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OPAL PSEUDOMORPHS FROM WHITE CLIFFS, NEW SOUTH WALES.

By C. Anderson, M.A., B.Sc., Mineralogist to the Australian Museum, and H. Stanley Jevons, M.A., B.Sc., late Lecturer on Mineralogy and Petrology, University of Sydney.

(Plates vi—vii., text fig. 4).

The occurrence of Opal at White Cliffs as pseudomorphic crystals, called locally "fossil pineapples" has been known for some time; they have been described by several observers, but no agreement has yet been reached as to the species of the original mineral. Recently several good specimens have reached Sydney and were examined by Professor T. W. E. David and the authors, the conclusions arrived at being set forth in the present paper.

Occurrence.—Before proceeding to the description of the specimens themselves, their mode of occurrence, so far as known to us, may be briefly alluded to. The White Cliffs Opal-field was first geologically examined in detail by Mr. J. B. Jaquet, and it is chiefly to his report[1] that we must turn for our knowledge. The opal is found in the Upper Cretaceous or "Desert Sandstone" Series, which at White Cliffs rests on Palæozoic slates of probably Silurian age. Overlying the Palæozoic strata are (*d*) coarse grits and sandstones, succeeded by (*c*) a thickness of fine white, kaolin-like material of highly siliceous composition and containing large waterworn boulders of quartzite with Devonian fossils. Concretionary nodules, and more rarely thin beds of gypsum occur in these deposits. Above this are (*b*) conglomerates consisting of small pebbles in a white siliceous matrix similar to *c*. It is in the beds *b* and *c* that the opal occurs. It is often found replacing various organic remains as Sauropterygian bones, Crinoid calices, stems, and separate ossicles, Belemnite guards and bivalve and univalve shells, as well as coniferous wood[2].

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[1] Jaquet—Ann. Rept. Dept. Mines and Agric. N. S. Wales, 1892 (1893), pp. 140—142.

[2] Etheridge—Rec. Austr. Mus., iii., 2, 1897, p. 19; Mem. Geol. Surv. N. S. Wales, Pal. No. 11, 1902, p. 10; Rec. Austr. Mus., v., 4, 1904, pp. 248, 251; *loc. cit.*, v., 5, 1904, pp. 306-316.

Pittman—Min. Res. N. S. Wales, 1901, p. 405.

Tate—Trans. Roy. Soc. S. Austr., xxii., 1898, p. 77.

The presence of Crinoids indicates an open fairly deep sea, whilst the conglomerates, boulders, opalised saurians and wood rather point to shallow water conditions with land at no great distance. In the absence of exact knowledge as to the vertical distribution of these fossils, it is idle to speculate on the geographical conditions obtaining at the time when the beds containing these enigmatical specimens were laid down. The presence of gypsum is not conclusive, for gypsum may originate either as a chemical deposit in an inland sea, or salt lake, or, on the other hand, may be formed subsequently to the deposition of the beds in which it occurs, for example by the action of decomposing pyrites on calcareous matter. According to Prof. J. D. Dana[3] where gypsum occurs not as continuous layers but in embedded, nodular masses, it was formed after the beds were deposited. This criterion does not help us to a conclusion, for Mr. Jaquet says[4] that the gypsum occurs both as isolated masses and as thin beds. In the recent surface deposits of the western districts of New South Wales gypsum is commonly met with as crystalline masses, where it is undoubtedly of secondary origin and due to chemical interaction between the constituents of the soil, and it is possible that a similar origin is to be assigned to the gypsum found in the opal-bearing beds. Against the likelihood of the gypsum being the result of evaporation in a land-locked sea is the comparative abundance of organic remains, for, when the water of an enclosed basin has reached a degree of concentration that permits of the deposition of gypsum from solution, animal life is usually absent. But it is conceivable that a temporary lake may have been formed as a remnant of a retreating ocean, and then subsequently re-united to the waters of the Cretaceous sea. Any solution of the problem presented by the pseudomorphs must be compatible with the presence of gypsum in the same beds.

Both gypsum and the mineral now known to us only as opaline casts have been converted into opal, the former partially, the latter entirely, by the action of highly silicated springs to which the general opalisation of the Desert Sandstone is usually attributed.

Previous Observers.—The pseudomorphs were apparently first observed by Jaquet,[5] by whom they were referred probably to

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[3] Dana—Manual of Geology, 4th ed., 1895, p. 554.

[4] Jaquet—*Loc. cit.*, p. 141.

[5] Jaquet—*Loc cit.*, p. 141.

gypsum. Later Weisbach[6] measured the angles and came to the conclusion that the original mineral was orthorhombic in system; he suggested sulphur. He was followed by Pelikan[7], who compared them to aggregates of gypsum crystals. Gürich[8] gives a more detailed account and concludes that the original mineral was monoclinic and probably identical with the original of the well-known "barley-corn" pseudomorphs from Sangerhausen, and similar pseudomorphs from elsewhere. But even if this conclusion be justified it does not settle the question, for at least five minerals have been suggested as the original of the Sangerhausen and similar specimens, celestite, perhaps, being regarded as the most likely,[9]

Description of Specimens.—The material for this paper was furnished by two specimens in the collection of the Geological Department, Sydney University, and five from the Australian Museum collection. That represented in Pl. vi., fig. 1, is the largest and best developed, hence it has supplied the bulk of the angular measurements by the contact goniometer. Unfortunately it is found that the angles vary somewhat, thus giving an element of uncertainty to the conclusions drawn therefrom; yet, by making a large number of measurements and taking means, it is hoped that a fair approximation has been made to the true angles.

The seven specimens vary in their greatest diameter from 11 cm. to 7·5 cm. approximately. They present a fairly uniform appearance, which is that of an irregular, radial aggregate of acute, tapering, four-sided pyramids. Owing to the curvature of the faces it is scarcely possible to secure exact measurements of the angles, though an attempt was made to counteract this source of error by making the goniometer arms tangent to the part of the faces close to the edges. An important feature in most of the pseudomorphic crystals is the well-marked cleavage (Pl. vi., fig. 2). It generally crosses one only of the four terminal edges, but sometimes passes over the apex and appears, though less strongly

6 Weisbach—Neues Jahrb., ii., 1898, p. 150.

7 Pelikan—Tschermak's Min. petr. Mitth., xix., 1900, p. 336.

8 Gürich—Neues Jahrb., Beil. Bd., xiv., 1901, pp. 478-483, fig.

9 Dana—Bull. U.S. Geol. Surv., 12, 1884, pp. 25-28; Syst. Mineral. 6th Ed., 1892, pp. 271, 907.

Miers—Min. Mag., xi., 1897, p. 264.

marked, on the opposite edge. In direction it is approximately parallel to the plane of two opposite edges, namely the plane bisecting the angles *bq* and *pd* (fig. 4). There is no sign of a second cleavage perpendicular to this plane. Three systems of striations are present, but they will be more fully described below.

As regards their composition, the pseudomorphs consist of precious opal of inferior quality and prevailing green or bluish tints, in other cases of common milky opal, or of clear glassy hyalite, with patches of the rarer black opal.

Measurements were made as a rule by each of us independently, but the agreement being close, only the mean values are given in the subjoined table. Provisional letters are assigned to the four pyramidal faces, the crystal being oriented by means of the edge on which the cleavage appears (fig. 4). The mean normal angles obtained plainly indicate that we are dealing with a monoclinic mineral having a plane of symmetry bisecting the angles *bd* and *pq*.

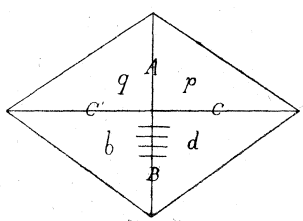

Fig. 4.
Schematic projection on a plane at right angles to the axis of elongation, with cleavage traces on edge *b*.

Conclusions.—The problem now is to find a mineral, monoclinic in symmetry, having a prominent cleavage perpendicular to the plane of symmetry, with angles approaching the values found, and the mode of occurrence of which is compatible with the geological conditions of the White Cliffs Upper Cretaceous beds. Obviously the facts of form already brought out dispose of the claims of gypsum, anhydrite, celestite and sulphur, while the angles do not even approximate to those of gay-lussite. After passing in review all the likely minerals that suggest themselves, we have come to the conclusion that the species most nearly fulfilling the required conditions is glauberite, sulphate of soda and lime, which is monoclinic in crystallisation, and has a perfect basal cleavage. In accordance with this theory, we have incorporated in the table the theoretical angles of glauberite, which we regard as corresponding to the measured angles of the pseudomorphs.

Pseudomorphic Crystals.										Glauberite.				
Normal Angles.	I	II	III	IV	V	VI	VII	VIII	Mean.	Normal Angles.	Indices.	Approximate.	Calculated.	
	°	°	°	°	°	°	°	°	°			°	°	′
$p \wedge q$	64	68	62	$62\frac{3}{4}$	$68\frac{1}{2}$	65	67	$64\frac{1}{4}$	65	$s \wedge s'$	$111 \wedge 1\bar{1}1$	$63\frac{3}{4}$	63	42
$b \wedge d$	84	89	92	$80\frac{1}{2}$	$82\frac{1}{2}$	85	—	$86\frac{1}{4}$	$85\frac{1}{2}$	$n'' \wedge n'''$	$1\bar{1}\bar{1} \wedge 11\bar{1}$	87	87	$7\frac{1}{2}$
$p \wedge d$	75	79	81	$83\frac{1}{2}$	82	84	79	76	80	$s \wedge n'''$	$111 \wedge 11\bar{1}$	76	75	58
$q \wedge b$	88	$78\frac{1}{2}$	82	[$92\frac{1}{2}$]	78	80	78	78	80	$s' \wedge n''$	$1\bar{1}1 \wedge 1\bar{1}\bar{1}$	76	75	58

If we are correct in regarding these specimens as pseudomorphs after glauberite, the original crystals must have been acute pyramidal in habit, with elongation in the direction of the clino-axis (Pl. vii., figs. 7, 9).

As the amount of error in measurements does not exceed 2°, the disagreement between the values obtained for the same angle on different crystals must be due to the varying amount of curvature and imperfection of form.

We next proceeded to confirm our results, and to explain, if possible, the divergence of the measured angles from the true values by determining the terminal angles between the edges A and B, and C and C′[10] (fig. 4), and the terminal pyramidal angles *sn″* and *s′n‴* (using the lettering of glauberite for corresponding faces of the pseudomorphs). The results are tabulated below :—

Angles.	Measured.	No. of Determinations.	Calculated.	Error.
	°		° ′	°
C ∧ C′	68½	10	78 42	10
A ∧ B	64	4	79 13[11]	15
s n″ / *s′ n‴*	50½	12	61 35[11]	11

The difference between the measured and the true angles is considerable, and some explanation must be forthcoming if our conclusions are correct. Now, on several specimens it is apparent that the cleavage is not exactly parallel to the plane of the two opposite edges C and C′. (fig. 1). This would be explained (assuming the original mineral to have been glauberite in which the cleavage is parallel to this plane) by a curving downward of those edges towards the cleavage. This downward curving could be accounted for by oscillatory combination of the *s* faces with a form *hkh* ($k > h$). No such form is recorded in Dana, but observation reveals the presence of a set of striations on the faces *s* and *s′* running parallel to the edge A. These striations would be a natural result of such an oscillatory combination, which

[10] A is the edge between *s* and *s′*; B the edge between *n″* and *n‴*; C and C′ the edges between *s* and *n‴* and *s′* and *n″* respectively.

[11] Taken from stereogram by Penfield's protractor.

would have the effect of displacing the edges C and C′ towards the cleavage lines crossing the edge B (Pl. vii., figs. 8, 9), and also of rendering the angle CC′ measured over the apex more acute (Pl. vii., figs. 2, 3). Another series of striations observed on the *s* faces of other crystals, and having a direction nearly parallel to the edges C and C′ may be due to the coming in of the *m* (110) face. The *n* faces are strongly striated, and in some cases distinctly stepped, the direction of the striæ and steps being parallel to the cleavage. These must be due to oscillatory combination of *n* with C (001), or *n* with *u* (112) or *v* (113), any of which would make the angle between the edges A B more acute than it would be in a perfect crystal (Pl. vii., figs. 8, 9).

We may now enquire what effect the oscillations described would have on the normal angles. It is readily seen that by their means the normal angle *ss′* would be enlarged, and the angle *n′′n′′′* diminished, while the angles *sn* would be either diminished or enlarged according as the effects of the oscillation of *(hkh)* on *s* or of (001) on *n* predominate. Now, from the mean values obtained by measurement, it will be observed that the departure from theory of the angles *ss′* and *n′′n′′′* is in the direction we should have expected. The mean value for the angle *sn* was found to be greater than the theoretical, which accords with our observation that the oscillation on the *n* faces is frequently much more pronounced than that on the *s* faces.

Glauberite is commonly found in association with rock salt, thenardite, mirabilite, and other sulphates, carbonates, &c., characteristic of salt lake deposits. It is soluble in water, and can, therefore, occur only in protected places or in arid regions. Most likely at White Cliffs it was formed in deposits of mud or ooze and not directly from solution. The consequent interference with the regular growth of the crystals may possibly account for the curvature of the faces through oscillatory combination. It is noteworthy that with the single exception of the thinolite of Lake Lahontan all the pseudomorphs resembling the Sangerhausen mineral, as also the pyramidal crystals of celestite from Virginia described by G. H. Williams,[12] which furnish the chief argument for the celestite origin, have been found embedded in clay, mud or marl. Thus it may be that the resemblance between specimens from different localities, which after all consists mainly in the curved and tapering form, is to be referred rather to the similar conditions of growth than to identity of species.

[12] Williams—Amer. Journ. Sci., xxxix., 1890, p. 183.

EXPLANATION OF PLATE VI.

OPAL PSEUDOMORPHS, WHITE CLIFFS, N. S. WALES.

Fig. 1. To the left of the central depression a crystal shows distinct cleavage traces on the edge.

„ 2. Several crystals show pronounced cleavage traces.

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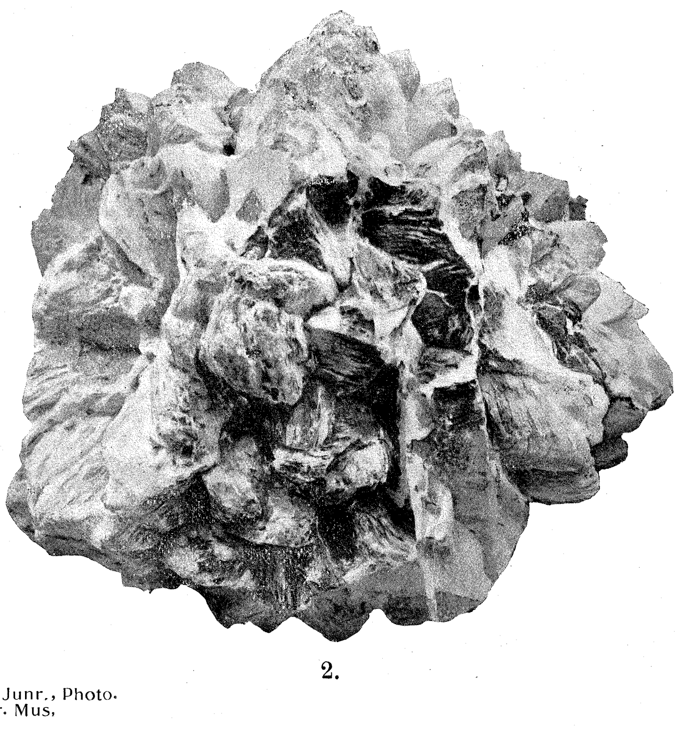


2.

H. Barnes, Junr., Photo.
Austr. Mus.

EXPLANATION OF PLATE VII.

GLAUBERITE CRYSTALS AND OPAL PSEUDOMORPHS, WHITE CLIFFS, N. S. WALES.

Forms :—*c* (001), *s* (111), *n* ($\bar{1}$11).

Fig. 1. Projection on (001) of a glauberite crystal showing the forms *s* (111) and *n* ($\bar{1}$11).

„ 2. The same, with oscillation of (131) on *s* and of *c* on *n*.

„ 3. Freehand drawing of a pseudomorphic opal crystal in similar position and showing the trace of the basal cleavage on *n* and striations supposed to be due to oscillatory combination of *s* with (131).

„ 4. Projection of a glauberite crystal on a plane perpendicular to the zone axis *s s'*.

„ 5. The same with traces of basal cleavage and (131) oscillating with *s*.

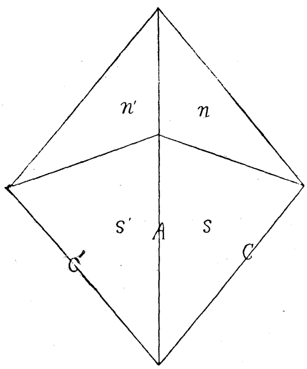
„ 6. Freehand drawing of pseudomorphic opal crystal in similar position showing cleavage traces.

„ 7. Projection of glauberite crystal on (010).

„ 8. The same with oscillation of (131) on *s* and of *c* on *n*.

„ 9. Freehand drawing of pseudomorphic opal crystal in similar position showing striations on *s* and cleavage traces on *n*.

Note.—*n'* in the right hand half of fig. 4 should read *n'''*, and in the left hand half *n''*.



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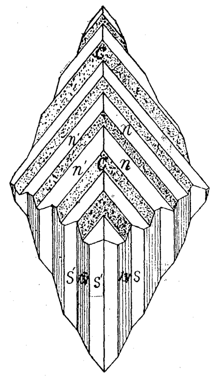

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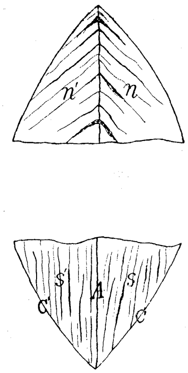

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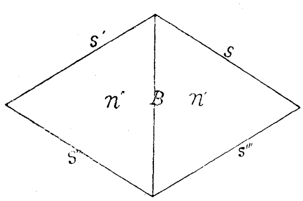

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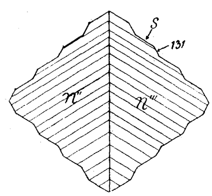

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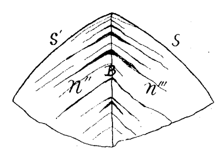

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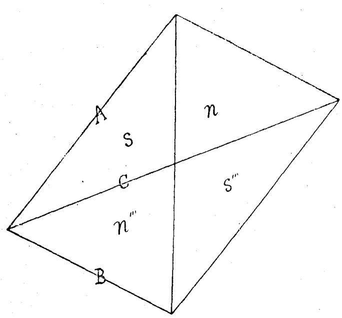

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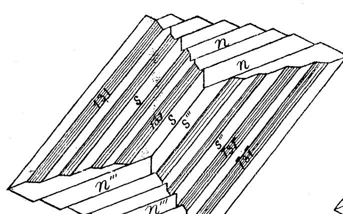

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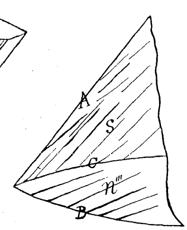

9

C. Anderson, del.,
Austr. Mus.

CORRECTIONS.

Page 34, in description of text figure—for "*b*" read "*B*."

„ 83, line 7—for "and" read "with."

„ 92, line 16—for "anhrydrous" read "anhydrous."

„ 134, liue 14—for "orthogonal" read "orthographic."

„ 256, footnote—for "portion" read "position."

„ 367, line 18—for "off" read "of."

„ 390, line 21—for "born" read "borne."

„ 393, line 18—for "dessication" read "desiccation."

„ 404, line 18—for "the faint line" read "a faint line."

Plate xx. explanation line 7 add *o* (112).

„ xxvii.—read xxviia.

Plates xlii., xliii., xlv., at foot of plate—for "H. Barnes, Junr., read "T. Whitelegge."

Plate liii—substitute the plate inserted in part 5 for that previously issued in part 4, on which the figure numbers were omitted.

„ lxxii. explanation—for "Rosewell" read "Russell."

lxxii explanation—for "dessication" read "desiccation."