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FOSSIL QUATERNARY AND LIVING FORAMINIFERA FROM ATHALASSIC (NON-MARINE) SALINE LAKES, SOUTHERN AUSTRALIA

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ABSTRACT—Five living species of foraminifera are recorded from athalassic saline lakes of southern Australia: *Elphidium* sp. and *Trochammina* sp. from ephemeral lakes and *Elphidium* sp., *Ammonia beccarii, Trichohyalus tropicus* and a miliolid from permanent lakes.

The ability of a species of *Elphidium* to live through the drying up phase of ephemeral lakes is demonstrated an an experiment on the post mortem discoloration of protoplasm of that species is documented.

The presence of *Ammonia beccarii* in Holocene lake sediments in western Victoria and from the Pleistocene of Lake Eyre indicates that both lakes must have had permanent saline water at the time.

INTRODUCTION

FORAMINIFERA HAVE been reported from a variety of non-marine environments. Resig (1974) described Recent foraminifera from a landlocked Hawaiian lake and reviewed relevant literature. Including her own study, Resig reported six known occurrences of foraminifera in strictly non-marine waters: salt pond near Deva, Rumania; water wells of Kara-Kum Desert, east of Caspian Sea; Wadi Rhir, Algeria; pools and springs near Erfurt, Germany; Salton Sea, California; Caspian Sea, U.S.S.R.; and Salt Lake, Oahu, Hawaii. For most of the reported occurrences the water was described as brackish and the foraminifera species diversity was low. The Hawaiian Salt Lake study yielded 41 listed species, but the majority were not represented by living material. Only five species were found to be alive at the time of collecting and live individuals comprised less than one percent of the sample.

Howchin (1901) reported the existence of foraminiferal tests in silt from Yorketown Lagoon in South Australia. Although only "dead shells" were observed, Howchin believed that they represented a living, though perhaps sporadic, population apparently of *Elphidium*. W. J. Parr described an occurrence of living foraminifera (*Elphidium*?) in an ephemeral saline lake near Douglas in western Victoria. The record is a handwritten, undated, draft which was forwarded to Prof. M. F. Glaessner some years after Parr's death in 1949 and which is now in the possession of Dr. B. McGowran.

The purpose of this paper is to further document the occurrence of foraminifera in southern Australian lakes. Survival of populations of foraminifera in ephemeral saline lakes is investigated and the paleoenvironmental significance of such populations is emphasized.

All the specimens illustrated here are deposited in the collection of the Geology Department, University of Adelaide.

LIVING FORAMINIFERA

Twenty-one athalassic (=non-marine *sensu* Bayly, 1967, p. 101), saline lakes in the Coorong District of South Australia have been surveyed as part of a larger faunal study (De Deckker and Geddes, MS in prep.). Sediment, water and vegetation samples were collected at bi-monthly intervals throughout 1978 and the presence of foraminifera was noted. The lakes are subject to drying up during the summer period (December–March) at least. Summer evaporation, high winter rainfall and fluctuating water tables (von der Borch, 1976, p. 962) cause extreme salinity variation, ranging from 10‰ to 180‰ or more. Especially at the end of the year, when the rate of evaporation is high, salinity rises rapidly before the lake dries.

Some of the foraminifera collected from the above mentioned lakes contained colored protoplasm (shades of green, brown and orange) and were considered to have been alive at the

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time of collection. However, Boltovskoy and Lena (1970) demonstrated that total decomposition of foraminiferal protoplasm may take several weeks, and sometimes months. Consequently laboratory studies were initiated to determine the time interval between death and loss of color of the foraminifera found in the lakes under investigation.

Each study involved 25 specimens of a species of *Elphidium* (*sensu* Hansen and Lykke-Anderson, 1976) collected from one lake. Initially, all tests were filled with orange colored protoplasm, except for their final chambers which were most often translucent. When such specimens were placed in sea water, pseudopodia protruded from the tests. They were therefore confirmed to have been living at the beginning of the study.

a) Specimens were observed in the original lake water at room temperature (20–28°C). The salinity of the water was 80‰. Over fifty days there was gradual shrinkage of protoplasm until only minute amounts remained as orange-red specks.

b) Specimens were dried for 20 minutes at 100°C. Then, within a week only one specimen retained its color, and this was also bleached after a second week.

c) Specimens were placed in distilled water at room temperature for 20 minutes, and allowed to dry. Then over fifty days at room temperature there was shrinkage of protoplasm and gradual loss of color until all individuals were bleached.

d) Specimens were removed from the lake water and allowed to dry at room temperature. Again there was shrinkage of protoplasm and gradual loss of color over the period of observation, only two individuals having any residual color after fifty days.

On the above laboratory evidence, it appears that in ephemeral saline lakes, prolonged conditions of evaporation and high salinity associated with the drying up phase will inevitably cause shrinkage of foraminiferal protoplasm and bleaching. Consequently, the colored foraminifera collected during 1978 are considered to have been living in the lakes that year (though they may not necessarily have been alive at the time of collection).

Foraminiferal densities (*Elphidium* sp. and *Trochammina* sp. together) up to 150 indiv./10 cm^2 were reported from the lakes studied. If, as is suggested by the laboratory evidence presented above, summer evaporation of lake waters kills the foraminiferal population, re-establishment of the fauna from year to year poses significant questions.

It is known that water birds can be transporting agents for micro-organisms in lakes. This factor was illustrated for ostracods by De Deckker (1977). Howchin (1901) thought that the foraminifera in Yorketown Lagoon resulted from the introduction of "spawn" on the legs of sea birds. Parr, in the undated manuscript mentioned above, records correspondence from Earland describing the recovery of foraminiferal tests from the stomach of a wild duck.

Despite the above it appears unlikely that or observed occurrence of foraminifera of low diversity (2 species) and numerical abundance (150 indiv./10 cm^2) resulted from avian introduction in the year of collection.

In February 1979, mid-summer, samples of muddy surface sediment were collected from a dried lake which, when filled with water the previous winter, had contained living foraminfera. Desiccation cracks were common and halite salt crystals occurred on and within the sediment. Surface temperatures above the lake bed were commonly 30–35°C and occasionally greater than 40°C.

The sediment nevertheless retained some moisture, which may be attributed to two factors. The lake bed was partly covered by a mat of dead halophytic plants, such as the aquatic grasses *Ruppia* sp. and *Lepilaena* sp., and the charophyte *Lamprothamnium papulosum*. This material would certainly have inhibited surface evaporation. The hygroscopic nature of the observed halite crystals would also have aided water retention.

In the laboratory, the samples were immersed in distilled water and salinity values up to twice that of normal sea water quickly established. Within two days, adult *Elphidium* sp. bearing orange colored protoplasm, some moving and extending pseudopodia, were observed in the samples.

It seems clear, therefore, that *Elphidium* sp. can survive the summer evaporative episodes of ephemeral saline lake cycles and provide the necessary numbers for re-establishment of the fauna in the following winters. Such survival probably involves some kind of "dormant" stage. Earland (in Parr's manuscript mentioned above) compared the foraminifera to other lower organisms and believed that they were able to exist in an encysted state in mud and so live through seasonal changes. No cysts were observed in our material.

Foraminifera probably experience optimum growth, and new generations appear, when the salinity of the lakes approaches that of sea water (Bradshaw, 1957, 1961). For some southern Australian lakes this condition can last for two months or more (De Deckker and Geddes, MS in prep.).

Two species of foraminifera were observed to be living in ephemeral saline lakes adjacent to the Coorong Lagoon, *Elphidium* sp. and *Trochammina* sp. (see Pl. 1–2). Specimens were most often found in the fine, grey clay forming the surface sediment typical of these lakes (von der Borch, 1965). They were also recovered from plankton nets passed through halophyte grasses above the lake floors.

Trochammina sp. was generally much less abundant than *Elphidium* sp. and only found in lakes which never reached salinities greater than 60‰ prior to the rapid drying up phase. The specimens collected in 1978 were all intact and were considered to have been living in the lake during that year at least. The small brown tests of *Trochammina* sp. are flexible and fragile, and, when removed from water, rapidly shrink and break. It is not known if this foraminifer can survive the drying up phase of a lake and no specimens with active pseudopodia have been observed.

Juvenile specimens of *Elphidium* sp. and *Trochammina* sp. were observed earlier in the year when water levels were high and salinity values were low. The presence of juveniles provided further evidence that these foraminifera were alive and reproducing.

Little Dip Lake (35°15′42″S, 139°48′44″E) is a permanent salt lake, not connected with the sea, 1.5 km south of Robe in South Australia. Samples of nearshore mud were examined for foraminifera. *Ammonia beccarii* (Linné), *Trichohyalus tropicus* (Collins), *Elphidium* sp. and ?*Triloculina rotunda* d'Orbigny were present. They contained colored protoplasm and were therefore alive at or near the time of collection. Details of colors are described in plate captions. Some tests lacked pigmentation and many showed signs of dissolution. These were not considered representative of the living fauna and were discarded for the present study. Little Dip Lake became separated from the sea by stranding sea-beaches during the last glacio-eustatic sea level oscillation in late Pleistocene time (von der Borch, 1976; Sprigg, 1979).

The salinity of this lake fluctuates, but has not been recorded above 33.1‰ (Bayly, 1970), and was 23.8‰ at the time of sampling. Bradshaw (1957, 1961) has demonstrated that *Ammonia beccarii* can grow and reproduce very successfully at such salinity values.

A. beccarii was never found in the ephemeral lakes adjacent to the Coorong, despite the fact that for most of the year salinity values fall within its range of tolerance as demonstrated by Bradshaw (1957, 1961). This foraminifer apparently cannot survive the summer evaporative episodes of ephemeral saline lakes as does *Elphidium* sp. Paleoecological implications of this observation are discussed below.

QUATERNARY FOSSIL FORAMINIFERA

Lake Keilambete.—A core containing 4 m of sediment was taken from the maar, Lake Keilambete, near Camperdown in Victoria, 35 km from the sea. Between 3.62–3.67 m the sediment was particularly rich in *Ammonia beccarii*. The age of this layer is thought to be between 7850 ± 165 and 14,300 ± 300 years before present. This estimate is based on lithological correlation with data prepared by Bowler and Hamada (1971) for a similar core from the same lake.

A. beccarii was present to the exclusion of other foraminifera. All ontogenetic stages were present (see Pl. 3). The tests were largely undamaged and showed no signs of significant transport or sorting. They were interpreted as a life assemblage (Raup and Stanley, 1971, p. 236) and indicate a permanent water mass at the time of deposition.

Occurring with the foraminifera was the athalassic ostracod *Australocypris hypersalina* De Deckker. Thus the salinity of the lake at the time of deposition was probably comparable with that of sea water.

In the maar Lake Gnotuk, also near Camperdown in Victoria, the following foraminifera were extracted from a core at depth 1.35 m (age >2600 BP): *Ammonia beccarii, Elphidium* sp., and a miliolid. Only a few specimens of each species were recorded.

Lake Eyre.—*Ammonia beccarii* was also described and illustrated from Pleistocene sediments in the northeastern corner of Lake Eyre (Ludbrook, 1953, 1955, 1965). Individuals of this species were described by Ludbrook to be abundant. Three other species, represented by individual specimens, were not thought to be significant because of their rarity and poor state of preservation.

Ludbrook (1955) reported that *A. beccarii* was always accompanied by an ostracod fauna. This latter material was re-examined by one of the authors (PDD). *Diacypris* sp. (= *Pontocypris attenuata* of Ludbrook) and *Reticypris* sp. (=*Cypris* sp. of Ludbrook) were identified. These are established saline lacustrine species. Their presence confirms that the *A. beccarii* population lived in a nonmarine environment.

This conclusion is further supported by other observations by Ludbrook. The narrow and elongate charophyte oogonia illustrated by her (1955, Pl. 1, figs. 2–4) appear to belong to *Lamprothamnium papulosum,* a species noted for its salt water tolerance (Burne et al., 1980). The recorded gastropod *Coxiella* sp. also indicates a saline lake environment.

It is concluded that at the time of deposition of the Pleistocene sediment studied by Ludbrook, part of Lake Eyre was a permanent saline water body.

Estuarine environments.—Because of its ability to thrive under a wide range of salinites, *Ammonia beccarii* may also constitute the dominant species of foraminifera in estuarine environments. Where *A. beccarii* assemblages are involved in paleoenvironmental reconstructions, estuarine sediments may however be distinguished from those of lakes.

Cores have recently been recovered from Pleistocene sediments thought to be the equivalent of the Glanville Formation (Firman, 1966; Ludbrook, 1976; Cann, 1978), in the Goolwa district of South Australia (Milnes, A.R., pers. commun.). A sample of unconsolidated sand, exclusively rich in *A. beccarii,* was examined by one of the authors (JC).

The foraminifera tests were mostly those of adults and many were damaged. Bivalve shell fragments were present, but no ostracods (which commonly have fragile shells in athalassic environments) were observed.

Sand clasts were well sorted, rounded and polished. The evidence appears to favor an estuarine environment of deposition for this sample.

CONCLUSIONS

1. A few species of foraminifera are regular, continuing faunal components of southern Australian athalassic saline lakes.
2. At least one species of *Elphidium* is able to withstand the drying up phase of ephemeral saline lakes. The species survives in sufficient numbers to maintain a continuing population.
3. It appears probable that *Trochammina* sp. is also able to maintain a continuing population in ephemeral lakes.
4. *Ammonia beccarii* can grow and reproduce in permanent saline lakes.
5. Fossil foraminifera provide useful data relating to salinity and permanence of ancient lakes.

SYSTEMATIC PALEONTOLOGY

ELPHIDIUM sp.
Pl. 1

Descriptions.—For all the specimens referred to this species in the present study, two different groups (called here A and B) were differentiated.

Group A
Pl. 1, figs. 7–16, 18–23

The test is planispiral, involute and finely perforate. Average diameter is 650 μ, average width through the umbilical region is 220 μ. The number of chambers in the final whorl is 9–13 and is most commonly 10–12. Chambers increase in size only gradually. Final chambers in adults are inflated giving a lobate periphery. There is no keel. The aperture is a thin interiomarginal arch-like slit surrounded by fine pointed tubercles. Sutures are broad, depressed, straight to gently curving, containing numerous tubercles and spanned by distinct retral processes. Umbilical features variable, but not distinctive; there is no umbilical boss. The color of protoplasm was orange or green.

Group B
Pl. 1, figs. 1–6, 17

Specimens of this group differ from the above in the following ways. There are fewer chambers in the outer whorl, the periphery is not lobate and chambers are more inflated in width. Sutures are narrower. The retral processes are more numerous and only distinct between the final few chambers. The umbilical region is more depressed. Specimens are generally smaller.

Remarks.—1. The genus *Elphidium* is used here in the sense of Hansen and Lykke-Anderson (1976).

2. Specimens comprising Group A were collected from five different ephemeral saline lakes and adjacent to Coorong Lagoon.

3. Specimens comprising Group B were collected from a permanent salt lake (Little Dip Lake, near Robe, S.A.) where salinity is fairly constant, except for one specimen (Pl. 1, fig. 6) which was found in an ephemeral salt lake adjacent to the Coorong Lagoon.

4. Despite the morphological differences described above, it is considered that some individuals of Group A are sufficiently similar to some of Group B, e.g. Pl. 1, figs. 4 and 15, that specific separation is unwarranted. It is considered likely that the morphological differences exhibited, though distinctive, result from contrasting environmental conditions such as variation in salinity, temperature, oxygen and water level in the ephemeral lakes versus stability of these parameters in the permanent lake.

5. Individual specimens, representative of Groups A and B, were sectioned to examine internal chambers. The sizes of the proloculi, and the numbers of juvenile chambers, were found to be approximately the same. It was concluded that the two groups do not represent megalospheric and microspheric forms of the species. The authors are grateful to Dr. H. Tappan Loeblich for suggesting that they investigate that possibility.

6. The figured specimens of Group A show some similarities with specimens of *Elphidium gerthi* van Voorthuysen, 1957 illustrated by Murray (1971, Pl. 67), by Hansen and Lykke-Anderson (1976, Pl. 5, figs. 7 and 8) and yet other specimens illustrated in the Norwegian Atlas of Continental Shelf Foraminifera (Norges, 1974). They are also similar to *Elphidium articulatum* (d'Orbigny, 1839) of Murray (1971, Pl. 63) and of Rosset-Moulinier (1976, Pl. 1, figs. 1–4). Those of Group B from the permanent lake resemble *Elphidium asklundi* Brotzen, 1943, as illustrated in the Norwegian Atlas.

7. None of the species of *Elphidium* mentioned above, nor any that are closely similar, appear to have been previously reported from

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EXPLANATION OF PLATE 1

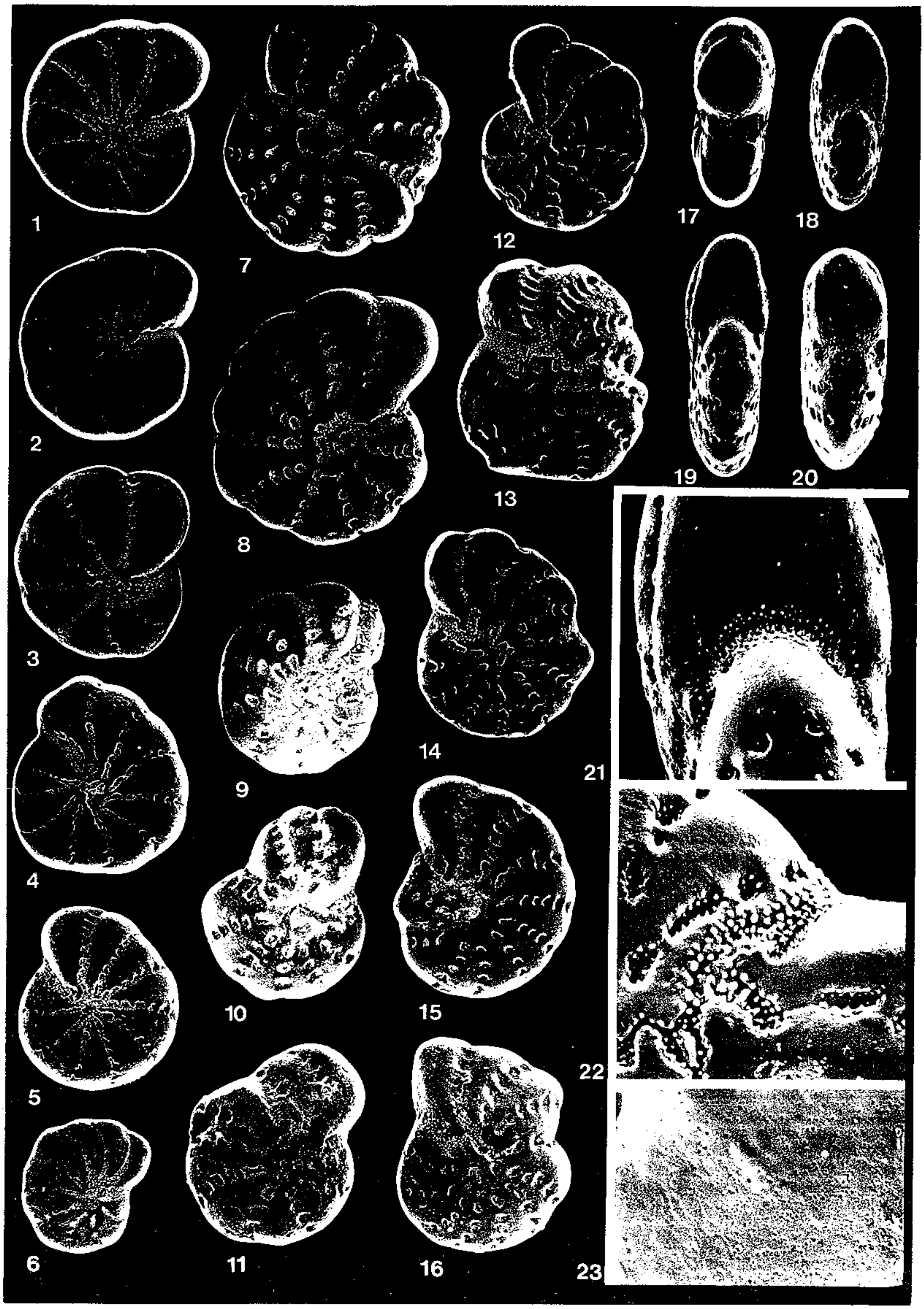
FIGS. *1–23*—*Elphidium* sp.; all Recent. *1–6, 17,* group B. *7–16, 18–23,* group A. *21,* detail of Fig. *19* to show aperture area. *22–23,* detail of Fig. *14* to show aperture area and pores respectively. Fig. *1–20,* ×68. Figs. *21–22,* ×230. Fig. *23,* ×920. Color of protoplasm: green: Figs. *2,7–10,12,17,* green yellow: *4–5,* orange: *6,11,13–16,18–23,* others not known. Localities: *1–5,17,* Little Dip Lake, near Robe, South Australia. All others are from ephemeral lakes adjacent to the Coorong Lagoon, South Australia. *6,* 36°19′52″S, 139°44′48″E. *7–9,* 35°52′19″S, 139°40′01″E; *10,* 36°29′38″S, 139°48′40″E. *11,13–16,18–23,* 35°25′48″S, 139°46′57″E; *12,* 36°19′46″S, 139°44′48″E.

EXPLANATION OF PLATE 2

FIGS. *1–19*—*Trochammina* sp.; all Recent. *1–15,* ×53; *16,* detail of Fig. *11* to show diagnostic lip around aperture, ×650; *17,* detail of Fig. *12* to show aperture, ×325; *18,* detail of Fig *13* to show details of wall structure, ×650; *19,* enlargement of Fig. *18,* ×570. Color of test: brown to grey brown. Localities: all from ephemeral lakes adjacent to the Coorong Lagoon, South Australia: *1,3,5,7–8,11–19,* 36°26′18″S, 139°47′11″E; *2,4,6,9–10,* 36°29′38″S, 139°48′40″E.

EXPLANATION OF PLATE 3

FIGS. *1–37*—*Ammonia beccarri* (Linné, 1758). *1–26,28,29,31,* Holocene, Lake Keilambete core, Victoria. *27,30,32–37,* Recent, Little Dip Lake, near Robe, South Australia. *1–8,* spiral view. *9–15,* umbilical view. *16–22,* selected juveniles showing proloculus (*16,* enlargement of Fig. *17*). *23–28,* side view. *29–37,* spiral or umbilical view of selected aberrant forms. All ×62 except Fig. *16,* which is ×190. Color of protoplasm: pale yellow: *30,34,35–36,* pink: *33,* dark grey: *37,* unknown: *27,32.*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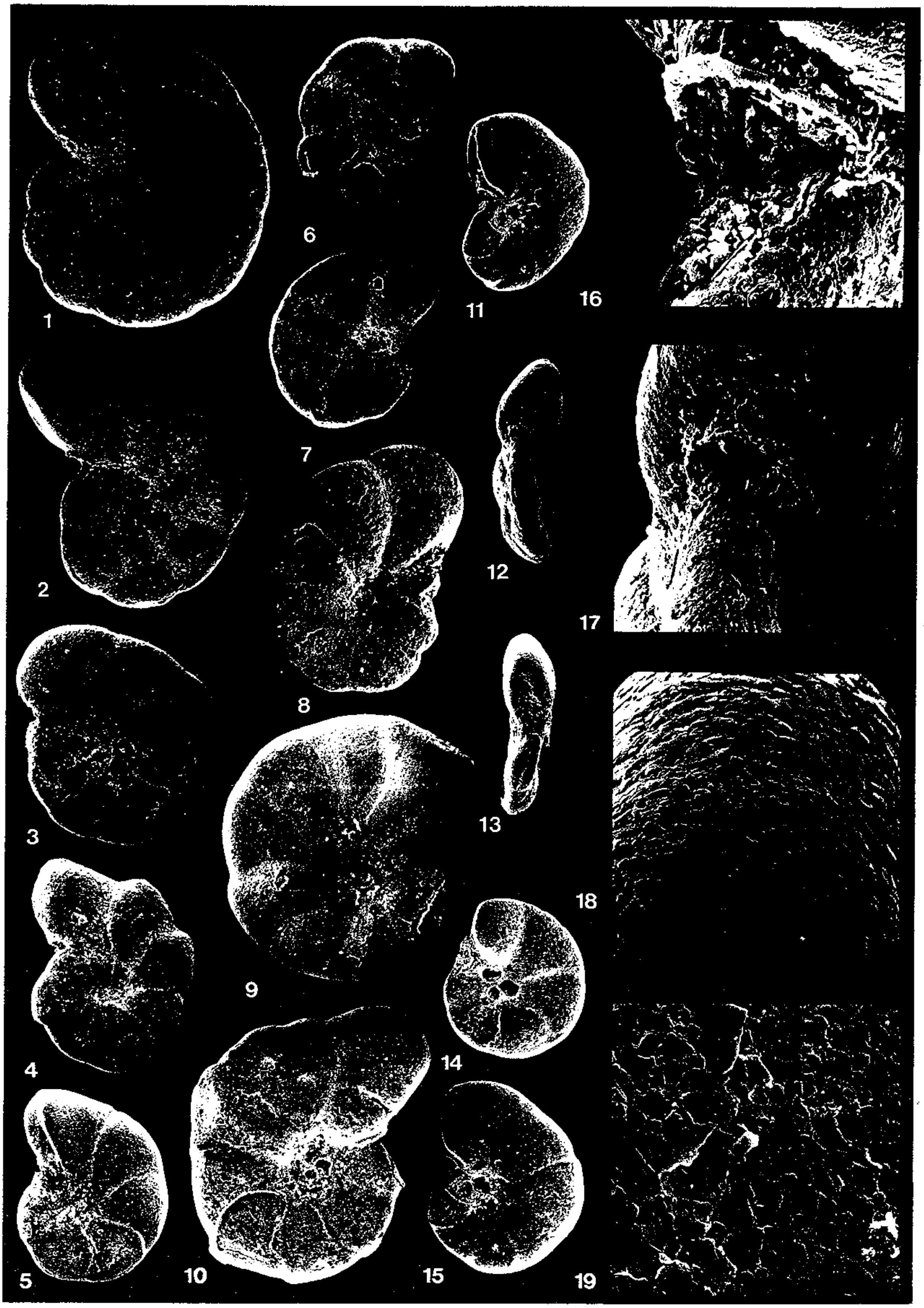
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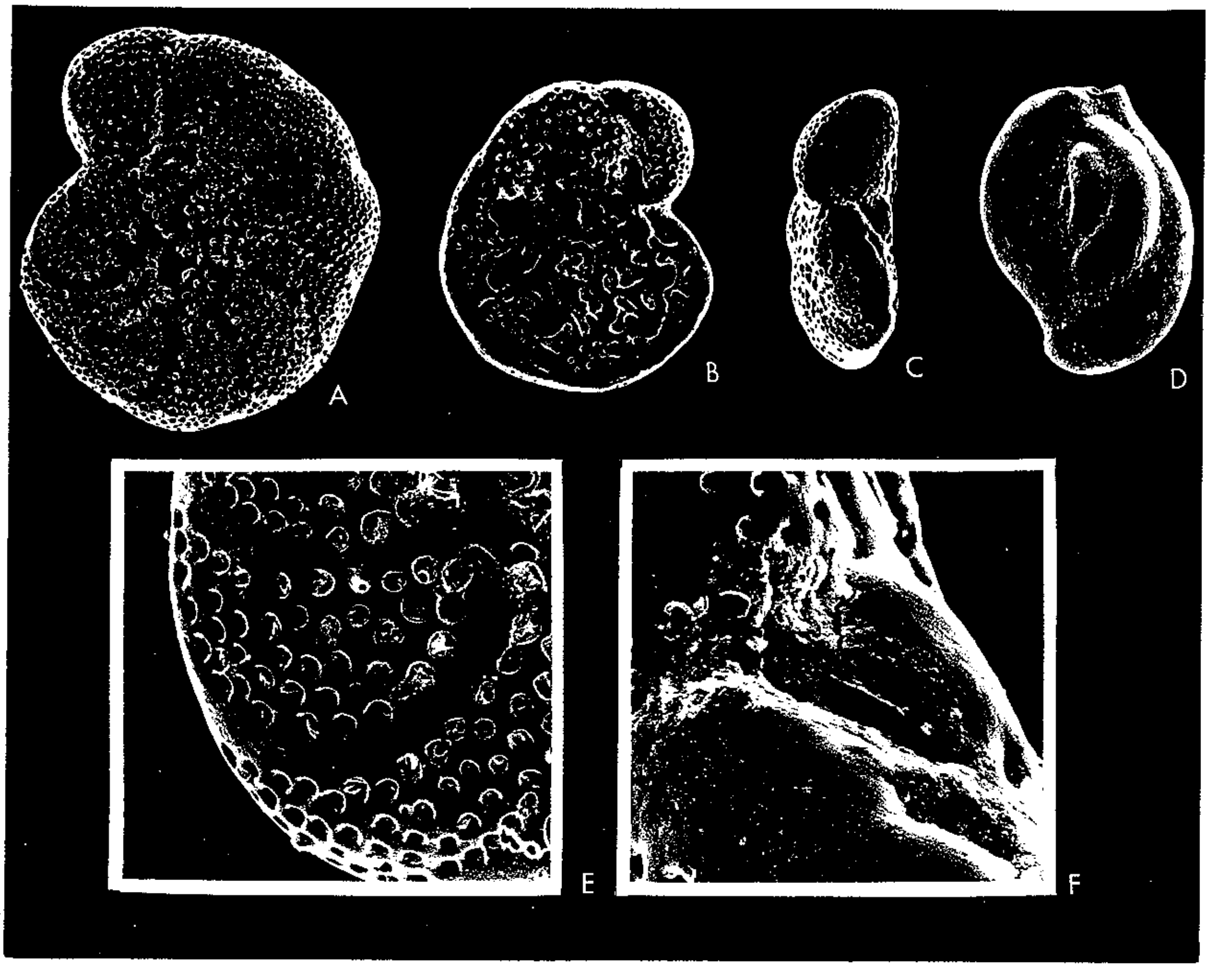

TEXT-FIG. *1*—*Trichohyalus tropicus* (Collins, 1958). *A*; spiral view. *B*; umbilical view. *C*; side view. *E*; detail of fig. *A*. *F*; detail of fig. *B* to show aperture. Figs. *A*–*C* ×53. Fig. *E* ×150. Fig. *F* ×380. Color of protoplasm: light brown to orange. Locality: Little Dip Lake, near Robe, South Australia. *D*; ?*Triloculina rotunda* d'Orbigny, 1893, ×60. Color of protoplasm: white. Locality: Little Dip Lake, near Robe, South Australia.

southern Australian waters, either lacustrine or marine. In view of the extent of morphological variation exhibited by the figured specimens no specific determination is provided at this time.

TROCHAMMINA sp.
Pl. 2

Description.—The test is trochospiral and depressed. Average greatest diameter is 700 μ; average width through the umbilical region is 170 μ. Seven to eight chambers are visible in the outer whorl. Sutures are mostly indistinct and gently curving. The umbilical surface is flattened, slightly concave in the umbilical region, and lacks a true umbilicus. The periphery is acutely rounded. The aperture is an equatorial, interiomarginal arch having a pronounced lip and extending towards the umbilical region.

There are no secondary cribrate apertures. The test is constructed of finely agglutinated, overlapping, plate-like grains and is very fragile. Tests may disintegrate when removed from water; most of the figured specimens, alive at the time of collection (?), show signs of cracks or fractures. The color is brown to grey-brown when alive; test retains color, but is paler grey when empty.

Remarks.—In the sense of Brönnimann (1979) the aperture characteristics of the illustrated specimens (Pl. 3) clearly place them within the genus *Trochammina,* but the depressed nature of the test and the lack of the characteristic deep umbilicus make it difficult to reconcile this species with the most commonly reported *T. inflata* (Montagu). It is recognized that the depressed form, including the concave apertural face of some individuals, may have resulted from shrinkage with desiccation, but the generally depressed form of the test was evident for living individuals.

In general outline the flattened tests of the figured specimens resemble that of *Jadammina macrescens* (Brady) as illustrated by Murray (1971, Pl. 13, figs. 1–5). The primary equatorial aperture also appears to be very similar, but our specimens lack the diagnostic, cribrate secondary apertures of *Jadammina*.

No specific determination is offered at this time.

AMMONIA BECCARII (Linné, 1758)
Pl. 3

The specimens illustrated in Plate 3 clearly belong to this species, *sensu* Schnitker (1974).

Figured specimens 1–26, 28, 29, 31 are fossils from the Lake Keilambete Holocene assemblage. Ontogeny is represented by the series 1–8, spiral views, and 9–15, umbilical views; 16–22 are selected juveniles. No preferred direction of coiling was apparent.

The other figured specimens 27, 30, 32–37 were living when collected from Little Dip Lake. Individuals show more thickened earlier sutures than those of the fossil material, and their spiral angles are more acute. Aberrant forms were present in both assemblages.

?TRILOCULINA ROTUNDA d'Orbigny, 1893
Text-fig. 1D

The specimen in Text-fig. 1D clearly belongs to the family MILIOLIDAE Ehrenberg 1839 (*sensu* Loeblich and Tappan, 1964) and was alive at the time of collection. Several other specimens of empty tests were present in the collected material. They are similar to the figured specimen.

The specimens are small (500 μ maximum length), translucent, quinqueloculine to triloculine in form with a bifid tooth. They are interpreted as juveniles of ?*Triloculina rotunda* d'Orbigny.

TRICHOHYALUS TROPICUS (Collins, 1958)
Text-fig. 1A, B, C, E, F

Diagnosis.—Our specimens are referred to this species on the basis of: trochospiral, plano-convex form of the test; presence of irregular, "vesicular" carbonate growth on the planar surface, covering all but the final two chambers; two whorls with 10 chambers in outer whorl; generally discorbid form shown by the spiral convex surface; coarsely punctate spiral surface, pores extending to outer part of the planar surface; small aperture on planar surface.

Remarks.—This species was first described by Collins (1958; Pl. 5, figs. a, b, c) as *Discorinopsis tropica.* A more complete description, though lacking priority, is offered by Hamlin (1960, Pl. 4, figs. 3–5), who presented the species as *Trichohyalus orfordensis.* Collins (1974) subsequently lists it as *T. tropicus.*

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ERRATA

The following errors, which the editors failed to correct after our examination of the proofs, are to be amended:

p.660 line 5 read: DE DECKKER
p.661 left, line 11 read: Lykke-Andersen; right l. 18 read our
p.662 right, line 3 from bottom read: In the maar, Lake Gnotuk
p.663 left, line 21 read: non-marine
p.664 left, line 10 read: Andersen; line 13 delete: and
p.669 right, line 9 read: (1958, Pl. 5, ...
p.670 left, line 7 read: p.285; line 19 read: Andersen; line 31 read 1953; right line 16 read: Resig, J.M.; line 21 read à test radiaire
Final line read: The University of Adelaide and the Salisbury College of Advanced Education both contributed $100 in support of this article.