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STRATIGRAPHIC AND ISOTOPIC AGES OF TERTIARY BASALTS AT MAUDE AND AIREY'S INLET, VICTORIA, AUSTRALIA

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ABSTRACT

Tertiary basalts at Maude and Airey's Inlet, Victoria, have been dated on the basis of foraminiferal and stratigraphic evidence and K-Ar determinations. The Maude Basalt, between two fossiliferous marine limestones, is shown to be early Longfordian (very early Miocene) in age, and has been dated by the K-Ar method as 21.4 m.y. Another basalt, overlain by marine limestone, at Airey's Inlet is stratigraphically older than late Janjukian (late Oligocene) and has been isotopically dated as 26.5 to 27 m.y. in age. The implications of these results in respect to local correlation, stages and foraminiferal zones, as well as agreement with the intercontinentally applied time scale, are discussed.

MAUDE BASALT

STRATIGRAPHIC RELATIONS AND AGE

In the vicinity of Maude (Figs. 1 and 2) and for about 10 km to the southeast the Maude Basalt (23 m thick at Maude; up to about 30 m thick elsewhere) overlies the Lower Maude Limestone Member of the Lower Maude Formation, and is in turn overlain by the Upper Maude Limestone (stratigraphic nomenclature after Bowler, 1963). The relationship between the basalt and the underlying limestone (Fig. 3) may be regarded as essentially conformable, although the contact is not well exposed; there is no evidence of notable erosion of the limestone, and the time interval between the cessation of limestone deposition and extrusion of the basalt is considered to have been negligible. The upper surface of the basalt is, in contrast, obviously eroded; pebbles of basalt are incorporated in basal beds of the Upper Maude Limestone and calcareous sediment fills deep crevices in the basalt.

The Lower Maude Limestone Member (9 m thick at Maude; up to 20 m thick elsewhere) contains a foraminiferal fauna in which planktonic specimens are very rare; benthonic species include Sherbornina atkinsoni Chapman, Calcarina mackayi (Karrer), Astrononion centroplax Carter and Amphistegina sp. (Use of generic names in this paper follows common usage in fairly recent Australian literature; some of these names have been lately revised or require revision). In terms of informal numbered zones based on Carter's (1958 a, b etc.) "Faunal Units", the Lower Maude Limestone Member most probably represents zone 5, although Victoriella conoidea (Rutten), characteristically present in this zone, has not been observed in the limestone; possibly the upper strata of the member extend into zone 6. Thus, in terms of southeastern Australian stages, used here in the redefined sense of Carter (1959), the Lower Maude Limestone Member is late Janjukian, possibly in part very early Longfordian, in age.

The numbered zones used here are regarded as informal regional time-rock, i.e., chronostratigraphic units, or approximating such as far as can be ascertained. Other workers, e.g., Wade (1964), Taylor (1966), Ludbrook and Lindsay (1969), have proposed different schemes of zonation and zonal nomenclature for application in southeastern Australia. These different schemes have been compared with each other (and with Carter's 'Faunal Units' and zones) and correlated with the internationally recognized sequence of P- and N- zones, based essentially on tropical planktonic foraminiferal associations, by McGowran et al. (1971). A single scheme of formally named Tertiary foraminiferal zones is not at present widely accepted in Australia.

In the vicinity of Maude, basal beds of the Upper Maude Limestone (12 m thick at Maude, thinner elsewhere) contain sparse foraminiferal assemblages. Wade and Carter (1957) recorded the presence of both Sherbornina atkinsoni and S. cuneimarginata Wade at the base of the limestone at Maude (locality F1 in Fig. 2, where Bowler's section 15 is exposed), while Bowler (1963) reported Lepidocyclina and Gypsina howchini Chapman from strata immediately overlying the Maude Basalt at this locality. None of these species has been observed in the basal beds of the formation at Maude by the present writers: however, S. cuneimarginata and Planorbulinella plana (Heron-Allen and Earland) have been noted at a higher stratigraphic level in the Upper Maude Limestone (just below Bowler's bed 'C'). To the south and south-southeast of Maude Globigerinoides trilobus trilobus (Reuss) is present at or very near the base of the limestone in some sections, e.g., at localities F3 (near Bowler's section 13), F6 and other exposures further southeast of Lownde's Bridge, while in other sections, e.g., F4 (= Bowler's section 12) and F5, both near 'The Pimple' hill, G. trilobus has not been observed in the lower 6 m of the formation, although other planktonic foraminifera, including rare Globoquadrina dehiscens (Chapman, Parr and Collins), are common. In sections at F2 (= Bowler's section 14), F4 and F6, P. plana and/or Operculina victoriensis Chapman and Parr are also present at or very near the base of the Upper Maude Limestone.

On the basis of the above evidence the Upper Maude Limestone in exposures south and south-southeast of Maude (i.e., in the vicinity of the localities from which samples of the Maude Basalt were collected for K-Ar dating) is regarded as representing zones 6 to 7 and thus as early to mid-Longfordian in age. At Maude, the limestone represents a similar time interval on the evidence of both Wade and Carter (1957) and the writers' observations. Bowler's (1963) record of Lepidocyclina, indicating Batesfordian age, is not in agreement with the conclusions of other workers.

Apparently the unconformity at the top of the Maude Basalt represents a relatively short break in the continuity of deposition. The basalt is regarded as equivalent in age to zone 6, probably to its lower rather than upper part and perhaps even as approximating the boundary between zones 5 and 6. Thus, the Maude Basalt is most probably very early Longfordian in age.

ISOTOPIC DATING

The isotopically dated whole rock samples of the Maude Basalt were collected at three localities up to 5 km apart (Fig. 2). The analytical methods and precision of argon and potassium determination in this study are the same as those reported by McDougall (1966) and Cooper (1963). The K-Ar results listed in Table 1 (a) are quite concordant and give a mean age of 21.4 ± 0.2 m.y., the error being one standard deviation of the mean (it is noted that this 21.4 m.y. age is slightly older than that referred to in Page and McDougall, 1970, due to a calibration adjustment). The errors quoted for individual ages are also one standard deviation as calculated from the uncertainties in the physical measurements. One of the results (69-9) has been duplicated to within experimental error and the average for the four samples of 21.4 ± 0.2 m.y. is regarded as a meaningful minimum age for the Maude Basalt.

DISCUSSION

The Oligocene-Miocene boundary is now generally equated, though not by all workers (e.g., Eames, 1970), with the base of the Aquitanian Stage. In the type Aquitanian region of southwestern France, the Aquitanian is separated from mid-Oligocene strata by an unconformity. As reported by Berggren (1972), the base of the Miocene has been drawn by the Committee on Mediterranean Neogene Stratigraphy a short distance above this unconformity at Moulin de Bernachon. The first evolutionary appearance of the Globigerinoides trilobus group, which includes several subspecies referred to under different names by different authors, is commonly known as the Globigerinoides Datum and is agreed to be closely correlative with the base of the Aquitanian Stage (e.g., Bandy, 1964; Blow, 1969; Berggren, 1969, 1972). Other authors have stressed, however, that such correlation cannot be regarded as precise; e.g., Scott (1972) has stated that the first evolutionary appearance of G. trilobus primordius Blow and Banner precedes the base of the stratotype Aquitanian. In terms of the widely used sequence of Banner and Blow's (1965) planktonic foraminiferal zones, the Globigerinoides Datum marks the base of Zone N4 as redefined by Blow (1969).

Using the K-Ar method, Turner (1970) dated volcanic rocks stratigraphically related to the boundary between the Zemorrian and Saucesian stages in California and concluded that this boundary is about 22.5 m.y. old. Blacut and Kleinpell (1969) correlated the Zemorrian-Saucesian boundary with the base of Bolli's (1957) Globoratalia kugleri Zone, which is equivalent to Zone N4 as originally defined by Banner and Blow (1965); i.e., its base is slightly higher than the base of Zone N4 as amended by Blow (1969). Largely on the basis of these conclusions Berggren (1969, 1972) assigned a 22.5 m.y. age to the Oligocene-Miocene boundary, which he equated both with the base of Zone N4 and the Globigerinoides Datum. Comparison of the opinions of various authors shows that detailed correlation of the series and stages defined in Europe with the tropical planktonic foraminiferal zones is still rather controversial. Recently Hornaday (1972) has criticized the validity of some such correlations and the hasty application of radiometric dates to some boundaries. Hornaday, following Bandy and Ingle (1970), correlated the top of the Zemorrian Stage with the top rather than the base of the Globorotalia kugleri Zone; however, in agreement with Berggren (1969, 1972), both Bandy and Ingle (1970) and Hornaday (1972) regarded the top of the Zemorrian Stage as corresponding closely to the Oligocene-Miocene boundary. Thus, while the base of Zone N4 and the Globigerinoides Datum may be slightly older than the base of the stratotype Aquitanian, Berggren's assignment of a 22.5 m.y. age to the Oligocene-Miocene boundary appears to be a satisfactory and the best available estimate.

In southeastern Australia, as elsewhere, precise recognition of the Oligocene-Miocene boundary is difficult. In this region the first appearance of Globigerinoides trilobus trilobus, marking the base of zone 7, is a stratigraphically more useful and a later event than the first appearance of the genus. Only rare specimens of Globigerinoides (e.g., the forms referred to as G. quadrilobatus primordius and G. q. altiapertura by Wade, 1964) have been recorded from strata recognized as older than zone 7 (including beds as old as zone 5). Thus, the Globigerinoides Datum is not a reliably recognizable horizon in southeastern Australia; a similar situation exists in New Zealand (Scott, 1970; Jenkins, 1970).

Carter (1958 a, b etc.) defined the top of zone 5 as coinciding with the disappearance of Victoriella conoidea and considered that Globoquadrina dehiscens first appears at a slightly higher horizon in zone 6. Other workers, e.g., Wade (1964) and Ludbrook (1971), have noted that in some areas the ranges of the two species overlap; hence Wade considered that G. dehiscens appears in zone 5 and Ludbrook that V. conoidea ranges upwards into the lower part of her Globoquadrina dehiscens dehiscens Zone. In New Zealand, occurrences of V. conoidea also coincide with the lower part of the range of G. dehiscens (Hornibrook, 1961). The distribution of the benthonic V. conoidea is certainly influenced by variation in facies; however, the planktonic G. dehiscens also occurs rather sporadically in strata corresponding to the lower part of its range, being generally absent from strata recognized as representing zone 5 and commonly rare or absent in beds belonging to zone 6. Whether the original definition by Carter of the boundary between zones 5 and 6 is retained or the base of zone 6 redefined as marked by the first appearance of G. dehiscens, is not very important for the purposes of the present discussion since in the areas considered here in detail the ranges of V. conoidea and G. dehiscens are mutually exclusive. In any case, correlation with overseas sequences is complicated by records of first appearances of G. dehiscens at apparently different stratigraphic horizons in different regions, as discussed by various authors (among them Jenkins, 1970, and McGowran et al., 1971). As also pointed out by McGowran et al., such correlation is further handicapped by the discrepancy between Bolli's (1957) record that G. trilobus trilobus first appears at the base of the Catapsydrax dissimilis Zone (i.e., at the base of Zone N5) and Blow's (1969) report that this appearance occurs in Zone N6; following McGowran et al. (1971), Blow's opinion is accepted here.

During the last decade the boundary between zones 5 and 6 or a closely corresponding horizon (Glaessner, 1959; Wade, 1964; Taylor, 1966; Ludbrook, 1967, 1971; Ludbrook and Lindsay, 1969), less commonly the boundary between zones 6 and 7 (Carter 1958 a, b; 1959, 1964; Reed, 1965), has been tentatively equated with the Oligocene-Miocene boundary by Australian workers. Recently the Oligocene-Miocene boundary, as corresponding to the base of the intercontinentally applied Zone N4, has been placed slightly below the top of zone 5 by McGowran et al. (1971). This may well be more correct than equating the top of zone 5 with the top of the Oligocene; both estimates are in agreement with Jenkins' (1966) report that Globoquadrina dehiscens is present in type lower Aquitanian, while Globigerinoides trilobus trilobus appears at a stratigraphically higher level.

If a horizon slightly below or even at the top of zone 5 is equated with the Oligocene-Miocene boundary, the 21.4 m.y. age of the very early Longfordian Maude Basalt agrees very well with Berggren's (1969, 1972) assignment of a 22.5 m.y. age to the beginning of the Miocene.

BASALT AT AIREY'S INLET

STRATIGRAPHIC RELATIONS AND AGE

At Split Point (Airey's Inlet; Fig. 1) basalt included in the Angahook Member of the Demon's Bluff Formation is unconformably overlain by the Point Addis Limestone Member of the Jan Juc Formation (Fig. 4; stratigraphic nomenclature modified after Raggatt and Crespin, 1955). The limestone is 23 m thick. The basalt is regarded as part of a truncated basaltic scoria cone (Singleton and Joyce, 1969); its base is not exposed. In coastal sections to the northeast the Angahook Member is represented largely by pyroclastic and continental sediments, which overlie the Anglesea Member (comprising both Anglesea Siltstone Member and Addiscot Greywacke Member of Raggatt and Crespin, 1955) of the Demon's Bluff Formation.

The Point Addis Limestone Member at Airey's Inlet contains a rather sparse foraminiferal fauna in which planktonic specimens are very rare. The benthonic foraminifera _Victoriella conoidea_, _Sherbornina atkinsoni_, _Calcarina mackayi_, _Astrononion centroplax_ and _Amphistegina_ sp. are present and _Crespinina kingscotensis_ Wade has also been recorded by Raggatt and Crespin (1955). Paleontologic and stratigraphic considerations, especially comparison with the section at Bell's Headland (19 km to the northeast; Figs. 1 and 4), exclude the probability that the basal strata of the limestone at Airey's Inlet are as old as zone 4; they are probably slightly younger than the base of zone 5.

Paleontologic dating of the Point Addis Limestone Member provides a reasonably accurate minimum stratigraphic age for the underlying basalt at Airey's Inlet. Estimates of the maximum age of the basalt are based on somewhat equivocal evidence, as discussed in the following paragraph.

The Angahook Member has been generally (e.g., Raggatt and Crespin, 1955; Singleton, 1968) regarded as equivalent in age either to the upper part of the Anglesea Member or to the lower part of the Jan Juc Formation in those nearby sections where the Anglesea Member is directly and conformably overlain by the Jan Juc Formation. Such a sequence is exposed only at Bell's Headland, where the lower part of the Jan Juc Formation, about 15 m thick and overlain conformably by the Point Addis Limestone Member, represents zone 4. Chiloguembelina cubensis (Palmer), present in the lowermost part of the Jan Juc Formation, is absent from the uppermost beds of zone 4 as defined by Carter (1958 a, b etc.), who referred to this species as Gümbelina rugosa. The upper strata of the underlying Anglesea Member have been commonly somewhat arbitrarily regarded as representing zone 3 or as Upper Eocene in age; very rare planktonic foraminifera have been observed in samples of the member from bores not far from Bell's Headland (K.J. Reed, unpublished report, 1961; Taylor, 1965). It is more probable that in respect to time of deposition these beds span a 'gap' separating zones 3 and 4. The top of zone 3 has been commonly regarded as marked by the disappearance of Globigerina linaperta Finlay; the somewhat later disappearance of the closely related G. angiporoides Hornibrook may be a more valid criterion since, as observed by Lindsay (1967), McGowran et al., (1971) and other authors, Carter's (1958 a) concept of G. linaperta apparently included G. angiporoides. It appears that extinction of both G. linaperta and G. angiporoides in

Victoria preceded by certain time intervals the initiation of deposition of the Jan Juc Formation at Bell's Headland. The existence of a 'gap' between zones 3 and 4, based on 'Faunal Units' originally defined from two widely separated areas (The Aire district southwest of the Otway Ranges, and Bell's Headland), has been recently implied by Ludbrook and Lindsay (1969). Equating the disappearance of G. angiporoides rather than G. linaperta with the top of zone 3 reduces the magnitude of the 'gap', but apparently does not eliminate it entirely; such elimination could be achieved, of course, by extending the definition of zone 4 downwards to include an appropriate interval of strata directly underlying the Jan Juc Formation at Bell's Headland.

In short, the available paleontologic and stratigraphic evidence indicates that the basalt at Airey's Inlet is definitely no younger than the lowermost part of zone 5 (late Janjukian). Similar evidence for the lowest stratigraphic limit of the basalt is rather tenuous; the basalt may be regarded as no older than zone 4, but the possibility that it is as old as zone 3 cannot be excluded.

ISOTOPIC DATING

Two whole rock samples of basalt from Split Point (Airey's Inlet) have been dated by the K-Ar method in duplicate. The two mean ages of 25.8 m.y. and 26.7 m.y. agree to within experimental error, but as the two measurements on sample 69-5667 are not quite concordant, it is suggested that the older age of 26.7 m.y. may be the more meaningful estimate. These limited data point to a 26.5 to 27 m.y. minimum age of the basalt at Airey's Inlet.

DISCUSSION

In recent years it has been generally agreed by Australian workers that the top of the Eocene in southeastern Australia is best recognized as marked by the disappearance of Globigerina linaperta

(Wade, 1964; Lindsay, 1967; Ludbrook and Lindsay, 1969; McGowran et al., 1971); this contrasts with Blow's (1969) report that G. linaperta disappears within Zone P16 rather than at the top of Zone P17. However, as discussed previously, there is some uncertainty concerning the criteria defining the top of zone 3 and hence as to whether the top of zone 3 should be equated with the top of the Eocene or with a higher Oligocene horizon. According to Blow (1969), the related G. angiporoides ranges upwards into the lower part of Zone P19. Zone 4 has been generally regarded as representing an early Oligocene (Wade, 1964; Singleton, 1968) or a mid-Oligocene (Ludbrook, 1967; Ludbrook and Lindsay, 1969; McGowran et al., 1971) time interval. The top of zone 4 is not far above the disappearance of Chiloguembelina cubensis; both Berggren's (1972) assignment of a 28 m.y. age (i.e., within Zone P21) to the Chiloguembelina (extinction) Datum and Blow's (1969) report that this genus ranges even higher, at least up to the top of Zone N3, favour the mid-Oligocene estimates of the age of zone 4. The top of the range of C. cubensis in southeastern Australia appears to agree well with Berggren's Chiloguembelina (extinction) Datum, but, as indicated by McGowran et al., (1971), to be lower than the top of the range of 'Chiloguembelina ex group cubensis' reported by Blow.

In contrast to the Maude Basalt, the basalt at Airey's Inlet cannot be firmly dated on the basis of paleontologic and stratigraphic evidence since reliable evidence in respect to its maximum stratigraphic age is lacking, as discussed previously. Thus the K-Ar age of the Airey's Inlet basalt cannot be readily applied in either supporting or contradicting Berggren's (1972) time scale. However, the dating of the basalt provides valuable evidence for local stratigraphic interpretation and correlation. The 26.5 to 27 m.y. age of the basalt at Airey's Inlet, corresponding to mid-Late Oligocene on Berggren's time scale, indicates that the basalt is equivalent in age to the upper part of zone 4.

Apparently the unconformity between the basalt and the overlying limestone, though spectacular in expression, represents a brief interval of non-deposition. Although the available paleontologic and stratigraphic evidence has permitted consideration of the Angahook Member as representing a time interval near the Eocene-Oligocene boundary (e.g., Ludbrook, 1967; Singleton, 1968), the K-Ar age of the Airey's Inlet basalt suggests that the Angahook Member is middle to late Oligocene (i.e., late Oligocene on Berggren's time scale), equivalent in age to zone 4 rather than zone 3 and to the lower part of the Jan Juc Formation rather than to the upper part of the Anglesea Member of the Demon's Bluff Formation.

In addition, the radiometric age of the basalt at Airey's Inlet indicates that zone 5 is no older than 26.5 to 27 m.y. As discussed previously, isotopic dating of the Maude Basalt suggests that the zone (and the Janjukian Stage) is no younger than 21.4 m.y. Thus zone 5 appears to represent a time interval of not more than 5 to 5.5 m.y.

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Table 1: K-Ar whole rock ages of basalts at Maude and Airey's Inlet.

Sample No.	K%		Radiogenic ^{40}Ar ($\times 10^{-10}$ moles/gm)	%^{40}Ar (radiogenic)	Age (m.y.)	Locality
(a) Maude Basalt						
69-9	0.887) 0.886)	0.887	0.342 0.347	38.3 68.6	21.5 ± 0.3 21.8 ± 0.4	Moorabool River, southeast of Lethbridge
69-10	0.866) 0.866)	0.866	0.335	33.8	21.6 ± 0.4	" " "
69-5663	0.917) 0.913)	0.915	0.347	53.4	21.2 ± 0.4	Moorabool River, east of 'The Pimple' hill.
69-5665	0.787) 0.791)	0.789	0.295	60.8	20.9 ± 0.3	Moorabool River, near Lownde's Bridge.
(b) Airey's Inlet basalt						
69-5667	1.218) 1.223)	1.221	0.547 0.581	42.0 61.8	25.0 ± 0.4 26.5 ± 0.5	Airey's Inlet, Split Point.
69-5869	1.271) 1.282)	1.277	0.607 0.615	35.4 34.2	26.5 ± 0.6 26.9 ± 0.6	" " "

Constants used: $\lambda_\beta = 4.72\times10^{-10}\ yr^{-1}$, $\lambda_\varepsilon = 0.585\times10^{-10} yr^{-1}$,

$^{40}K/K = 1.19\times10^{-2}$ atom percent.

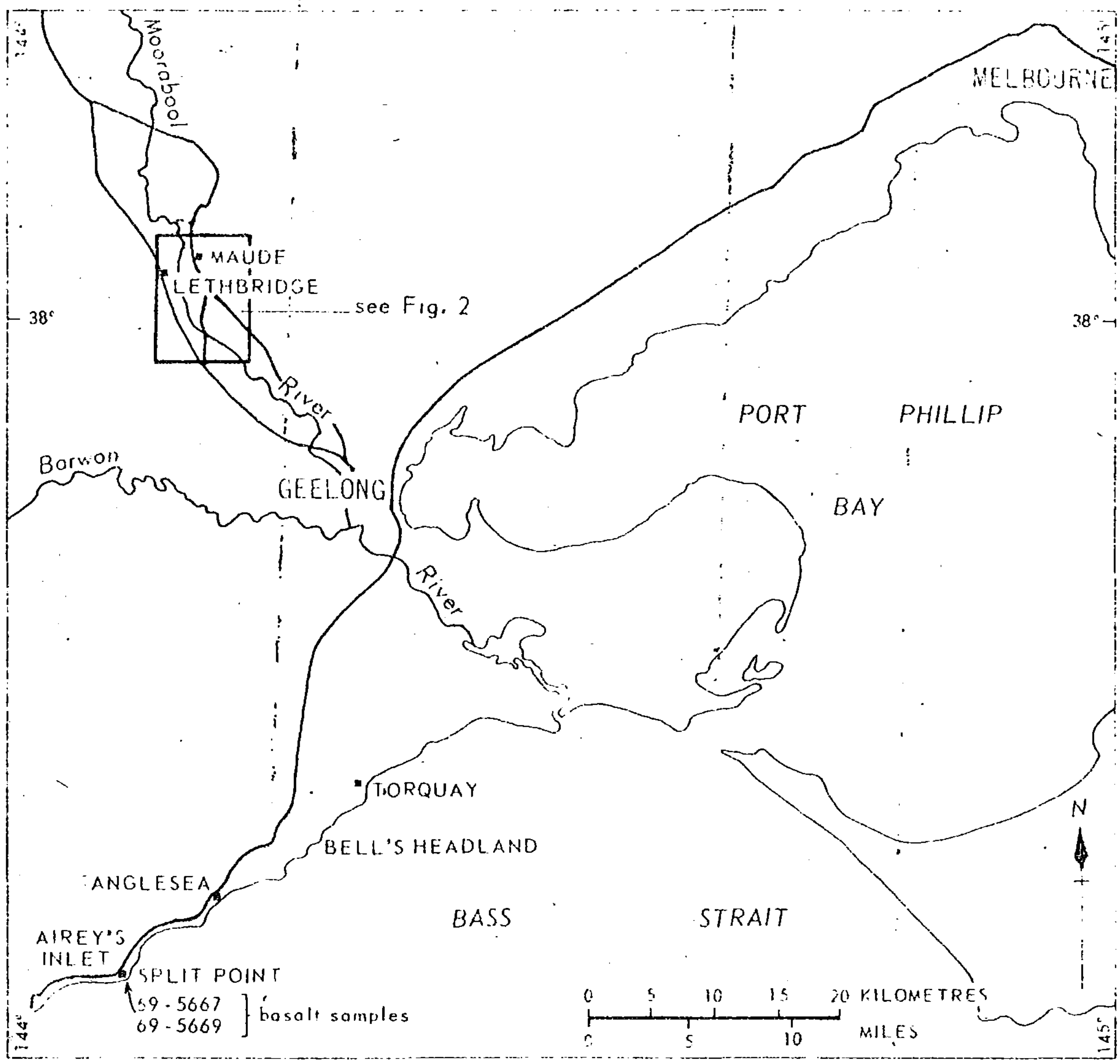

Fig. 1. Locality Map.

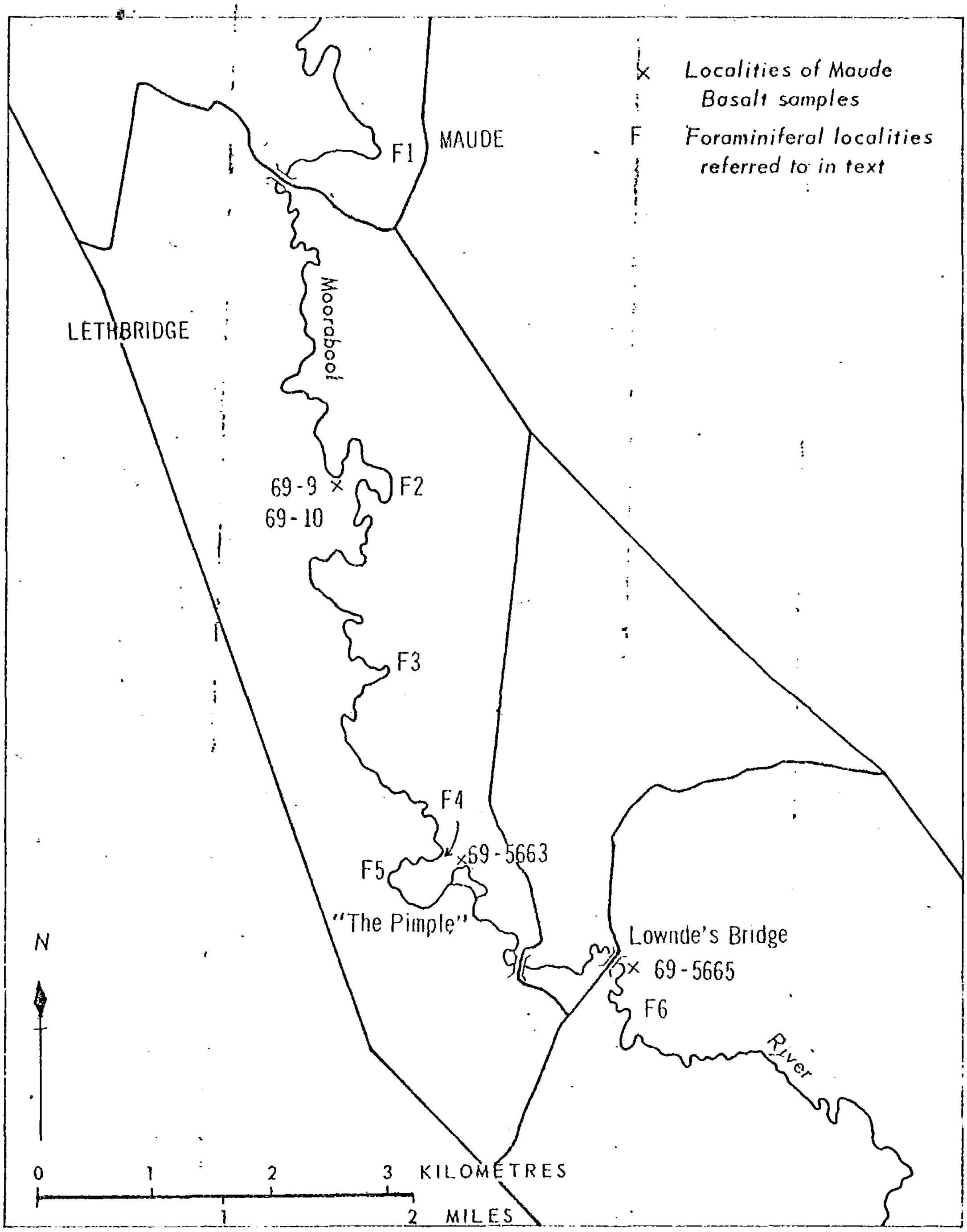

Fig. 2. Maude area locality map.

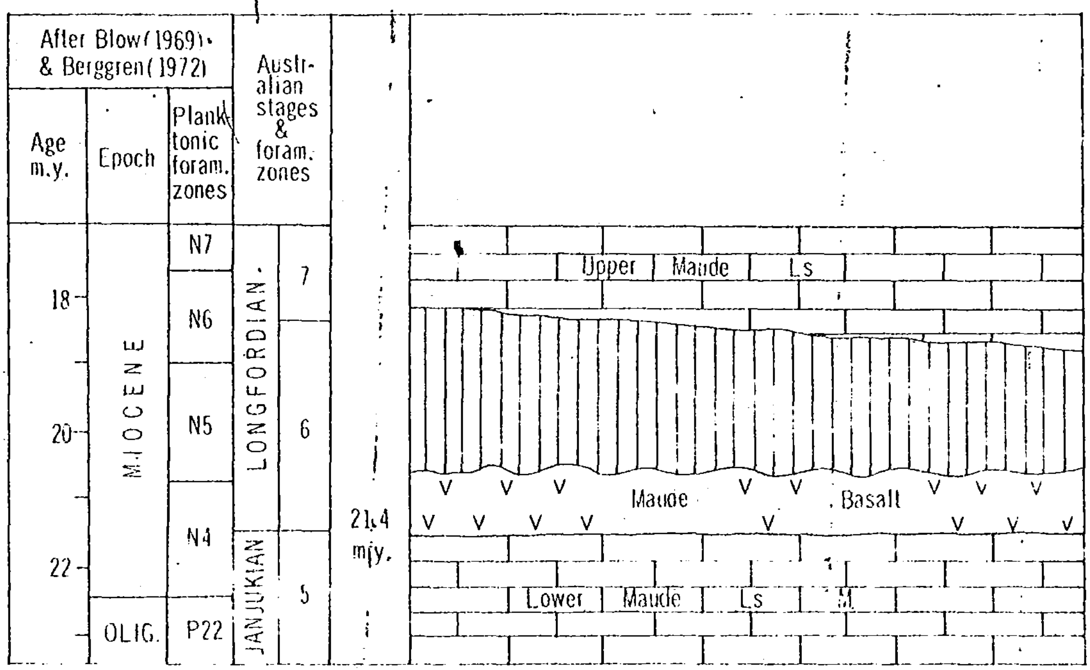

Fig. 3. Stratigraphic relationships in the vicinity of Maude.

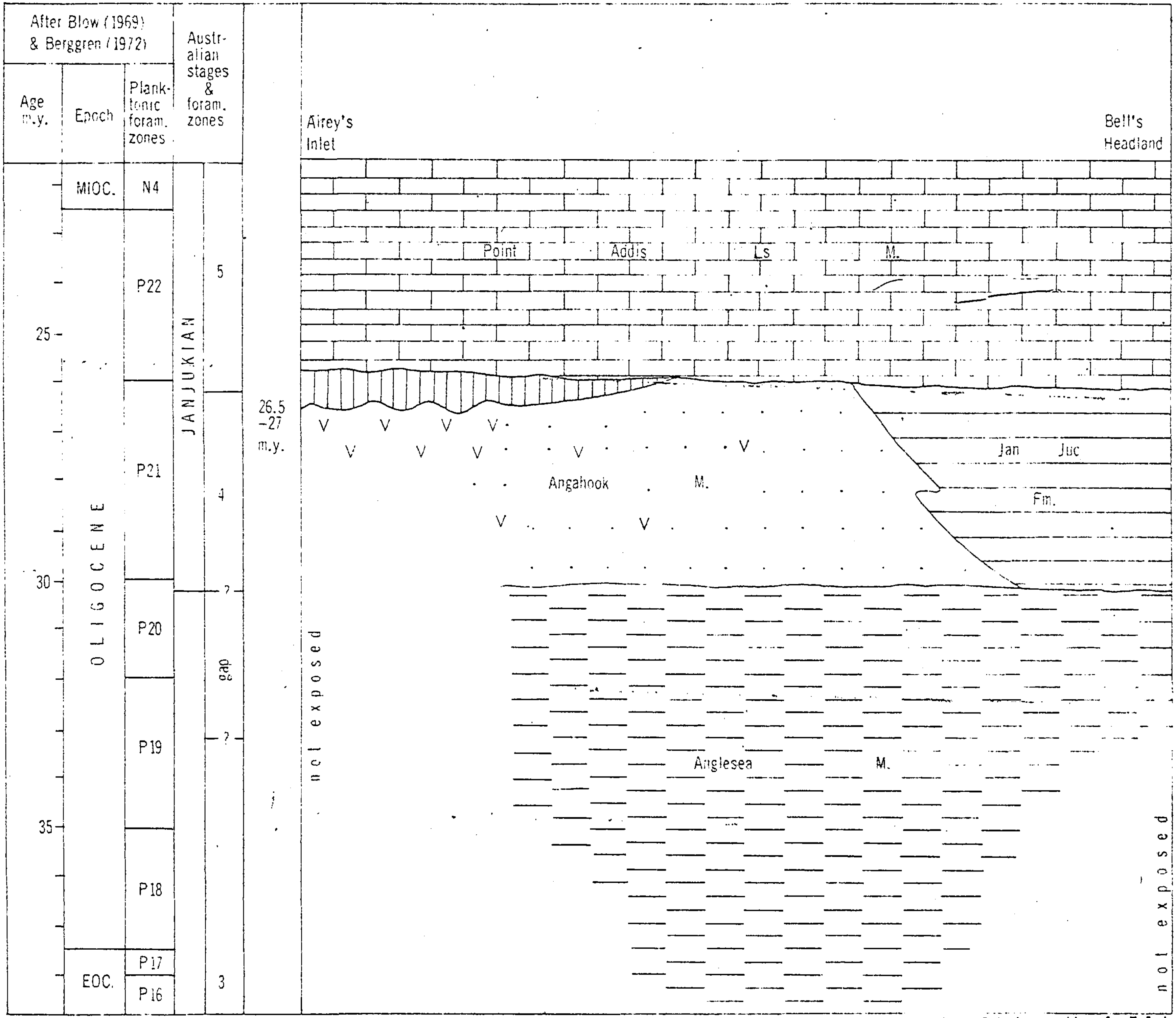

Fig. 4. Stratigraphic relationships at Airey's Inlet and Bell's Headland. Stratigraphic relationships in the interval between Airey's Inlet and Bell's Headland are shown in a generalized way; in most of the coastal exposures the Point Addis Limestone Member has been removed by erosion.