CALCAREOUS CONCRETIONS IN THE LOWER CRETACEOUS SEDIMENTS OF SOUTH-EASTERN ALEXANDER ISLAND

By R. R. HORNE *and* BRIAN J. TAYLOR

ABSTRACT. The morphology, composition and origin of two forms of calcite-cemented concretion are described from the Lower Cretaceous sediments of south-eastern Alexander Island. The larger "cannon-ball" concretions occur in massive sandstone horizons, whereas the smaller "cement-stone" forms are abundant within some of the mudstone beds. The origin of both forms is considered in terms of the relationship between an organic nucleus and the host rock, the grain-size and permeability of the host rocks, and the migration of calcium carbonate in solution. Comparable occurrences of calcareous concretions are also discussed.

Two types of calcareous concretion, which occur in the Lower Cretaceous sedimentary sequence of south-eastern Alexander Island (Fig. 1), are described. Large, carbonate-cemented "cannon-ball" concretions are present in massive sandstone and smaller "cement-stone" concretions occur in massive mudstones.

CALCAREOUS CONCRETIONS IN SANDSTONE

Morphology

Thick massive horizons of feldspathic tuffaceous sandstones are extensively developed in the deltaic facies sequences of the Lower Cretaceous sedimentary succession in south-eastern Alexander Island (Horne, 1968*a*, 1969). Almost every bed of these sandstones encloses large concretions, the majority of which are ellipsoids or oblate spheroids ranging up to 1·5 m. in maximum diameter (Figs. 2, 3 and 4). The field term "cannon-ball concretion" has been applied by the authors to this more common sub-spherical type. However, at certain localities planar rounded bodies of identical material, in places coalescing laterally into a continuous stratum concordant with the bedding, occur in the midst of similar sandstone horizons. The contact of the concretions with the enclosing sandstone is well defined and the weathered surfaces have a typical red-brown coloration.

Where they are developed in laminated sequences they are less regular in shape as a result of the varying permeability of the different lithologies. The trace of the bedding lamination can be seen to pass through the concretion without apparent deflection (Fig. 5a). In one example (Fig. 5b) the trace of the cross-lamination in a yellow sandstone can be followed through a concretion. These observations confirm the belief that these concretions are post-depositional and diagenetic, essentially intraformational structures. In some cases the bedding shows distortion around the concretion, presumably as a result of differential compaction.

The so-called "hollow" concretions are composed of an outer shell of carbonate-cemented material identical to that forming the homogeneous "cannon-ball" concretions, and succeeded inwards by a core of sand (in many cases enclosing an organic nucleus) identical to that outside the shell.

A number of the concretions, particularly those of "hollow" type, are distinctly oblate with their shortest axis normal to the bedding. The concretion shown in Fig. 5c shows thickening of the vertical parts of the shell, suggesting flowage as a result of flattening. In an adjacent concretion in the same bed, however, maximum rim thickness occurs in the horizontal parts (Fig. 5d). The majority of the homogeneous concretions possess a well-defined parting parallel to the bedding (Fig. 4). Radial cracking is characteristic of the thinner-shelled "hollow" concretions (Figs. 5d and 6a).

Composition

The concretions are composed of clasts similar to those forming the matrix sandstone, and they are cemented by calcium carbonate. This cement forms up to 50 per cent of the bulk of the concretions and it is always many times that of the enclosing sandstone. In certain specimens the calcite is coarsely crystalline and the rock has a "poecilitic" texture. Although the clastic material in the concretions is generally similar to that forming laterally equivalent parts

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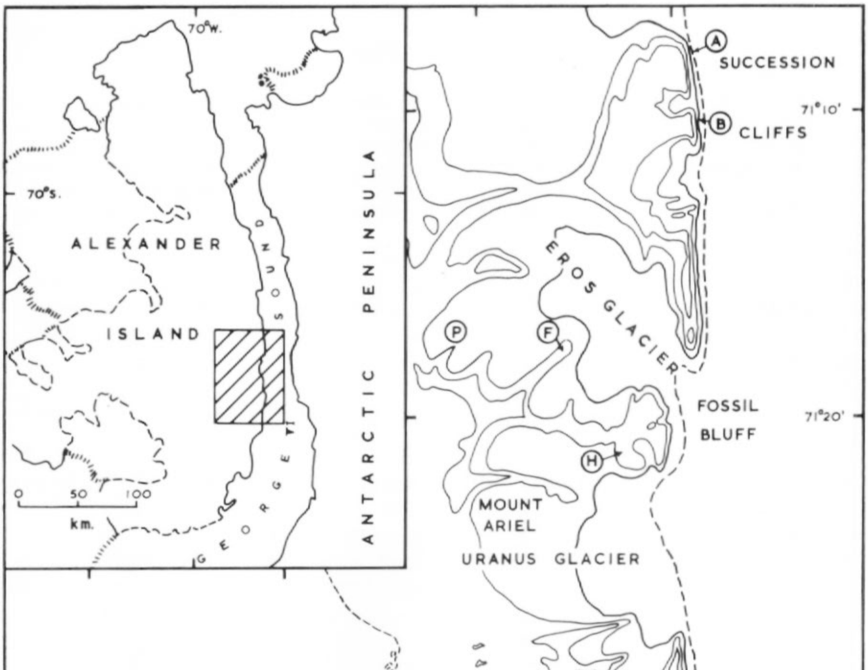

Fig. 1. A map of part of south-eastern Alexander Island showing the locality letters and station numbers referred to in the text. The inset indicates the location of the area in relation to Alexander Island.

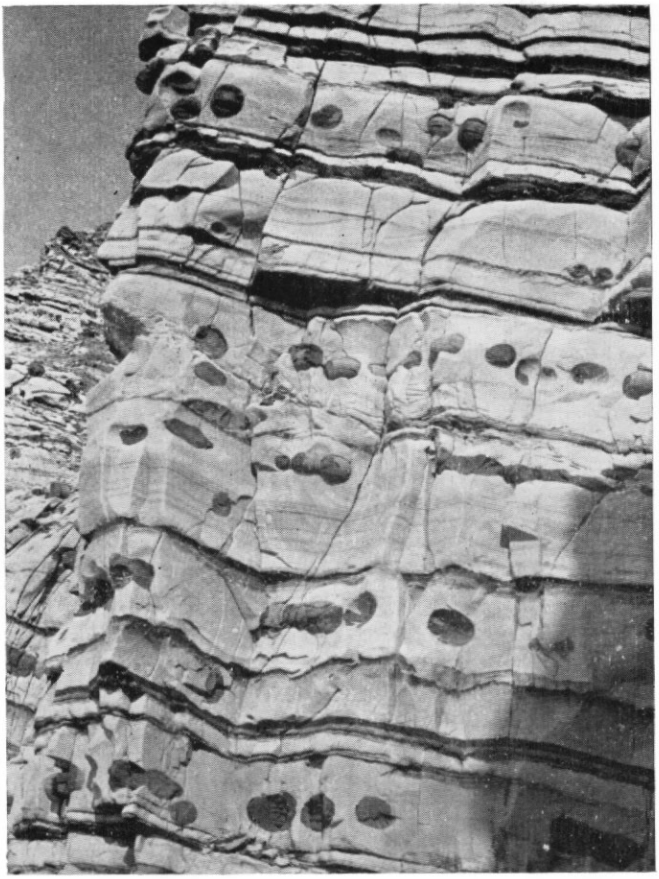

Fig. 2. Red-weathering "cannon-ball" concretions in rhythmically bedded sandstones and mudstones of a deltaic facies at station KG.70. The section in the foreground is approximately 20 m. thick.

of the surrounding sandstone, distinct differences can be seen in thin section. The carbonate cement tends to selectively corrode the detrital grains, the finer intergranular material being preferentially attacked while the large grains appear to have been weakly dissolved and embayed.

Origin

These "cannon-ball" concretions have undoubtedly resulted from the accretion and precipitation of calcium carbonate; it has been carried in interstitial solution around some nucleus of deposition which in some cases is preserved in the core of the concretion. Their development in terms of number, size and morphology within any sandstone horizon was probably controlled by three factors: the availability of suitable nuclei, the presence of sufficient calcium carbonate in solution within that specific horizon and the permeability of the enclosing sediment.

Many of these concretions are obviously centred on a nucleus, which is usually a carbonized plant fragment (Fig. 6a), a fossil shell or a sedimentary fragment usually composed of mudstone (Fig. 6b). There appears to be a relationship between the type of nucleus and the morphology of the enclosing concretion. In those concretions with mudstone nuclei the concretionary material is usually continuous from the margin to the contact with the lithic nucleus. In such a case, the nucleus may have been chemically inert but it apparently had a

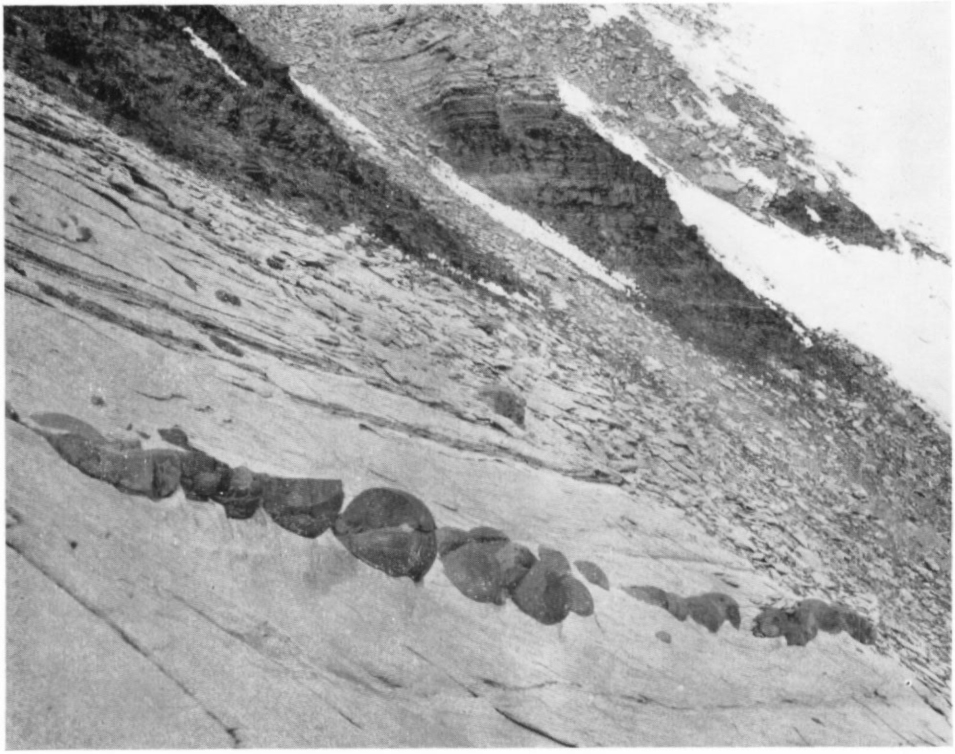

Fig. 3. Brownish weathering cannon-ball concretions arranged along an ill-defined bedding plane within a 25·9 m. thick sandstone at Succession Cliffs (locality A). The overlying siltstones are 12·2 m. thick.

dilatant effect on the adjacent, partially packed sand, resulting in a decrease in pore pressure and migration of solutions of calcium carbonate towards the nucleus (Mead, 1925).

In contrast, the so-called "hollow" concretions (Figs. 5c, d and 6a–d) either have no obvious nucleus or are centred on a plant fragment (Fig. 6a) or fossil shell. It seems probable that the fossil material, whether preserved or not, had a distinct chemical effect on the fluid phase in the adjacent sand, causing the initial precipitation of calcium carbonate in a shell defining the outer limit of this envelope. The chemical effect may have involved an increase in the pH by the release of ammonia or amines from the decaying organic matter (Weeks, 1957).

In certain sandstone horizons, calcite is either sparse or absent and concretions are no[illegible] developed even where suitable nuclei are available. Diagenetic authigenic zeolite (laumontite) is widespread, giving the rocks a mottled appearance, and fragments of sediment are surrounded by laumontite-rich aureoles rather than by carbonate concretions (Horne, 1968*b*).

Another important factor is the degree of mobility of the pore solutions within the sand. The thick, isotropic sandstone horizons persisted in a water-saturated and "quick" or mobile state for a considerable period after deposition. In such horizons true sedimentary structures are absent but gravity structures and inclusions of angular mudstone fragments, apparently derived from overlying fractured beds, are common. "Cannon-ball" concretions are consequently abundant in such massive isotropic sandstones but their development is relatively inhibited in sandstones showing syndepositional structures such as cross-lamination. Where concretions have developed in interbedded sandstones and mudstones, the morphology of the concretion is strongly influenced by the permeability of the different sediment types (Fig. 5a).

The formation of elongated masses of concretionary material broadly conformable with the general bedding of the sediments can be explained as resulting from carbonate deposition

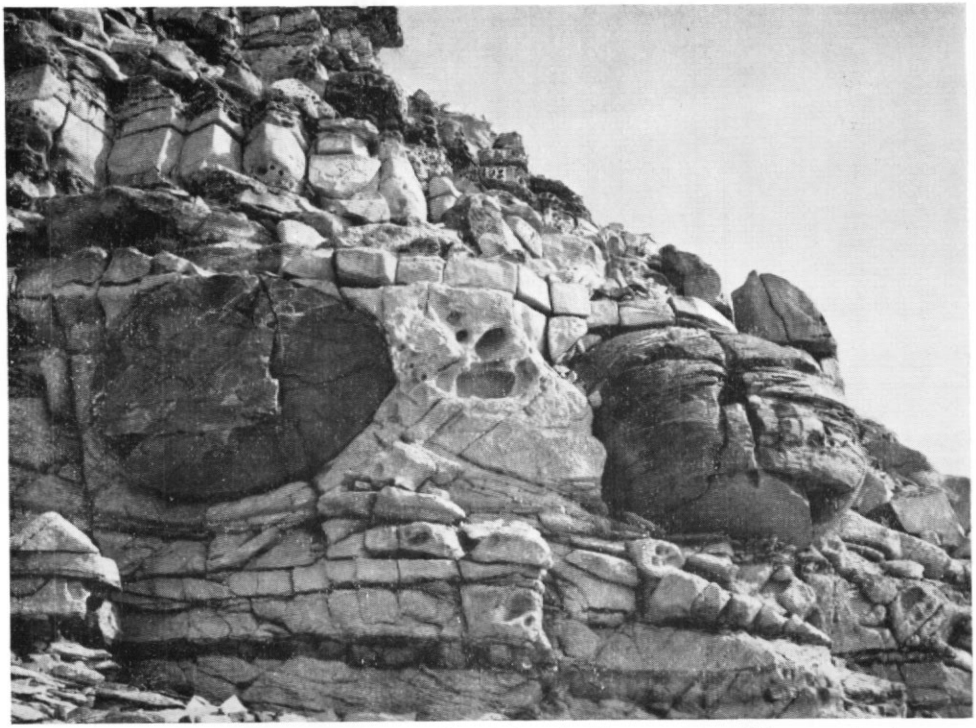

Fig. 4. Brownish weathering cannon-ball concretions 1·2 m. in diameter exposed in a massive honeycombed sandstone at the western end of Mount Ariel.

about part of a bedding surface on which organic material (most probably fragmented plants) was concentrated.

Comparable occurrences

Similar concretions have been described from other circum-Pacific successions showing close lithological, faunal and structural similarities to the Aptian sediments of Alexander Island.

Briggs (1953) has described and illustrated calcareous concretions identical in every detail to those of Alexander Island from the Upper Cretaceous Panoche Formation of the Diablo Range, Coast Ranges, California. Exposures of the Panoche Formation are "dotted with reddish-brown, spherical cannonballs, which attain a diameter of 10 feet [3 m.] or more".

In the Cretaceous sediments of the Patagonian Cordillera, Katz (1963) has observed that "head-size, spherical concretions are very abundant in the La Vega Sandstone", a member of the arkosic Tres Pasos Formation, which is similar in many respects to the arenaceous facies of the Alexander Island Cretaceous succession.

In the Clarence Valley, New Zealand, "sandstones with 'cannonball concretions' are widely distributed in the south-west part of the district" (Suggate, 1958). As in Alexander Island, these concretions are present both as spheroids and as conformable bands of concretionary material. Suggate recorded that the concretionary sandstones also contain "mudstone fragments and bands of mudstone". Hay (1960) observed "calcareous sandstone concretions, ranging up to six feet (1·8 m.] in diameter" in massive sandstones of Maastrichtian age in north Auckland.

Calcareous concretions are numerous in both the Sandebugten and Cumberland Bay Series of South Georgia (Trendall, 1953, 1959). The age of the former sequence has not yet been determined whereas the latter is, in part at least, Lower Cretaceous. These sediments had been

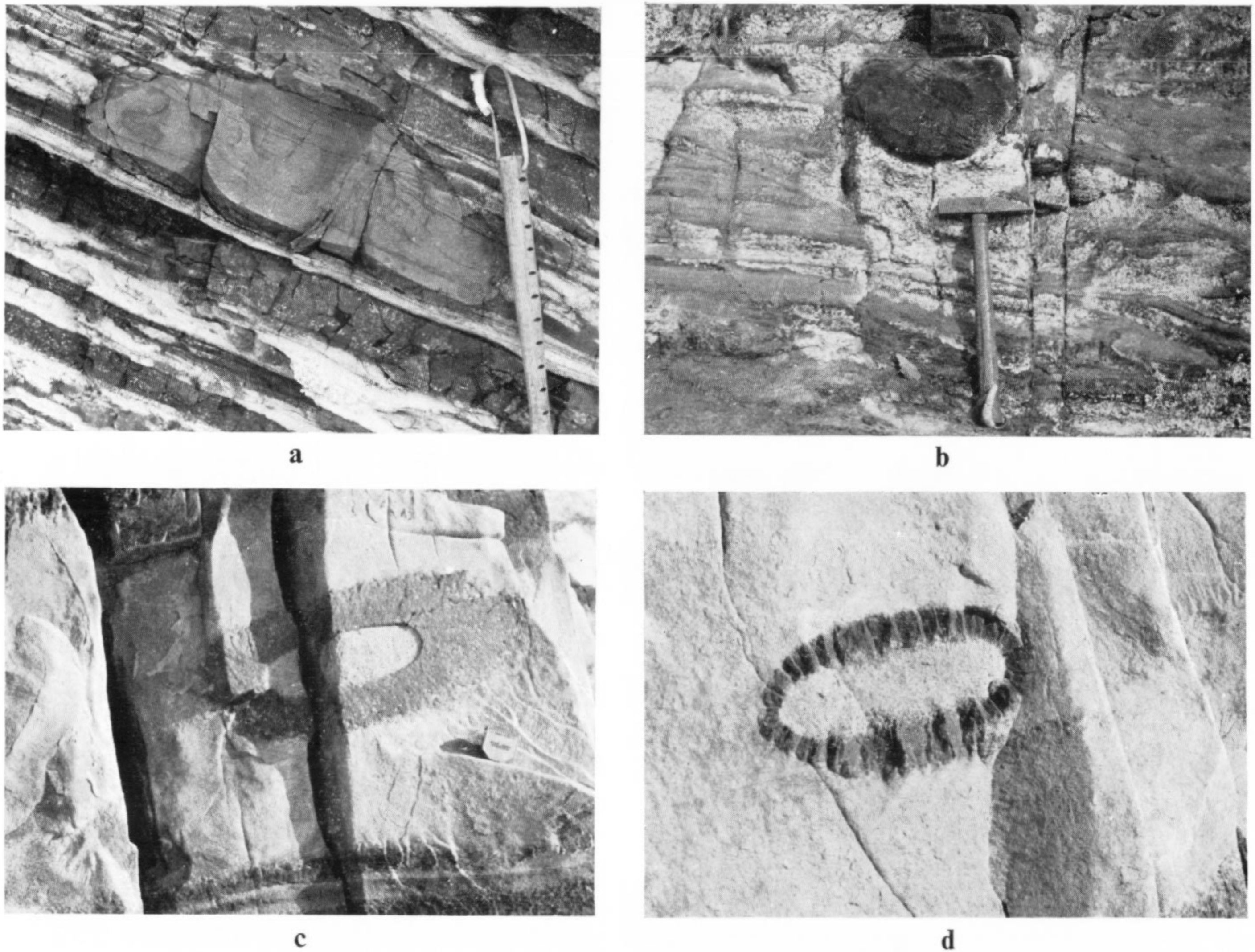

Fig. 5. a. A "cannon-ball" concretion whose morphology is controlled by the permeability of the sandstone–mudstone interlaminations. The trace of the beds passes through the body of the concretion. The hammer shaft in this and succeeding illustrations is scaled in 2·5 cm. units.

b. Cross lamination in yellow sandstone passing through a "cannon-ball" concretion. The hammer shaft is 35 cm. long.

c. An ellipsoidal "hollow" concretion in the sequence shown in Fig. 2. This concretion has a sharp inner margin and a diffuse outer one; the maximum thickness is on [illegible] vertical parts of the rim. The steel rule has a long edge of 5 cm.

d. A similar "hollow" concretion showing strong radial cracking. The long axis of the concretion is 45 cm. This concretion has a maximum thickness on the horizontal parts of the rim.

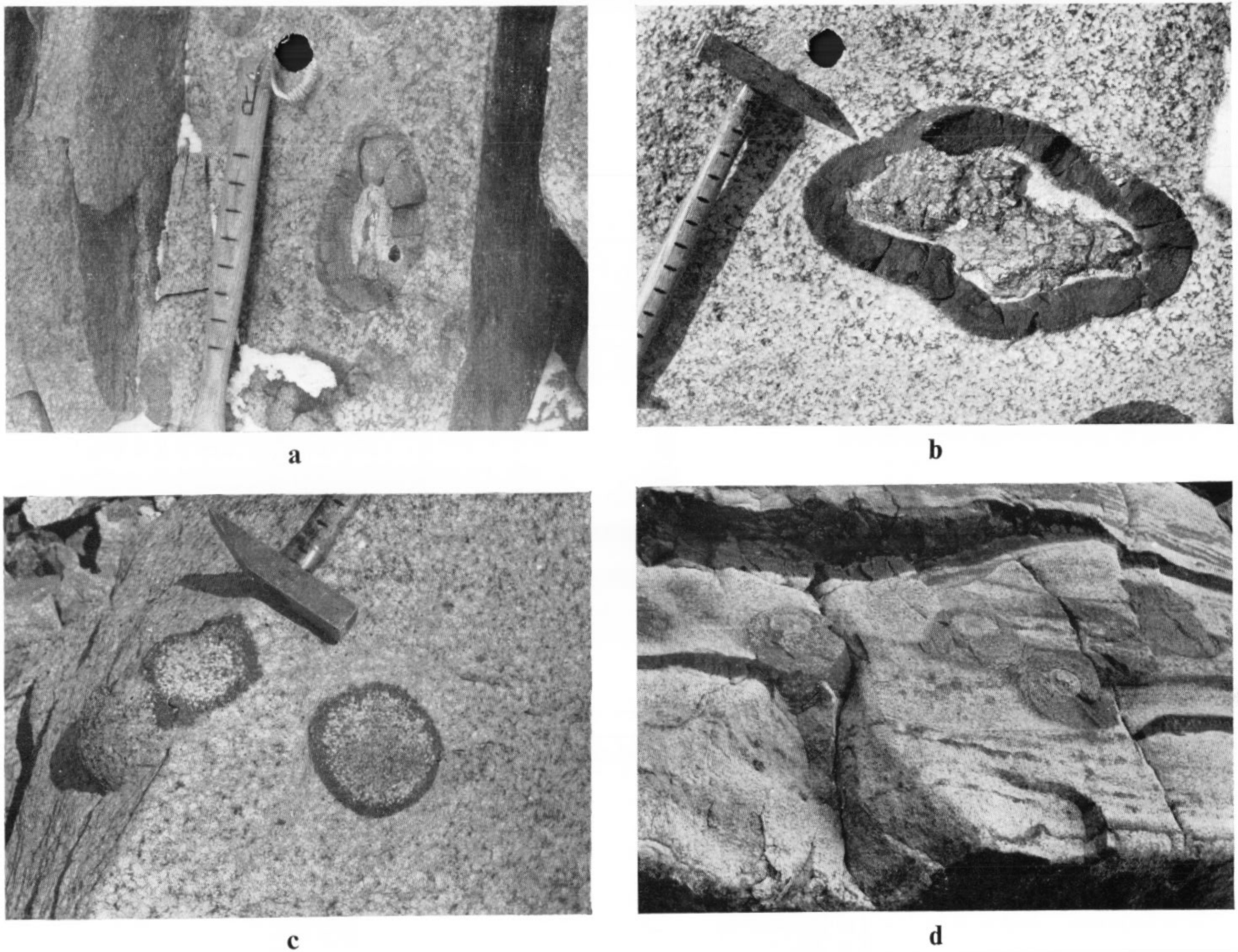

Fig. 6. a. A "hollow" concretion in mottled sandstone centred on a carbonized plant fragment and enclosing a fragment of mudstone. Radial cracking is again apparent.
b. A "hollow" concretion with a large core of grey mudstone and crude radial cracking.
c. Three "hollow" concretions in mottled tuffaceous sandstone, illustrating their sharp outer contact and diffuse inner margin.
d. "Hollow" concretions with only a small core of sandstone and a proportionally thicker rim occurring in the sequence shown in Fig. 2. The bed containing these concretions is 1·5 m. thick.

classified as tuffs by Trendall but they are very similar in mineralogy and texture to what have been described as tuffaceous sandstones in Alexander Island.

In the Upper Cretaceous (Lower to Middle Campanian) of the James Ross Island area there are large numbers of spherical concretions which are renowned for the well-preserved fossils they contain. Other concretions have mineral nuclei or no apparent organic or inorganic core (personal communication from J. S. Bibby). These concretions are undoubtedly smaller than those of Alexander Island; they contain glauconite and some are distinctly lensoid in appearance (notably those within the Upper Kotick Point Beds at Kotick Point, James Ross Island). Because the concretions normally weather out from the enclosing sediments which are frequently structureless, Bibby (personal communication) was unable to ascertain whether any sedimentary structures common to the host rocks passed through the concretions, but he agreed with Ball (1960) that the concretions were "post-depositional" in origin. However, Ball did not say whether he meant early diagenetic or epigenetic.

Despite their vastly greater age, the carbonate-cemented concretions in turbidite sandstones of the Cambrian of North Wales (Crimes, 1966) show a close similarity to those of Alexander Island. Although they frequently transgress bedding planes, in a number of cases they terminate sharply upwards, but never downwards, against bedding planes. This evidence, together with the presumed absence of the upper intervals of the classic turbidite, has been considered by Crimes as evidence of erosion of the upper parts of the concretions and therefore of their very early diagenetic origin. However, it has been demonstrated from Alexander Island (Fig. 5a) and South Georgia (Trendall, 1959) that many concretions exhibiting the ability to grow across bedding planes also have sharp downward terminations against beds apparently similar to those which have been transgressed.

CALCAREOUS CONCRETIONS IN MUDSTONE

Occurrence

Small calcareous concretions or "cement-stones", only a fraction of the size of the cannon-ball concretions, are fairly abundant in the more argillaceous parts of the Fossil Bluff Series. They are particularly common in the basal 18·3 m. of indurated mudstones at the northern part of Waitabit Cliffs, in a sequence of moderately oxidized siltstones at locality P (Fig. 1) and within a few beds overlying the massive-bedded sandstone cliffs at Fossil Bluff and locality H. At the last two localities, the concretions could be used for correlation purposes. Elliptical concretions are also fairly common in the two belemnite shell banks or "battlefields" at Mount Ariel, although here they may have been transported from their place of origin with the pebbles, stem fragments and innumerable belemnite rostra.

Appearance and lithology

The concretions, which are composed of a dense, brittle and generally light grey calcitic mudstone or limestone, are spherical, elliptical or even tuberose in shape (Figs. 7 and 8a–c) and most of them are elongated parallel to the bedding planes. They range in size from less than 2·5 cm. in diameter to lenses 3 m. long and 0·6 m. thick. The contacts between the concretions and the enclosing mudstones and siltstones are usually well defined by differences in colour, lithology and relief, and the concretions often protrude from the host rocks which bend over and under them, probably as a result of differential compaction.

Some concretions such as those at Waitabit Cliffs are concentrically layered and contain small euhedral crystals of iron pyrites, whereas others enclose a core which is usually elongated parallel to the long axis of the concretion and composed mainly of calcite (with subordinate iron pyrites) or of a sediment of slightly contrasting lithology. The sedimentary cores may be coarser- or finer-grained than the outer margins of the concretions.

Micro-fossil fauna

Other concretions, like those at James Ross Island, contain cores of fossils including *Inoceramus*, ammonites, belemnite phragmocones, diminutive gastropods, a decapod, arenaceous Foraminifera, calcispheres (*Oligostegina* ?), a variety of recrystallized Radiolaria

Fig. 7. A tuberose calcareous concretion 60 cm. long and 3·5 cm. wide at locality G. The concretion may have formed around some large branched burrow.

(stichocorythinids and adelocyrtidinids) and some small fragments of fish test. Some Radiolaria are pyritized. In one concretion (KG.15.3) both Radiolaria and calcispheres are particularly abundant in the outer margins but they are rare in the more coarsely crystalline core where only a few Foraminifera are preserved. The Radiolaria have not been examined in detail but undoubtedly the commonest forms are those resembling *Dicolocapsa*, *Tricolocapsa* and *Dictyomitra*, the first two genera having been recorded from the Aptian of Annenkov Island, off South Georgia (Wilckens, 1932). Micro-fossils similar to *Dicolocapsa* have sometimes been referred to as *Diplopsphaeria* (Kaisin, 1961). Another Radiolaria which might be present in Alexander Island is *Cyclastrum* which is confined to the Cretaceous (Campbell, 1954). The relative abundance of Radiolaria in both the concretions and the surrounding sediments may be due in part to contemporary volcanism which introduced silica into the sedimentary basin, thus indirectly promoting the growth of these micro-fossils (Katz and Watters, 1966, p. 340).

At locality F, the outer margins of several concretions are characterized by relatively large numbers of strongly orientated small dark-coloured tubes resembling fine needles. These tubes, which are between 57 μm. and 1 mm. in diameter and at least 2 cm. long, are composed of several concentric layers of virtually isotropic (?) collophane which surround a core of more coarsely crystalline calcite (Taylor, 1969). The tubes probably represent some form of tubicolous polychaete resembling *Hyalinoecia* or *Spiochaetopterus*.

Many of the larger fossils within the concretions, especially the belemnite phragmocones, are full-bodied like the fossil fish in concretions from the Lower Cretaceous of Colombia (Weeks, 1953).

In one of the largest cement-stones (KG.15.5; Fig. 9), an epicentric core composed of angular fragments is surrounded by successive layers of finely banded calcite and by a thicker layer of mudstone containing vermicular structures (Taylor, 1967; Thomson, 1967) similar to trace fossils from the Yakutat Formation (Upper (?) Cretaceous) of Alaska (Ulrich, 1910,

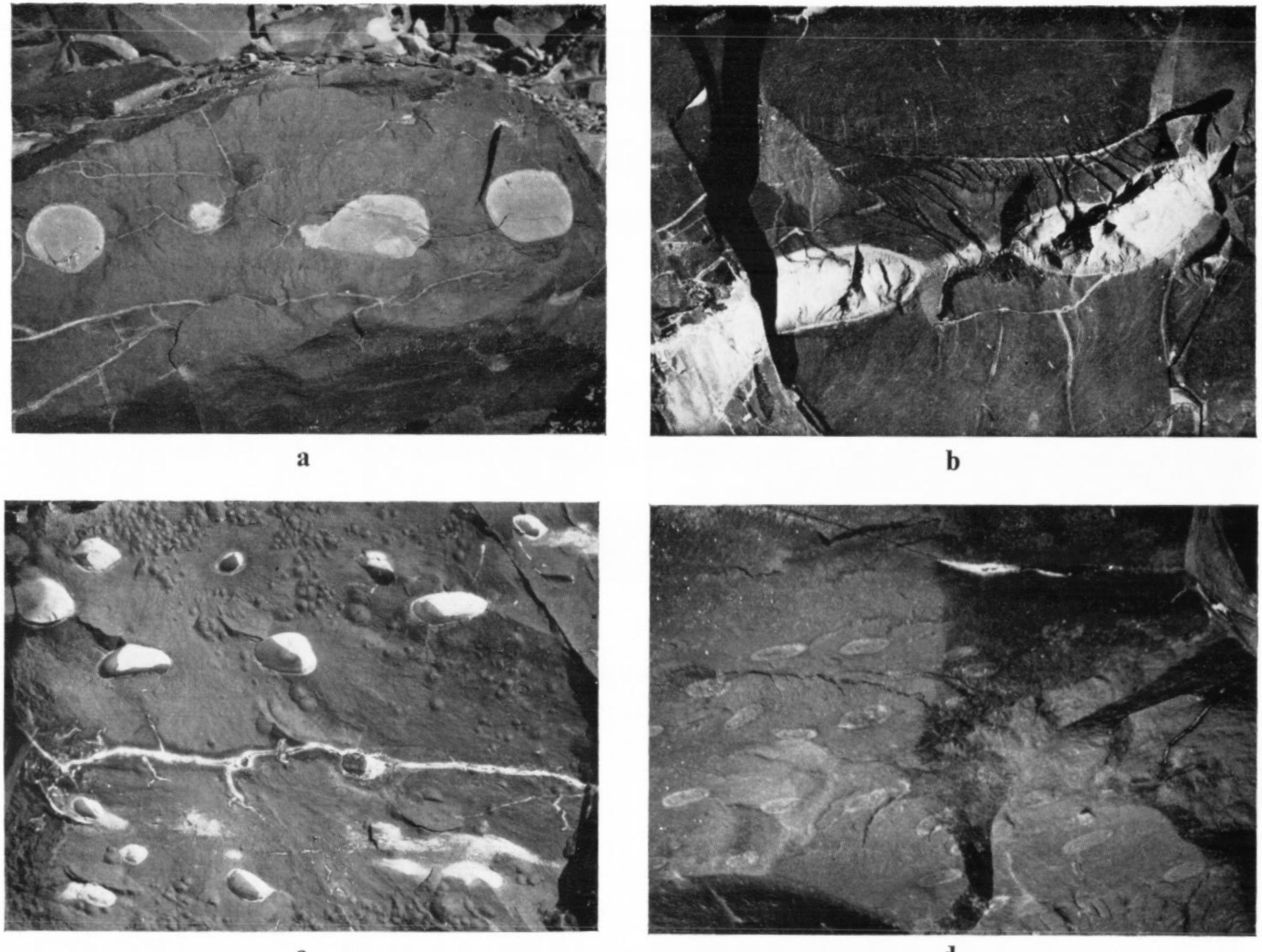

Fig. 8. a. Small calcareous concretions developed in the basal 18·3 m. of indurated mudstones at the northern part of Waitabit Cliffs. The concretion on the left is 9 by 8·5 cm. in size.

b. Sausage-shaped calcareous concretions developed within the same stratum as those in Fig. 8a. The concretion on the right is 45 cm. long.

c. Sev[illegible] concretions, some of them concentrically laminated, dev[illegible]ed in the basal 18·3 m. of mudstones at Waitabit Cliffs. Many of the limonitized concretions have weathered out. The laminated concretion near the centre is 5·5 by 3·5 cm. in size.

d. A "swarm" of generally elliptical and concentrically layered concretions in unit 119 at Succession

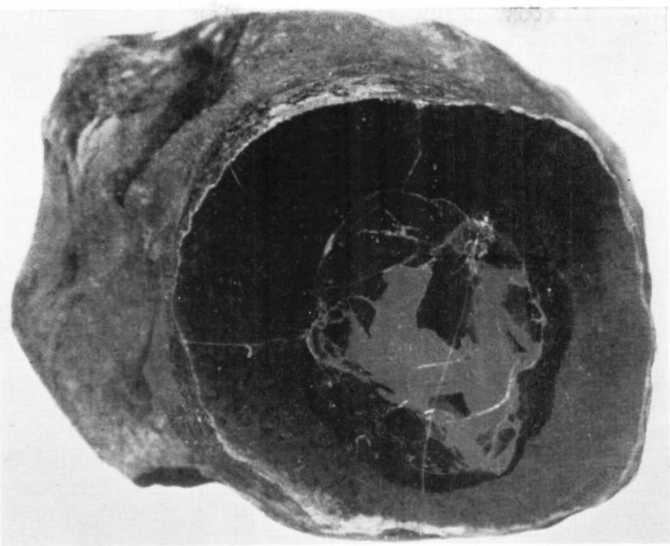

Fig. 9. A polished section cut in the horizontal plane of a concretion collected from locality P, showing a layer of bioturbated mudstone surrounding a core composed mainly of calcite (×1·1).

pl. XV). These vermicular structures suggest intensive bioturbation of the sediment by some lithophagic organism, probably a soft-bodied worm.

Concretions in thin section

In thin section, the small calcareous concretions are composed mainly of finely crystalline calcite which has replaced much if not all of the original argillite. Although the contact between a concretion and the surrounding sediments appears to be quite sharp in the field, there is a narrow transition zone where partial replacement by calcite has occurred. Within the finely crystalline calcite, small grains of quartz, feldspar, biotite, epidote, zircon and ilmenite (altered to leucoxene) are present although the larger grains are etched. In some concretions with mineral cores, the finely granular calcite comprising the axis of the concretion is surrounded by several concentric layers of strongly cleaved and radiating aggregates of calcite. Radial cracks filled with the same mineral also occur in some concretions, many of which contain numerous spherules or cubes of iron pyrites which may have had an early diagenetic origin. Within one concretion, at the contact between the core and surrounding sediment, and elsewhere in several others, there is a rhomboidal texture which probably represents an originally coarser crystalline texture that has been modified by solution. In part this relic texture has been accentuated by authigenic prehnite which has grown between the original crystal boundaries. A partial analysis of a concretion (KG.15.17) from locality P indicates that it is composed mainly of calcite and contains 1·88 per cent of Fe_2O_3, 0·24 per cent of TiO_2 and only 0·28 per cent of P_2O_5 (personal communication from L. M. Juckes).

At Succession Cliffs (locality B), generally elliptical and concentrically layered bodies occur as a "swarm" within one bed and over a limited extent of outcrop (Fig. 8d). These concretions, which have an average length of 2·5 cm., probably owe their shape to compaction but the reason for their occurrence in large numbers in such a small area is more problematical.

Black concretions

M. R. A. Thomson collected a number of indurated black concretions (resembling coal balls) from Keystone Cliffs and the northern part of Waitabit Cliffs at a height of approximately 305 m. in the succession. At Waitabit Cliffs, the usually oblate concretions occur in an horizon composed of green shale fragments which are embedded with pebbles and rolled belemnite rostra in a fine-grained mudstone. At Keystone Cliffs, where the concretions are commoner, they occur between 6·1 and 122 m. above a major thrust and within a succession of poorly fossiliferous mudstones disturbed by some form of burrowing organism similar to *Chondrites* (personal communication from M. R. A. Thomson). These concretions, which are highly carbonaceous and less calcitic than the cement-stones, are amber-coloured in ordinary light and they contain a number of as yet unidentified Radiolaria as well as prisms of *Inoceramus* and a nodosariaid Foraminifera. They are probably very similar to the nodules which are the principal source of the macro-fauna in the Upper Cretaceous of Cape Lamb, Vega Island, where the fossils occur as central cores (Bibby, 1966, p. 24). These Upper Cretaceous nodules are evidently much larger than those from Alexander Island.

Sedimentary environment

Most of the small calcareous concretions of Alexander Island occur in poorly fossiliferous sediments containing numerous nodules of iron pyrites and exhibiting a moderate to strong iron oxide pigmentation. Many pyrite nodules are partly if not completely altered to limonite and are surrounded by iridescent oxidation haloes. At Waitabit Cliffs, those beds containing most of the concretions have a fauna comprising mainly diminutive gastropods, *Entolium*, *Pinna*, *Rotularia* (some of the shells of which are partly pyritized) and fish teeth together with fragmentary plant material, but at Fossil Bluff and locality H there are large numbers o[illegible] purple-stained *Entolium*, *Pholadomya* (?) (in assumed living positions) and relatively common stems and pteridophyte-like fronds. According to Imlay (1961, p. 15), *Entolium* is indicative of shallow-water conditions which may, in this instance, have been relatively quiet because many of the paired shells are only slightly offset at the hinge line. In the Jurassic coal measures of the south-eastern Caucasus, concretions are almost completely absent from the deltaic sediments but they become increasingly numerous in the more marine environments, the calcite-pyrite concretions occurring almost exclusively in the deeper-water sediments (Brovkov, 1964).

In Alexander Island the smaller size of the cement-stones and black concretions compared with the cannon-balls is undoubtedly due to differences in grain-size and permeability of their respective host rocks.

In the middle part of the succession at Waitabit Cliffs, where mudstone concretions 7 cm. in diameter occur in the more argillaceous sediments, Thomson collected a number of small gastropods, two of which are perhaps of some environmental significance in connection with the formation of these concretions. These two gastropods, which were found in a silty mudstone immediately below the concretion horizon, have been identified by Thomson (personal communication) as *Rissoina* sp. and they are thought to be similar to *Rissoina inca* d'Orbigny, a modern form from South America. According to Wenz (1938–44), the Rissoinidae are marine although they prefer brackish water conditions. The sediments in which the two *Rissoina* occur contain a relatively high percentage of iron pyrites and they are encrusted with gypsum, the sulphate probably being derived from the pyrite. These sediments, which also contain *Lingula*, were probably lagoonal and pass upwards into cross-bedded deltaic sandstones characterized by the larger cannon-ball concretions.

Cement-stones somewhat similar to those described from Alexander Island occur in th[illegible] Monterey Formation (Tertiary) of California (Bramlette, 1946), the Cretaceous Yahgan Formation of Navarino Island, southern Chile (Katz and Watters, 1966), and in shales and calcareous shales of Lower Albian age in Colombia (Weeks, 1953). Many of the Colombian concretions are petroliferous.

Weeks (1953) has suggested that because calcareous concretions are usually found in successions lacking limestones or with only impure limestones, they indicate a euxinic environment. Although the Fossil Bluff Series was probably not deposited in a closed basin, it is evident from the amount of disseminated and aggregated iron pyrites that the waters were probably moderately acidic and may, therefore, have inhibited the development of carbonate. The occurrence of *Lingula*, which can tolerate such conditions, and of boring or perforating algae within the decapod cuticles suggests that such an environment existed for at least part of the Upper Aptian; according to Hessland (1949, p. 410), boring algae are most prolific in "fairly stagnant and shallow bays of the warm seas". This general poisoning may only have occurred from time to time without necessarily causing the mass mortality of the fauna.

Origin of the concretions

Although the environmental conditions were probably euxinic, the amount of ammonia resulting from the decomposition of the organisms or amines was probably sufficient to increase the pH around the dead animal (or plant) and alkalize the immediate surroundings resulting in localized deposition of carbonate (Weeks, 1953), which had been derived from dissolved calcareous material and from increasing quantities of CO_2 produced by energetic bacterial activity during diagenesis (Chilingar and others, 1967). The more calcitic concretions are present in the more highly calcareous sediments. Carbonate fixation presumably continued until the production of ammonia ceased or until there were no more dissolved carbonates in the vicinity. The presence of full-bodied fish in the Colombian concretions and of well-preserved and generally uncrushed belemnite phragmocones and other invertebrates in the Alexander Island concretions strongly suggests that many if not all of them formed soon after the death of the core fossil but before it disintegrated. According to Lippmann (1955) and Seibold (1962), who studied the porosity of concretions in argillaceous sediments from northern and south-western Germany, concretions form in the uppermost few metres of the sediment. It is interesting that, while fragmentary fish material is present throughout the Fossil Bluff Series, no fish preserved "in the round" were recorded although they are apparently often found in concretions ranging from Upper Devonian to post-Pleistocene (Weeks, 1953, p. 167).

Because most if not all of the cracks in concretions have V-shaped terminations and fail to reach the outer surface, Vital' (1959) suggested that crystallization and lithification of concretions begins at the periphery. He also found that minor elements such as nickel, cobalt, vanadium and chromium were more abundant in the surrounding rock than in the concretions, inferring that these elements do not migrate during diagenesis.

The fractures in the Alexander Island concretions are either radial or oblique to the surface but there are three other features which suggest that the concretions consolidated inwards: namely, a virtually unaltered outer "skin", a median area composed of concentric layers of calcite and a central core which is often formed of brecciated fragments. This type of core presumably represents the accommodation effects resulting from the loss of moisture and attendant contraction in volume of the concretion. Some of the angular and brecciated fragments representing the banded calcite have been completely re-orientated and a considerable amount of secondary calcite growth has taken place, often in the form of rosettes.

CONCLUSIONS

The two forms of concretion described here are regarded as having essentially similar origins. The dominant factor appears to have been the action of organic decomposition products which created a chemical environment conducive to the precipitation of calcium carbonate. Certain of the "cannon-ball" concretions, however, appear to be centred on inorganic nuclei and in these cases a physical process (such as dilatancy) is invoked to explain the migration and precipitation of calcium carbonate.

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