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PALAEOPEDOLOGY OF THE MURRAY RIVER REGION BETWEEN MILDURA AND RENMARK, AUSTRALIA

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Introduction

'In dry climates, where water seldom or intermittently leaches rocks, saprolitization does not occur, although fossil saprolites, indicating earlier more humid conditions, may be present'. Dorothy Carroll (1970)

This describes well the study area with which this *Memoir* is concerned. The sediments of the region (and so the substrate for the soils) consist chiefly of silica (fine sand) and clay. They have originated in the humid zone of the Great Dividing Range. Silica is a stable primary mineral, and clay a stable secondary mineral. Silica results from the weathering and erosion of igneous and sedimentary rocks, while clay is a common product of that process. The long traction of the sediments and the low dynamics of the river system in the Murray River have resulted in only the finer fraction reaching the study area. Coarser sediments are common on the E. side of the Murray Basin, but finer sediments characterize the W. side.

Water, the solvent par excellence, is active both in the provision of these sediments and their transport to the sedimentary plain. But water is scarce in the region W. of the Dividing Range, so carbonates (calcite, dolomite), sulphates (gypsum) and chlorides (halite) accumulate at the surface of the terrain. For the minerals involved, see Segnit, this *Memoir*.

In the accompanying paper on the geology and geomorphology of the region, tectonic movements are described that have led to the sinking of the area and the preservation of paleosols by burial. On the other hand, the surface of the plain (disregarding discontinuous superficial deposits) is of Pliocene/Pleistocene lacustrine clay and sand N. of the Murray River, and Pleistocene dune sand S. of the river. The surfaces are relict. In the incised river valley tract, a significant area is occupied by Pleistocene terrace sediments (Rufus Formation). This antiquity of surfaces leads to many polygenetic profiles. On the other hand, the dunefields and the lunette on the E. side of Lake Victoria have preserved series of paleosols.

The dryness of the country, combined with the general fineness of the sediments, leads to

1. Considerable wind traction of sediments, with dunes as a common landform. As the E-W. dune system and the lunettes are relict, this process was more active in the past.
2. Wind-winnowing with airborne fine sediments as a result. The increase of this process during droughts indicates that it must have been a major factor during still drier periods in the past. Thus
    (a) More clay and silt are found in sand dunes (geomorphic highs) than would be otherwise expected.
    (b) Because of the accumulations of mineral salts on the terrain, these likewise become airborne, resulting in more accumulation in the dunes and elsewhere than would be otherwise expected (e.g. Gill, this *Memoir*, Fig. 10).

Thus the geologic and geochemical characteristics of this dry land make their unmistakable impress on the soils. In the humid areas seaward of the Dividing Range, these strongly alkaline conditions are replaced by neutral to acid ones. Iron is there accumulated in podzolic hardpans and as pedalferric nodules. The murray River country is marked by the bright reds and yellows of a highly oxidized terrain, but the carbonates prevent the accumulation of iron. On the other hand, pyrolusite is ubiquitous. In the study area it occurs in sediments, on ped and crystal faces, on opal, on carbonate nodules, on silcrete, on fossil bones, and so on. It occurs, often as dendrites, on Aboriginal skeletons, including Upper Holocene ones.

An interesting project would be to quantify and date the accumulation of pyrolusite, so that it could be used for relative dating. This would be possible in the humid areas also. In Western Victoria (a given climate), the accumulation of maghemite on a given substrate (basaltic ash) on a given slope (volcanic ash cone) is a function of time; the same applies to the associated pyrolusite. Also with time the profile deepens and becomes more complex (uniform/duplex). The maghemite nodules increase in size with time, beginning as dust and passing through sizes only a few millimetres in diameter to pea-size, and sometimes larger. Under the conditions defined, maghemite dust has formed in the Holocene, while the minute nodules are latest Pleistocene to earliest Holocene. The youngest profile with pea-size buckshot gravel is 20,000-25,000 years old (Camperdown). Manganese dioxide was used as an age indicator in the dry Tule Springs country in U.S.A. (Shutler 1968).

Pyrolusite accumulates in the acid humid areas and in the alkaline dry areas as well because its solubility is not affected by pH. 'Under highly oxidizing conditions MnO_2 is the stable phase over the whole range of pH' (Mason 1966, p. 171). The dry country thus acts as a huge fractionating column separating the manganese from the iron. Manganese so accumulated on a terrain over a long period could later be washed into shallow seas and form the manganese-rich sediments of this type known from various parts of the world. It may well be that such deposits could assist palaeoclimatic interpretations. Tindale (pers. comm.) says manganese dioxide was used by Aboriginals as a paint.

As no pedologist could be found to prepare an account of the palaeopedology to include in this volume, the present writer (a geologist) has written this paper because the paleosols are a key to a number of aspects of the geologic history. They provide time datum planes through strongly interdigitating sediments, they trace the palaeoclimatic change from humidity to aridity, they mark out the evolution of diverging climatic patterns landward and seaward of the Dividing Range, and they measure the pulse of the stable/unstable phases in the extensive E-W. dune system. See Gill, this *Memoir*.

Three Soil Types

In the stratigraphic sucecssion, three grossly different soil types register in the rocks major changes in the environment between the Pliocene and the present:

3	Soils accumulating carbonates	Quaternary
2	Soil accumulating silica	Plio/Pleistocene
1	Soil accumulating iron (lateritic)	Pliocene

Chronology is discussed in the accompanying paper. Each of the above soil types registers a different climate, and each records a steady state condition of the terrain which allowed the pedogenic processes to continue for a long time. Each of the soil types was developed over a large area (at least 250,000 km^2), and the general geomorphology has been that of a flatland. Each buried soil represents a stratigraphic disconformity. In the dry country, a paleosol represents a depression of the dune morphology. Most paleosols were eroded before being buried under a new formation.

The present carbonate soils are not well understood. The early settlers came from humid land and did not understand them at all. The methods imported from their homelands caused havoc to the topsoils, leading to extensive erosion and widespread dust storms. This has now been brought under considerable control, but it can still be questioned whether there is not too much disturbance of the surface leading to erosion and loss of fine fractions plus humus. Soil is 'one of the most important natural resources'. The ash and charcoal of Aboriginal middens are probably the most sensitive materials to erosion on the landscape, yet such materials up to 2,000 yr old are found in the surface soil showing that the land surface presently in a state of erosion had been stable for a couple of millenia. The youngest soil of all is a thin carbonate crust on fans developed on the slopes of the W. shore of Lake Victoria. This crust is now being rapidly removed, but its age by radiocarbon dating of carbonized twigs is 'modern' (therefore less than 200 yr) so this erosion has occurred since European occupation.

Lateritic Profile

1. *Yelta, Victoria*

The oldest buried soil found in the study area is a massive mottled zone of a lateritic profile. I am indebted to Mr G. Blackburn of C.S.I.R.O. Division of Soils for examining the occurrence for me and confirming that it is lateritic. Figure 1 provides a section of the Murray River cliff on the S. (Victorian) side at Yelta, W. of Merbein and E. of the bridge to Curlwaa. Underneath the Blanchetown Clay, and therefore older than it, is the Moorna Formation, characterized by its varied sediments including coarse-grained ones (both exceptional features in this country). This formation is Upper Pliocene (Marshall, Gill, this *Memoir*) and the paleosol is within it at Yelta. The sediments lateritized are poorly sorted sands that include grains 2 mm in diameter, which is exceptional in this region where the normal range is clay to fine sand, but not unusual for the Moorna Formation.

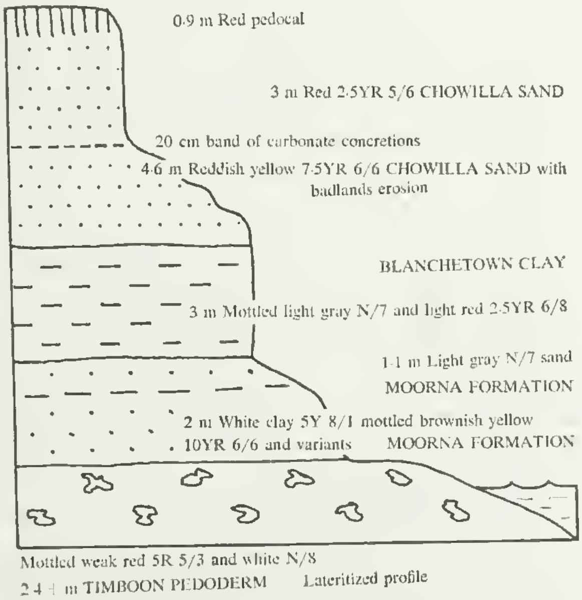

Fig. 1—Surveyed section of Murray River cliff on S. bank at Yelta, Victoria. For map see Gill on Geology of area, this *Memoir*.

The part of the lateritic profile preserved is the mottled zone, which consists here of white N/8 sand with mottles of weak red 5R 5/3 grading to red 7·5YR 4/6 with some minor reddish yellow 7·5YR 6/6. A rhizomorph about 6 mm in diameter was noted and a burrow about 3 mm in diameter set obliquely. This horizon is strongly compacted, and forms a ledge at the foot of the cliff, although this is mostly covered with wash from the cliff. High river levels sweep parts of it clean for a while, but at the W. end where the river impinges on the cliff, the outcrop can always be clearly seen. The mottles are usually 15-25 cm in diameter. On the day of the survey 2·51 m of the mottled zone was exposed, but it could be seen continuing down some distance under the water of the river. It is difficult to be sure of the underwater extension, but it was judged to be at least as deep as the section exposed.

The sediments lateritized are of riverine facies, and apparently were part of a fluvatile plain or terrace, sufficiently high to be drained in the dry season. The terrain almost certainly supported a subtropical rainforest (Gill 1961 a, b). The climate was of the monsoon type, with leaching warm copious waters in the wet season, followed by a dry season when the water table fell and air entered to oxidize the rocks. No greater contrast is possible than this rainforest palaeo-environment with abundant deep-leaching acid waters, and the present semi-arid sparsely-vegetated terrain with shallow strongly alkaline soil.

2. *Paringi, N.S.W.*

On the Sturt Highway between Euston and Mildura, 29 km from the latter on the N. side of the Murray River where it meets the highway, badlands erosion has exposed the section shown in Fig. 2. This section was surveyed from a lone tree on the W. side of the de-

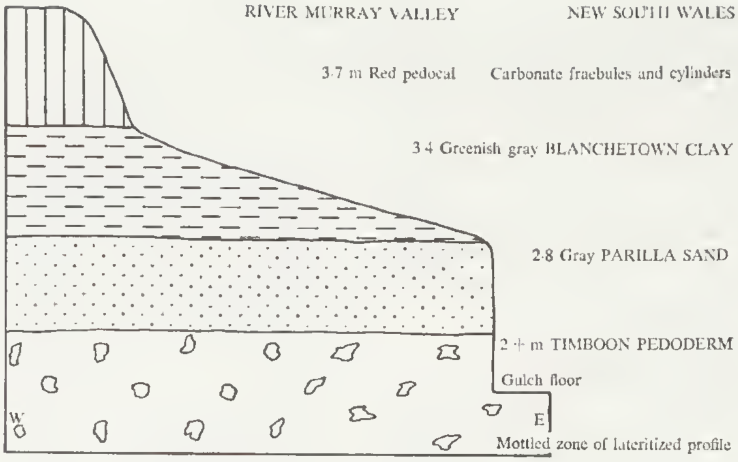

Fig. 2—Surveyed section of Murray River cliff on N. bank at Paringi (not Paringa), N.S.W.

bouchement of the gulch to its floor. Beneath the Blanchetown Clay is a gray clayey fine sand presenting vertical walls along the gulch, all of which characters belong to the Parilla Sand, so the sediments are referred to that formation. Below this a very compact mottled zone occurs with nearly 2 m outcropping, but continuing to a greater depth as was proved by a spade hole. The background varies from white N8 to light gray 5Y 8/1 with mottles up to 18 cm diameter, although these may coalesce into larger sizes. The mottles are red 2·5YR 4/8.

If the formation with the paleosol is Parilla Sand or older, then the fossil soil is developed in an older substrate here than at Yelta. This need cause no surprise. Evidence of intraformational erosion is widespread. The paleosol occurs only as remnants, and the A horizon is nowhere preserved. At Paringi, a channel 4·5 m wide is cut in the top of the mottled zone, and is c. 1 m deep. Above the mottled zone is a hard layer c. 18 cm thick, but it is not present over the channel. The hard layer consists of coarse sand to laminated silt. In the channel is a variety of sediments with current-bedding.

A lateritic profile infers tectonic stability for a considerable time, while widespread erosion infers terrain instability. The latter was probably caused by the Kosciusko uplift.

3. *Distribution*

Rowan and Downes (1963, p. 17) record lateritic profiles in NW. Victoria. One locality is Robinvale lock, where Segnit (this *Memoir*) has proved kaolinite. The writer (Gill 1966) has recorded a lateritic profile at Ultima in N. Victoria. At Tammit Station c. 14 km from Euston, N.S.W., I noted below the homestead a platform of ferricrete 1-1·5 m thick extending c. 80% of the distance across the river. The material was tested with a penetrometer and found to vary from 6 kg/cm² to hard solid ferricrete. Colour varied from yellowish red 5YR 5/6 to very dusky red 7·5R 2/2, and the substrate from silty to sandy gravel. Disconformably over the ferricrete there was mottled clayey fine sand to sandy clay, which was light gray 5Y 7/2 to white 5Y 8/2 with reddish yellow 7·5YR 6/6 mottles 1-20 cm diameter. The top metre of this formation was somewhat concretionary, forming a shelf on the shore; it varied from 12 kg/cm² to solid. The clay just above the ferricrete had some rhizomorphs. A bore is needed to prove whether or not this is a true lateritic profile.

A very extensive literature exists on lateritic profiles in Australia, but some dealing with adjacent areas are Blackburn and Leslie (1958), Dury (1971), Faniran (1970), Firman (1967), Grubb (1971), Jessup (1960 a, b) and Twidale (1972).

4. *Age and Nomenclature*

The A.O.G. oil bores show that this paleosol overlies marine Cheltenhamian (uppermost Miocene) sediments. At Yelta the paleosol is in the Moorna Formation which is Upper Pliocene. This dating fits the evidence available in S. Victoria (Gill 1971). Fisher (1958) has pointed out the importance of lateritization as a concentrator of minerals. I think that the large concentrations of alluvial gold found in Victoria were a function of deep kaolinization of the bedrock, followed by fluviatile sifting to remove the saprolite.

The laterite constitutes an important time datum plane through very variable rocks. It is the only paleosol that can be traced with confidence landward and seaward of the Great Dividing Range, and indeed over the whole of SE. Australia. Fig. 3 shows diagrammatically the contrasting series of main pedologic types N. and S. of the Dividing Range in a section from the study area to the Western District of Victoria (Gibbons and Gill 1964).

The laterite profile is the only common denominator

With respect to nomenclature, the writer thinks that the close association of a paleosol with an ancient terrain can best be expressed by using the same name. In SE. Australia laterite is associated with the Timboon Terrain (Gill 1964), so applying the term of Brewer et al. (1970), the nomenclature would be the *Timboon Pedoderm.*

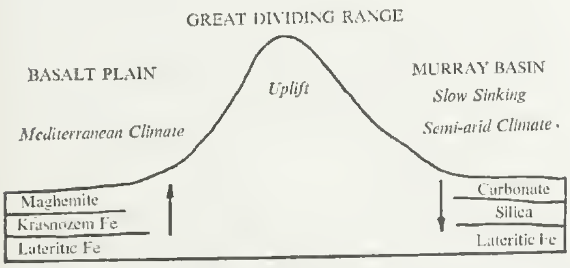

Fig. 3—Diagram to show the different existing ecologies N. and S. of the Great Dividing Range along a section from the study area to W. Victoria. The succession of soil types from the Pliocene to the present is shown for each region, indicating that in the Pliocene the two had similar ecologies, viz. monsoonal rainforest producing lateritic soil profiles.

Soil Accumulating Silica

1. *Stratigraphic Occurrence*

The lateritic profile accumulated non-magnetic alpha iron oxide. Higher in the sequence is a paleosol that accumulated silica. It formed common opal in clay and dolomite, while in sand it formed a range of rocks from lightly bonded silicified sandstone to ringing silcrete. The Timboon Pedoderm occurs in the Parilla Sand and the Moorna Formation, while the silica-amassing pedoderm occurs in the younger Blanchetown Clay and Chowilla Sand. This statement applies to the study area, which is on the down-warped side of the Pinnaroo Block, involving the Lake Victoria Syncline. On the geomorphic highs other relationships are possible. At the Chowilla dam site, the silicified zone occurs on but not in the Parilla Sand. Firman (1967, p. 170) says the siliceous cap is on the *eroded* surface of the Parilla Sand. This is the Karoonda Surface or Terrain (Firman 1966), and so applying the nomenclatorial principle defined above, the paleosol would be called the *Karoonda Pedoderm.*

2. *Distribution*

This pedoderm is very widely distributed, and in many places influences the cliff profiles. Both the opal and silcrete were widely used by the Aboriginals for implements. The Karoonda Pedoderm is present in the Chowilla dam area, along Salt Creek (Pl. 32, fig. 1), at Cal Lal, on Nampoo, Warrakoo, Moorna and other stations along the river, at Merbein, and along the river further to the SE., including Robinvale. Indeed it is almost ubiquitous. Pedogenic silcrete is common in the dry interior of Australia. A vast literature is involved, but it suffices for the present purpose to mention the work of a geomorphologist (Mabbutt 1965), a pedologist (Stephens 1971), and a geologist (Wopfner, H., and Twidale, C. R. 1967). In Central Australia it is common for silica to be found in various parts of the lateritic profile. Much difference of opinion has been evident as to the cause of such occurrences. It is pointed out that in the Lake Victoria syncline there is an extended (and not telescoped) sequence. The siliceous horizon is later than the lateritic profile, so the possibility should be considered that in non-depressed areas these two horizons could be telescoped, i.e. the profile is polygenetic.

3. *Age*

The Parilla Sand and the Moorna Formation are Pliocene in age (Gill, this *Memoir*). As the age of the succeeding Blanchetown Clay is not known with accuracy, it is called Plio-Pleistocene. The Karoonda Pedoderm has not been found in the stratigraphic sequence higher than the base of the Blanchetown Clay. It is commonly in Chowilla Sand under the clay. These two formations interdigitate strongly, and the paleosol is a time datum plane through them. On Salt Creek, Kulcurna Station, the paleosol can be traced from Chowilla Sand into Blanchetown Clay and then into Chowilla Sand again. In the latter, the horizon consists of silicified sand, while in the Clay it consists of common opal. Segnit et al. (this *Memoir*) have described the nature of the opal in the Karoonda Pedoderm at Sharp Point (N. bank of Murray River) on Nampoo Station, E. of Cal Lal (Pl. 32, fig. 2). There two opal horizons occur in this the thickest known section of Blanchetown Clay. A gell-like material under the lower opal proved to be highly disordered sodium montmorillonite. Celestite occurred between the two opal beds; barytes and sepiolite were found but not *in situ* (Segnit, this *Memoir*).

4. *Climatic Association*

The lateritic profile (Timboon Pedoderm) is associated with tropical or subtropical monsoonal conditions, but the Karoonda Pedoderm is associated with the incoming of the present semi-arid conditions. On the E. wall of Salt Creek on Kulcurna Station, where the Blanchetown Clay lenses out to nothing (an old lake shore) towards the south, a black clay yielded palynologic evidence of a flora directly comparable with the present semi-arid one (Churchill, this *Memoir*). A short distance above these fossils in the same section is the silicified sandstone of the Karoonda Pedoderm. This paleosol is therefore a little younger than the changeover from the previously humid climate to the present dry conditions. The Sharp Point section on Nampoo Station c. 10 km to the E. shows that a lake dried up and the soil was formed on its floor. The dolomite is interpreted as a function of a drying up of saline waters. Rhizomorphs show that trees or shrubs grew on the old lake floor. After the paleosol was developed, lacustrine conditions returned, and the water was fresh as is shown by the ostracod fauna.

In the cliffs near Kulcurna Station, and on Salt Creek, there are widespread siliceous rhizomorphs that bear witness to the existence of a land surface, a soil, and vegetation.

In many places (e.g. in cliffs on the W. side of Six Mile Creek on Neilpo Station, and in the Bone Gulch area on Moorna Station further W.) deposits of gypsum characterize the lowest part of the Blanchetown Clay. At Six Mile Creek rosettes and other crystalline masses of gypsum have been seen up to 0·5 m in diameter. The site was worked commercially at one time. This horizon of gypsum could be due to a period of drying up that followed the freshwater phase indicated by the ostracod bands. (For stratigraphy and palaeontology, see Gill this *Memoir*).

Pedocals

Three minerals characterize the terrain in the study area at the present time—a carbonate (calcite), a sulphate (gypsum) and a chloride (common salt). All are present in both earthy and crystalline forms. The carbonate is particularly abundant. In the soil profiles it occurs in earthy form, as fracbules, and as a solid hardpan. It has been estimated that on the average there are in this country $\sim$ 800,000 metric tonnes (or tons) per km^2. Commonly the profile at the surface is polygenetic, as successive deposits of carbonate and radiocarbon dates establish. The persistence of all this carbonate at the surface bears witness to the persistence of semi-arid conditions over a long time preventing its solution and removal. These successive carbonates record the pulse of palaeoclimatic change.

No greater pedogenic contrast could be provided than the calcite fracbules of the highly alkaline terrain of the study area, and the maghemite nodules (gamma iron oxide) requiring an acid water-logged soil for their normal formation. Neverthess, buckshot gravel is found in this region. It was noted c. 50 km W. of Cobar, N.S.W., and in Cobar itself. W. of the railway station at Diapur, Victoria (422 km from Melbourne, elevation c. 198 m) a cutting reveals at the top some 2 m of calcareous clayey fine sand with derived buckshot gravel (maghemite fraebules). The fraebules are quite out of character with the calcareous terrain, and belong to some previous period of more humid conditions.

N. of the Murray River in the study area, the general terrain is one of Blanchetown Clay with surficial sand. Here the carbonate fraebules are at or near the surface. S. of the Murray River, the terrain is dominated by a system of E-W. dunes with two or more paleosols marked by aggregations of earthy carbonate. Beneath the dunes are hard calcitic fraebules as are found at or near the surface N. of the river. The geomorphology and stratigraphy of these paleosols is given in an accompanying paper (Gill, this *Memoir*). In that paper the evidence for climatic oscillation is given. Alternate phases of terrain stability and instability existed. The paleosols are associated with the stable phases, when the climate was more humid, because the carbonates were carried down to the B horizon instead of accumulating at the surface. Southward of the Dividing Range, during the drier phases, carbonates developed in the B horizons in areas where no carbonates accumulate at present (Gill 1973). Where carbonate deposition is well developed, the amount of mineral present is far more than could possibly be derived from the rocks present, so must have been transported in. On the geomorphic highs at least, the transport must have been aeolian—further evidence of terrain instability. Firman (1969) has referred to this pedocalcic complex as the Bakara Soil, which, following the nomenclature of Brewer et al. (1970), would become the Bakara Pedoderm.

1. *Carbonate Glaebules*

Blandowski and many other early explorers comment on the 'numerous nodules of limestone' in the dry country. As they came from a humid country, these would be strange to them, but they are certainly characteristic. X-ray analysis shows the mineral to be calcite. All the nodules have amorphous centres. Some are completely amorphous and various sizes of this type up to 15 cm diameter have been sectioned. Such are crystalline and compact throughout. Others have the exterior covered with fine laminations of calcite, but the laminated part is a smaller proportion of the diameter than the amorphous part. A third type consists of nodules that have been incorporated in a larger nodule. The principle of super-position applies here, and the nodules incorporated in the middle of the large one must be older. The smaller nodules are commonly 2-3 cm in diameter, while the compound ones occur up to 20 cm in diameter. Plate 33, fig. 1 shows a section through such a nodule. A comparatively rare type is the septarian nodule, and is characterized by cracks over its surface that have been infilled since formation. The cracks are pronounced on the upper surface but fade away on the lower surface. They appear to be a function of long exposure. One of these was black, but the colour disappeared on firing in a crucible so the black material was apparently organic. Other black nodules owe their colour to being used by the Aboriginals as oven stones.

2. *Ages of Carbonates*

The oldest soil at the present surface is represented by the top 6 m of the terrain on the N. side of the Murray River, where it is developed mostly in Blanchetown Clay. It is illustrated by the cover picture of this *Memoir*. Superimposed on this is the complex of calcrete-bearing soils, which extend down over eroded surfaces to within about 6 m of the river level, e.g. at Moorna E. oxbow lake. Smaller, less regular fraebules occur on the Rufus Formation, a ?Mid-Pleistocene terrace in the present valley tract. The E-W. dune system, best developed in the study area S. of the Murray R., is characterized by a series of pedocals that have amassed earthy carbonate, which also is calcite. The large lunette on the E. side of Lake Victoria has red paleosols, and the amount of carbonate amassed is small. The lunette onlaps relict 'islands' of Rufus Formation, and so is younger than that formation.

As the paleosols are of considerable importance for stratigraphy, they are discussed under that section in the accompanying paper, as also is the chronology. The youngest soil dated gave a modern age on charcoal, and this shows that the process of carbonate deposition is continuing at present. Paleosols of the order of 16,000 yr and 28,000 yr B.P. are recorded from the E-W. dune system, these dates according well with those of other workers. Under the dune at Berribee Station was a paleosol exceeding the range of C14 (> 34,300 yr, N.Z. R2729/3).

A complex calcite fraebule, such as that illustrated in Pl. 32, fig. 1, gave a radiocarbon age of 27,800 ± 1,900 yr B.P. (GaK-1727) for the outermost 5 mm of the laminated cortex, 28,000 ± 1,800 yr (GaK-1728a) for 5-10 mm from the surface, and > 31,700 yr (GaK-1728b) for the small included fraebules forming the centre of the nodule. The specimen came from the inland end of the Moorna E. oxbow lake on Moorna Station, W. of Wentworth, N.S.W., where the nodules are grubbed from the ground for road-making. Solid pans of calcrete appear in places. Dr T. A. Rafter of the New Zealand Institute of Nuclear Sciences expressed interest in these nodules so some were forwarded to him. He analysed one with the following results:

R2182/2A	Outer layer	$\delta\,^{13}C$ wrt PDB — 5·2‰	18,800 ± 380 yr B.P.
R2182/2B	Intermediate layer	$\delta\,^{13}C$ — 3·3‰	34,400 ± 100 yr B.P.
R2182/2C	Inner layer	$\delta\,^{13}C$ — 3·1‰	33,500 ± 900 yr B.P.

There is not necessarily any contradiction in the results from Japan and New Zealand. Different nodules were assayed, although from the same site. Both obtained younger dates on the outside and older ones in the middle, which super-position demands. The soil is polygenetic, and so evidences of soil formation at various periods are to be expected. In this region, soil formation occurred at roughly 16,000 yr, 28,000 yr and 34,000 yr. Each assay picked up two of these three phases. The matter requires further investigation. In view of the long time gap prior to the 34,000 yr paleosol, the comparatively small fraebules on the Rufus Formation with extinct marsupials that is probably mid-Pleistocene, the lack of understanding of the carbonate cycle, and the surprises that have come from U/Th check on the C14 ages of marine carbonate, I have some doubts about the older calcrete datings.

There is quite an amount of variation in the chemistry of these large nodules because they have incorporated different portions of the substrate, quite apart from any variation in the secondary carbonate. Professor K. Kigoshi has kindly permitted me to quote the following analyses by H. Ito and himself of the nodule he assayed. The first three parts numbered in the table below, are the three portions used for dating, while the fourth is from the very centre of the nodule. The figures are percentages:

	Fe_2O_3	Al_2O_3	CaO	MgO	SiO2	Na_2O	CO_2	H_2O	Total
1.	1·03	2·60	43·0	2·10	12·05	0·257	32·0	3·10	96·17
2.	0·322	0·933	48·5	1·81	6·21	0·214	32·9	3·51	94·40
3.	0·682	1·24	43·6	1·28	15·48	0·328	31·36	1·80	95·82
4.	0·951	1·98	39·1	1·41	22·3	0·338	27·40	2·25	95·74

The three nodule fractions assayed by Rafter, 2A-C respectively, had 35·8, 35·5 and 34·2% of CO_2.

The Moorna Formation (Gill, this *Memoir*) is Pliocene in age, and over it is the Blanchetown Clay-Chowilla Sand complex. Low in this stratigraphic horizon is the Karoonda Pedoderm, but below it (and therefore earlier) were found the sediments which yielded palynologic evidence of the incoming of arid conditions similar to the present. That time is 1·5—2m.y. ago, on present understanding, and more carbonate paleosols than exist would be expected for that period. It is possible that they have been formed and then leached or eroded away, during humid intervals.

For discussion of the dating of these pedogenic carbonates, see Rightmire (1967), Williams and Polach (1969), Bowler and Polach (1971), and Williams and Polach (1971).

3. *Vectors of Carbonate Deposition*

Difference of opinion exists on how carbonate is deposited in the soil profiles of dry lands:

(a) That the carbonate is carried down gravitationally by rain water, i.e. vector normal to ground surface and sense downward.

(b) That the carbonate is carried upwards in solutions rising by capillary attraction. 'Caliches seem to form *per ascendum* by capillarity' (Termier and Termier 1963, p. 402), i.e. same vector but sense upward.

The above two views have been placed in apposition, but this may be a false antithesis. Special conditions are required for capillary action, but when they are present, the rise of solutions may indeed occur. On the other hand, calcrete has been deposited in coarse gravels, where capillary action probably could not occur.

The author's observations suggest that deposition can take place in any vector and in either sense, but that the downward transport of carbonate in solution is the commonest process. That it was in solution is shown by radiocarbon dating. Calcite dust from Tertiary limestones, older paleosols, and such, all combine to form a soil that gives consistent radiocarbon dates over thousands of square kilometres.

Deposition from all directions is shown by the millions of spherical calcrete nodules with a cortex of regular laminations (Pl. 33). Downward movement is shown by Pl. 33, fig. 3, where the large nodules are aggregations of smaller ones united by enveloping laminate calcite, as shown in the section Pl. 33, fig. 1. The small nodules protrude through the bottom, but are thickly covered on top (Pl. 33, fig. 1). The nodules in Pl. 33, fig. 3 are in place, having been exposed by deflation at the edge of the Moorna E. oxbow lake. An excavation was carried out on the flat ground at the NW. end of the lake, and this encountered such nodules in place:

0·15 m	Loose red sand
0·25	Closely packed carbonate nodules with complex ones as in Pl. 33, fig. 1 at the top, merging into
0·76	Scattered nodules in red sandy Blanchetown Clay, merging into
1·5+	Light gray weathered Blanchetown Clay with five layers of softer rather irregular (but generally platey) carbonate nodules, plus some rhizomorphs.

Nearby are areas where a solid harpan covers the calcite spherical nodules (Pl. 33, fig. 2). This locality is at the end of long low slope, and it has been noted that other areas of maximal development of calcrete are so placed. It would seem that the heavy rain that occasionally falls soaks through the loose surficial sand, then accumulates at the foot of the slope where its load of carbonate is deposited on drying out. This also appears to be the process by which the 'indurated layer' on the alluvial fans on the W. side of Lake Victoria (C14 date 'modern') are formed. Nevertheless, the small spherical nodules occur over the whole terrain. These nodules are quarried for the roads, and some of these quarries are on geomorphic highs, e.g. the road up the E. side of Lake Victoria. They are a normal pedogenic product and not evaporites as some have suggested.

Hawley et al. (1968), working in the Rio Grande valley, noted that 'There is a direct correlation between geomorphic surface age and thickness and morphological complexity of associated caliche'. 'Ground water and capillary-fringe processes did not play a significant role in caliche genesis. The C14 analyses indicate that the age of the caliche generally increases with depth. There is strong evidence for aeolian origin of much of the carbonate in the caliche.' These comments apply well to our study area.

In Western Victoria, a thick hardpan of calcrete is covered in some areas by a comparatively thin layer of laminated mammillary calcite (Gill 1973). The hardpan is Last Glacial ($\sim$ 20,000 yr B.P.) while the laminated calcite is Postglacial (~ 8,700 yr). As the hardpan is more or less impenetrable, the younger layer must have been deposited from above and not *per ascendum*. Moreover, the hardpan has developed in aeolianite as the B horizon of a terra rossa. The highly calcareous matrix has been leached almost free of carbonate which has been deposited downwards into the hardpan.

In both Western Victoria and the study area there are some well developed rhizomorphs. As these root casts thin downwards, it is difficult to see how the root cavity (and no more) could be filled with secondary carbonate if it were ascending by capillary attraction. In the study area (and many other sites in the semi-arid country) cylinders of carbonate have been collected loose on the surface, and *in situ*. Some of these are thought to be rhizomorphs that have broken into sections, while others almost certainly are infilled burrows. Such were studied at the N. end of Lake Wetherell in the Menindee district. Some were about 2·5 cm in diameter with irregular sides, and a tendency to a spiral arrangement (cf. Gill, this *Memoir*, Pl. 7, fig. 5). Some carbonate cylinders from apparent burrows were tested for phosphate, but the results were negative.

4. *Lunette Paleosols*

On the E. side of Lake Victoria is a large lunette some 14 km long. It is remarkable for two features:

(a) The sand is a grade finer than is usual for dunes (see grain size analyses, Gill this *Memoir*) due to the general fineness of the sediments in this river regime of unusually low dynamics.

(b) The stratification is mostly subhorizontal. The strong W. winds apparently kept this fine sand in a state of constant blowout.

As a result the paleosols are mostly subhorizontal. Figure 4 shows diagrammatically the basic pattern of paleosol occurrence. However, the red soils frequently bifurcate. The largest number seen was when in drought conditions, the S. wall of a gulch showed five red paleosols plus the columnar gray soil at the present surface (Gill, his *Memoir*, Fig. 42). Aboriginal middens are associated with the paleosols, making possible the radiocarbon dates shown in Fig. 4. This series of paleosols needs study by a pedologist. They reflect more humid conditions in that they are not full of carbonates as is the present terrain.

A comparable suite of fossil soils occurs in the E-W. dune system (Woorinen Formation) of this region. The lowest soil shown in Fig. 4 is of the same age as the youngest found in the E-W. system in the study area. Firman (1969 and references) has applied the name Loveday Soil to the paleosols of the Woorinen Formation.

Paleosol Succession

The sequence of fossil soils described in this paper is thus:

Holocene Unnamed

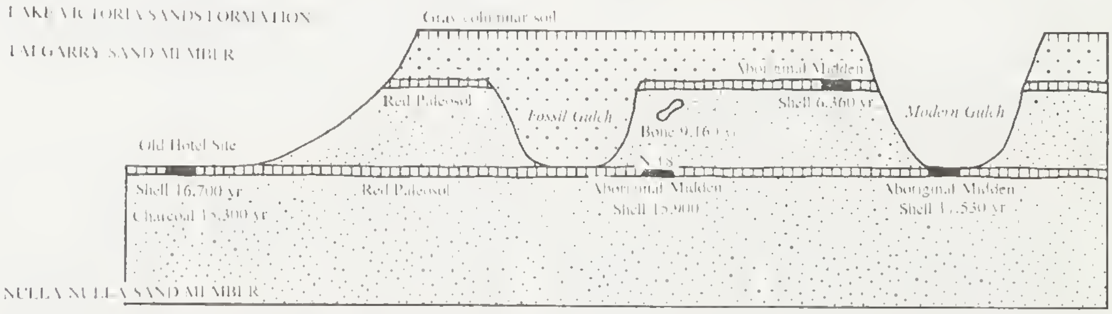

Fig. 4—Diagram of the basic paleosol occurrence in the Lake Victoria Sand (lunette, E. side Lake Victoria, N.S.W.) with chronology. The paleosols are of the order of 6,000 and 17,000 yr old. The latter is the date of the youngest paleosol in the E-W. dune system (Woorinen Formation). In places in the lunette the paleosols divide to give a complex sequence.

Pleistocene	Loveday Pedoderm (pedocal series)
	Bakara Pedoderm (pedocal complex)
Plio-Pleistocene	Karoonda Pedoderm (silcrete/opal)
Pliocene	Timboon Pedoderm (lateritic).

Comment

These notes have been prepared in the hope that they will encourage a full study of the soils and paleosols of this area. Geologically and palaeoclimatologically they have proved to be very significant, and no doubt they will prove to be as rewarding pedologically.

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Explanation of Plates 32-33

PLATE 32

Fig. 1—N. bank of Murray R. at Sharp Point. Nampoo Stn., E. of Cal Lal and W. of Wentworth, N.S.W. (Site 4) showing at base white dolomite (partly replaced by opal) in Blanchetown Clay. Chowilla Sand overlies this, and the sand in turn by another layer of dolomite and opal. When Lake Bungunnia dried up, it ceased depositing Blanchetown Clay and deposited dolomite. Pedogenic processes on the dry lake bed resulted in deposition of silica and formation of rhizomorphs. The Chowilla Sand is a channel deposit. During the re-establishment of Lake Bungunnia, another

dolomite layer was deposited, and the process of silica deposition repeated.

Fig. 2—Exhumed Karoonda Terrain forms a platform on the E. bank of Salt Creek (as it does at Cal Lal and elsewhere), Kulcurna Stn., N.S.W. Opal was deposited in clay or dolomite, while sands were silicified to various degrees. This horizon is the Karoonda Pedoderm.

Fig. 3—Mottled zone of a lateritic profile at the base of the cliff forming the S. bank of the Murray R. at Yelta, N. Victoria. This is the Timboon Pedoderm.

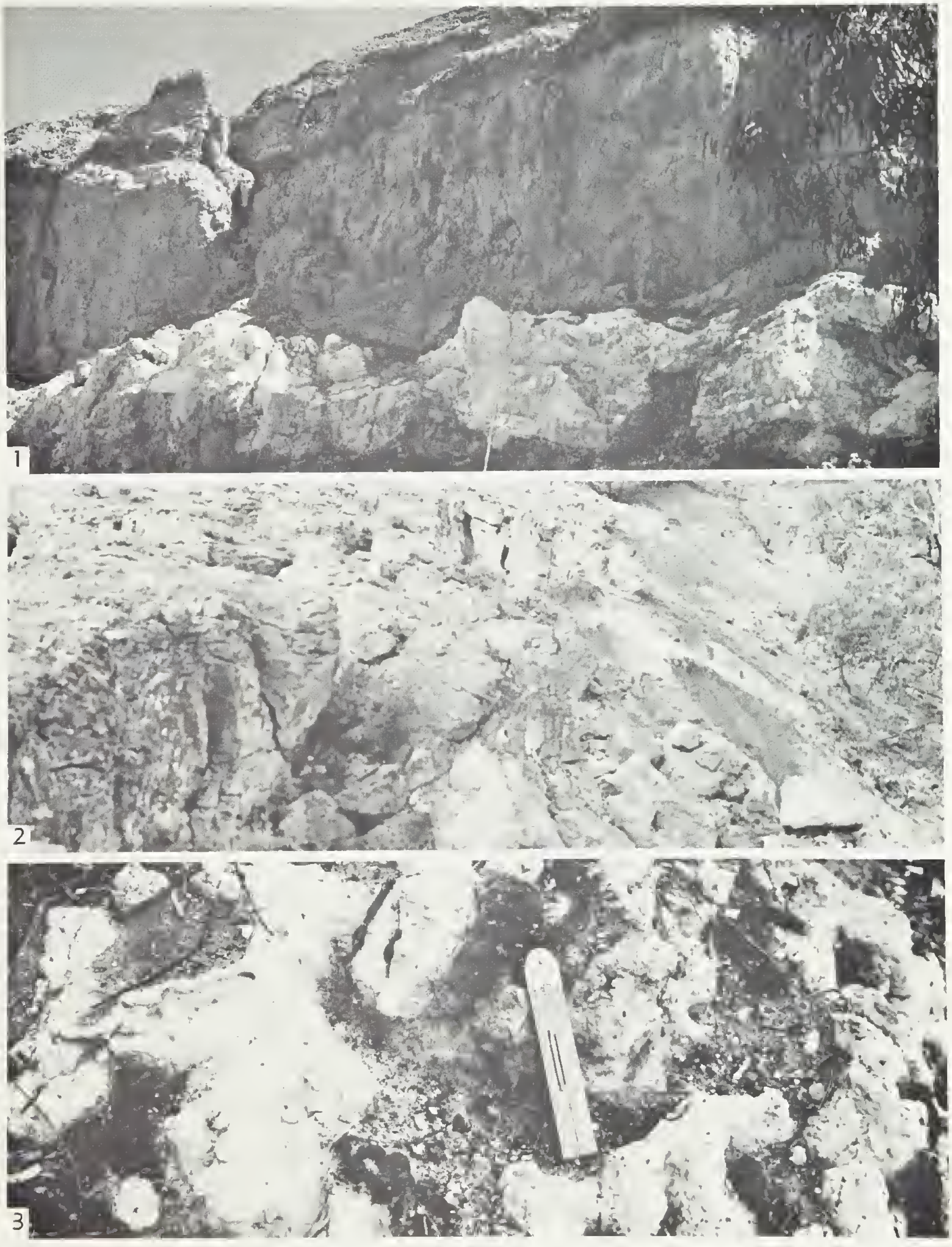
Plate 33

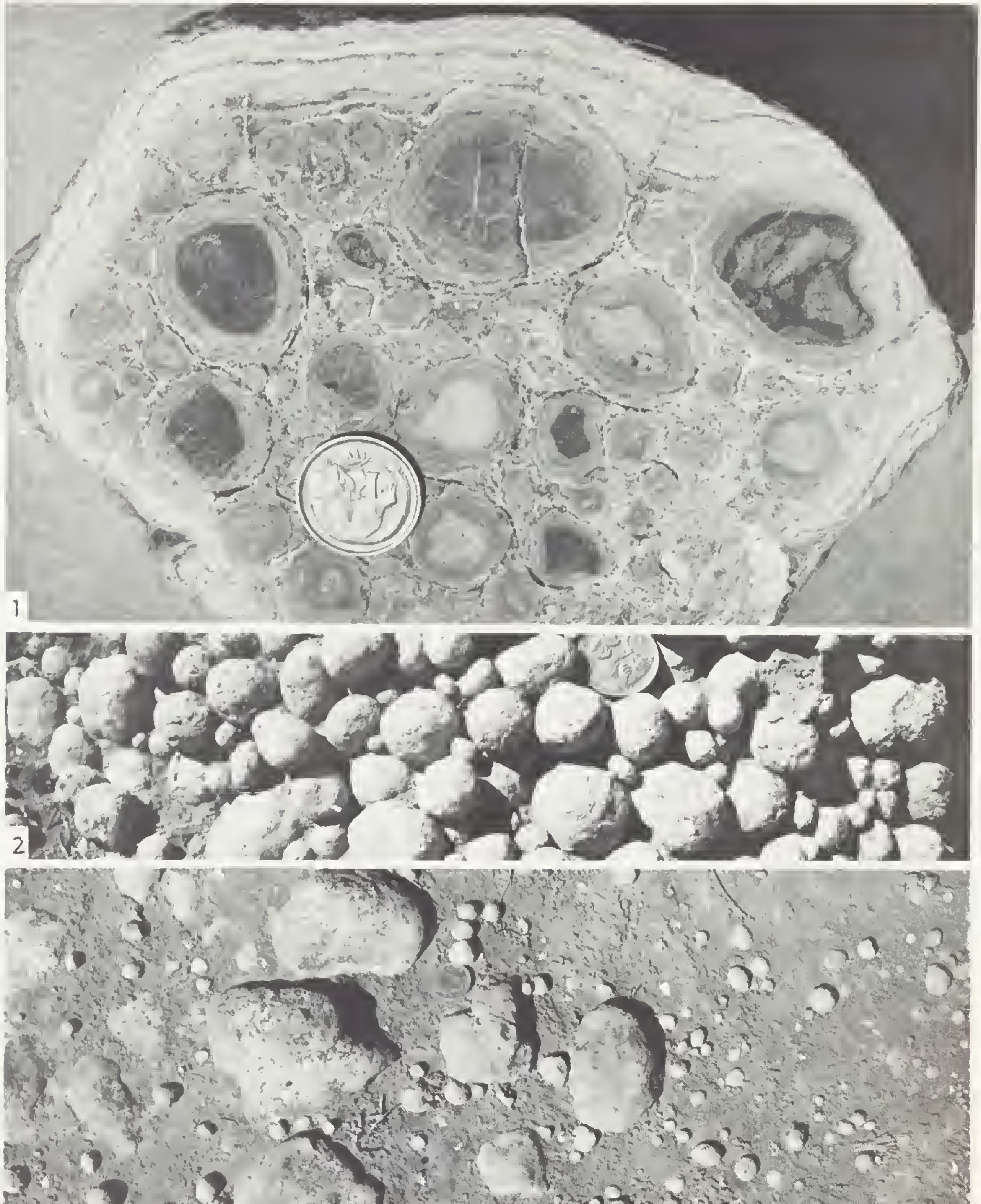
Fig. 1—Polished section through one of the compound nodules at the NW. corner of the E. Moorna Stn. oxbow W. of the Darling Anabranch. Note the older generation of carbonate fraebules enclosed in the laminated calcite envelope. The coin is 1·7 cm diameter. Site 13.

Fig. 2—Same site. Carbonate fraebules as they occur on the ground surface where it has been eroded by wind and rain at the edge of the oxbow cliff. The coin is 1·9 cm in diameter.

Fig. 3—Same site. Large nodules as in Fig. 1 *in situ*, but exposed by erosion. The upper surface has always a thick layer of secondary carbonate. but the enclosed fraebules project out of the thin bottom layer, proving a predominantly downward movement of the carbonate, but the enclosed fraebules project out of the thin bottom layer, proving a predominantly downward movement of the carbonate. The coin is 2·8 cm in diameter.

—All photos by the author.

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