestone in veins by replacement of carbonic acid with boric acid is a natural working hypothesis that deserves experimental investigation. The relations of the deposits to basalt lava flows indicate the probable origin of the boric acid at the time of the extrusion of these lavas, although it may also be necessary to assume that this acid continued to find its way into solution of the circulating ground waters long after the period of the lava extrusions.

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