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Age constraints on Oligocene sedimentation in the Torquay Basin, southeastern Australia

S. McLAREN*, M. W. WALLACE, S. J. GALLAGHER, J. A. DICKINSON AND A. McALLISTER

School of Earth Sciences, University of Melbourne, Vic. 3010, Australia.

The Otway, Gippsland and central coast basins (including the Torquay Basin, Sorrento Graben and Port Phillip Basin) preserve one of the most complete records of Mesozoic and Cenozoic sedimentation in southern Australia. However, robust age constraints on sedimentation are scarce. Strontium isotope analysis of calcitic bioclasts from the Jan Juc Marl of the Torquay Group, Torquay Basin, gives a range of possible ages between 24.2 and 27.9 Ma for the Jan Juc Marl, and an age of 24.24 Ma (+1.3 Ma, −1.2 Ma) for the base of the Point Addis Limestone. These data demonstrate that the Jan Juc Marl and the lower Point Addis Limestone are age-equivalent facies representing deep- and shallow-water sedimentation, respectively. ^{40}Ar/^{39}Ar whole-rock analysis of the underlying Angahook Formation basalt of the Demons Bluff Group gives an eruption age of 28.7 ± 0.2 Ma. The upper boundary of the Angahook Formation is a subaerial exposure surface and paleoshore platform over which younger marine sediment onlapped during subsequent marine transgression. These new age constraints provide an improved age datum, of around 28.7 Ma, for the base of the Janjukian Stage. This age is very close to the European Rupelian–Chattian boundary, which is the accepted boundary between the Early and Late Oligocene with an estimated age of 28.4 Ma.

KEY WORDS: argon–argon dating, geochronology, Janjukian, strontium-isotope stratigraphy, Tertiary.

INTRODUCTION

Tertiary sedimentary basins in southeastern Australia were major sediment depocentres from the Early Cretaceous to the Middle Miocene. Sedimentation in these basins represents a record of rifting related to the separation of Australia and Antarctica and together the basins preserve one of the most complete records of Mesozoic and Cenozoic sedimentation in southern Australia.

Tertiary depocentres include the Otway and Gippsland Basins, and the central coast basins including the Torquay Basin, Sorrento Graben and Port Phillip Basin (including the Ballan Graben) which lie between the two (Abele *et al*. 1988) (Figure 1). The sedimentary record in these basins forms the basis for the Australian regional stages of the Tertiary defined by Singleton (1941). The Singleton (1941) subdivision, along with subsequent refinements, has provided a framework for relating Australian sea-level events to a global stratigraphic context (McGowran *et al*. 1997). Development of biostratigraphic zonation relationships for the defined stages has been subject to ongoing work (Li *et al*. 1999), although given the absence of key zonal planktonic foraminifera in the generally shallow platformal marine limestone and marl, zones and ages cannot be tightly constrained. The absence of robust biostratigraphic or chronostratigraphic constraints has limited the applicability of the defined regional stage names, and these are rarely used outside southeastern Australia.

Exposures of Torquay Basin sediments on the Torquay coast represent the most complete and continuous Oligocene section in Australia and form the type section for the Janjukian Stage, first introduced by Hall & Pritchard (1902) and later redefined by Singleton (1941) and Raggatt & Crespin (1955). The base of the Janjukian Stage is defined by an unconformity between the terrestrial and marginal marine Demons Bluff Group and the overlying marine carbonate of the Jan Juc Marl of the Torquay Group; the top of the stage is defined by the contact with the overlying Puebla Formation (Figure 2). The Janjukian has been dated between Early Oligocene and Early Miocene using foraminifera (Li *et al*. 1999) and nannofossils (Siesser 1979) and is thought to be equivalent to the European Chattian and the New Zealand Whaingaroan and Duntroonian Stages. However, correlation with these standard international stage names is still unresolved, largely because few age constraints are available for the southeastern Australian sediment. Using strontium isotope stratigraphy and ^{40}Ar/^{39}Ar step-heating we report new age data for (i) the Angahook Formation of the Demons Bluff Group and (ii) the Jan Juc Marl and the Point Addis Limestone of the Torquay Group. These new age data provide an important tie on

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*Corresponding author: mclarens@unimelb.edu.au

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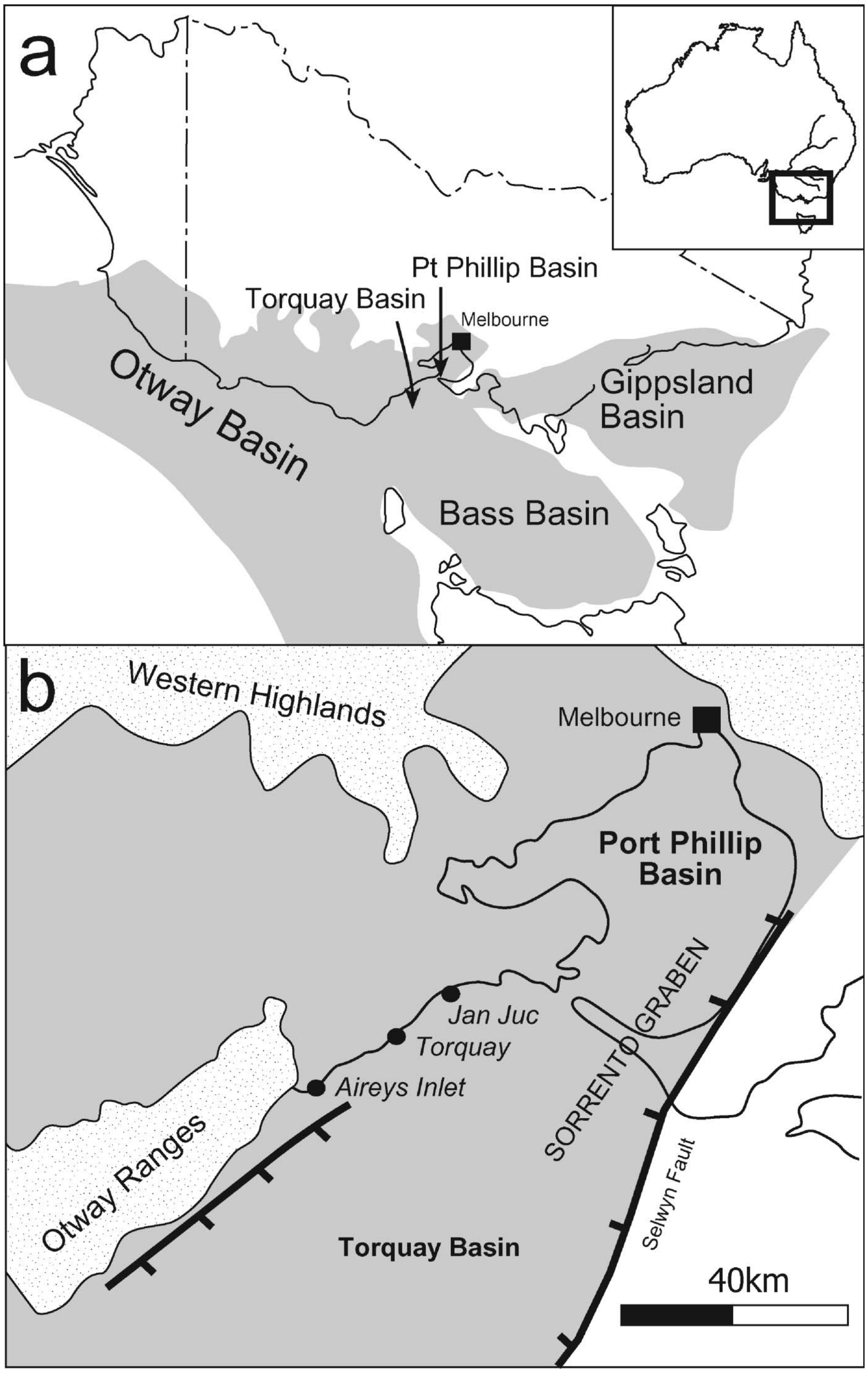

Figure 1 (a) Location map showing major Tertiary basins in southeastern Australia. (b) Central coast basins region, including the Torquay Basin.

the chronostratigraphy of the Janjukian Stage and its biostratigraphic zonation. The time-scale of Gradstein *et al.* (2004) is used throughout this paper. Relevant age datums are defined thus: Eocene–Oligocene, 33.90 ± 0.1 Ma; Early–Late Oligocene, 28.45 ± 0.1 Ma; Oligocene–Miocene, 23.03 ± 0.0 Ma.

STRATIGRAPHY

The largely non-marine Otway Group consists of volcaniclastic and fluvial sediments, and forms the basal sedimentary package in the central coast Otway and Gippsland Basins (where it is called the Strzelecki Group). The Otway Group was deposited in the Early Cretaceous (Dettmann & Playford, 1969) and is overlain unconformably by the non-marine Paleocene to Middle Eocene Eastern View Group, a sequence of brown coal, clay and sand (Raggatt & Crespin 1952, 1955). The age of the coal measures at the top of the Eastern View Group is constrained to the Middle Eocene *Nothofagidites asperus* pollen zone (Christophel *et al.* 1987; Holdgate *et al.* 2001).

The Eastern View Group is overlain by terrestrial and paralic sediments of the Eocene to Oligocene Demons Bluff Group. The Demons Bluff Group [originally defined by Raggatt & Crespin (1952) as the Demons

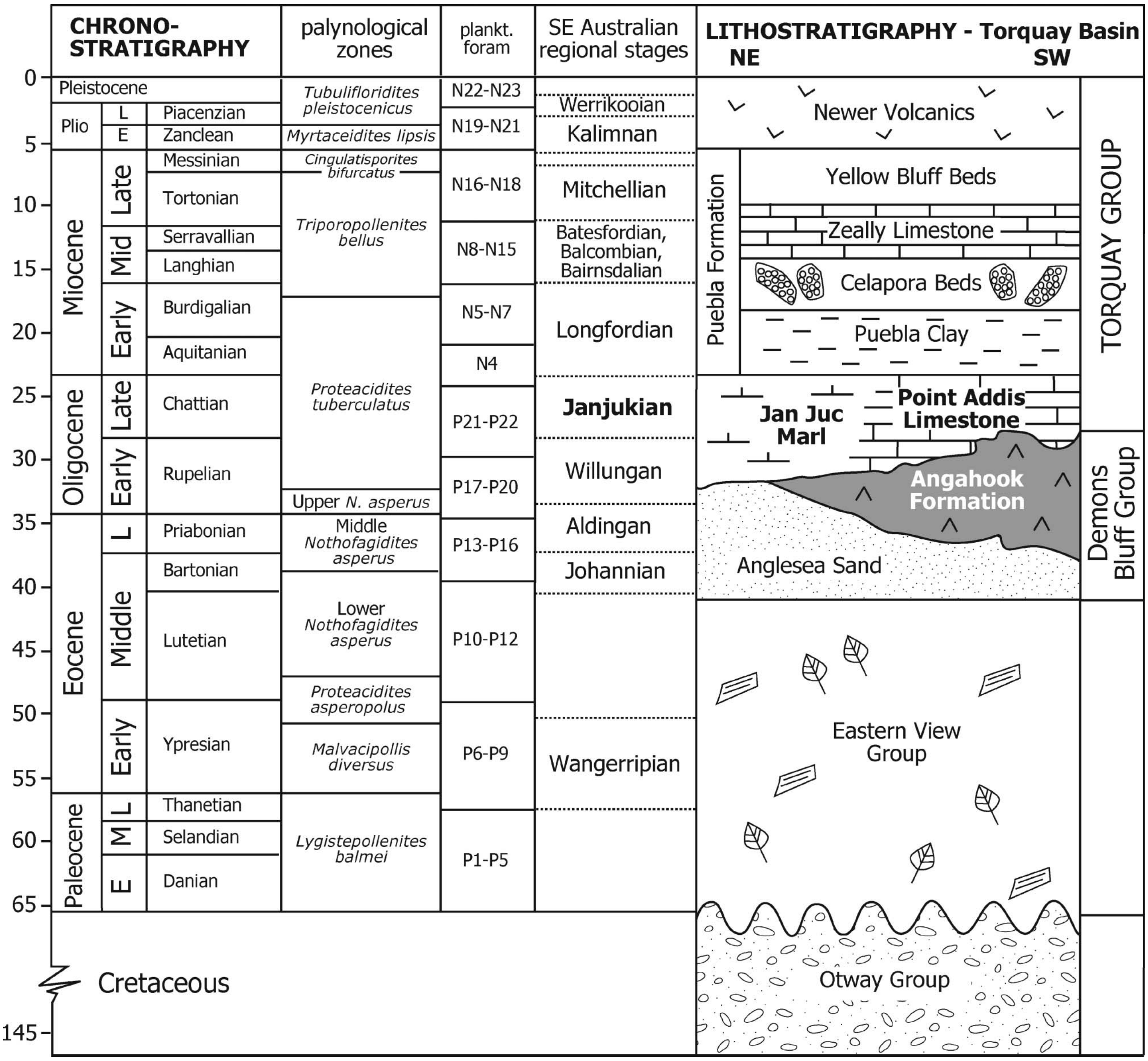

Figure 2 Stratigraphy of the Torquay Basin, showing the relationship of map units to chronostratigraphic, foraminiferal and palynological zonation with respect to the time-scale of Gradstein *et al.* (2004). Modified from Abele *et al.* (1988), McGowran *et al.* (1997), Nicolaides & Wallace (1997), Holdgate & Gallagher (2003).

Bluff Formation and renamed by Trupp *et al.* (1994)] consists of the marginal marine Anglesea Sand, and sandstone, conglomerate, claystone, basalt and pyroclastics of the Angahook Formation (Singleton 1973; Holdgate *et al.* 2001). It is thought to correlate with the largely subsurface Nirranda Group in the Otway Basin to the west, and the Traralgon Formation in the Gippsland Basin to the east (Abele *et al.* 1988; Gallagher & Holdgate 2000).

The Demons Bluff Group is overlain by marine carbonate of the Torquay Group (Raggatt & Crespin 1952) (Figure 2). The sequence of deposition from the Otway Group to the Torquay Group has been interpreted to represent a transgressive sequence deposited on a shallow to open shelf (Reeckmann 1979; Nicolaides & Wallace 1997).

The age of the terrestrial and marginal-marine units of the Otway, Eastern View and Demons Bluff Groups are well constrained from palynological floras. However, there are only few existing age constraints available for the overlying Torquay Group. Stratigraphic relationships within the Torquay Group and between the Torquay Group and the underlying Demons Bluff Group are also poorly resolved. In this section, we summarise existing stratigraphic, chronological and field data focusing on the Demons Bluff and Torquay Groups. Although much of the Torquay Basin succession occurs offshore, good exposures are found in coastal sections from the Otway Ranges to around Torquay in the northeast (Abele *et al.* 1988) (Figure 1). Observations along a coastal section from Aireys Inlet towards Torquay, where the units and their contacts are best exposed, form the basis of this paper.

Demons Bluff Group: Angahook Formation

The Angahook Formation is a volcaniclastic unit in the marginal-marine Demons Bluff Group (Raggatt & Crespin 1952; Reeckmann 1979). It is lithologically varied and consists of shallow-marine sedimentary units as well as basalt, tuff, breccia and pyroclastics (Reeckmann & Partridge 1988; Abele *et al.* 1988). Previously the Angahook Formation has been thought to be equivalent in age to either the upper 'Anglesea Member' or the lower 'Jan Juc Formation' (Raggatt & Crespin 1955). More recently Reeckmann & Partridge (1988) reported spore–pollen ages for sediments of the Angahook Formation within the Upper *Nothofagidites asperus* (Early to Late Oligocene) and *Proteacidites tuberculatus* (Late Oligocene–Early Miocene) zones. Two duplicate whole-rock K–Ar ages between 25.7 ± 0.4 and 27.6 ± 0.6 Ma (*25.0 ± 0.4* and *26.9 ± 0.6* Ma) with a mean of 26.9 ± 0.8 Ma for the Angahook Formation basalt from Aireys Inlet, reported by Abele & Page (1974), provide the only numerical age constraints on deposition of the Demons Bluff Group. Note that these ages have been recalculated using the revised decay constants recommended by Steiger & Jäger (1977); the original published ages of Abele & Page (1974) are indicated in italics.

Singleton & Joyce (1969) suggested that the Angahook Formation was part of a truncated scoria cone while Holdgate & Gallagher (2003) reported basalts and laterally equivalent pyroclastic sediment in coastal exposures near Aireys Inlet. The presence of an unconformity between the Angahook Formation basalt and the overlying Point Addis Limestone was first recognised by Hall (1910). Reeckmann (1994) agreed with this observation and suggested that the Angahook Formation basalt represented a subaerial flow. In contrast, Cas & Wright (1987) and Bourton (1988) have reported peperitic textures and pillow structures from the same coastal exposures around Aireys Inlet and suggest that the basalt is a shallow-level intrusive into the limestone.

Torquay Group

The Torquay Group comprises Oligocene to Miocene marine limestones and marls of the Point Addis Limestone, Jan Juc Marl, Puebla Clay and Zeally Limestone (Raggatt & Crespin 1952). [The Point Addis Limestone, Jan Juc Marl and a series of transitional sediments have previously been referred to as the Jan Juc Formation (Reeckmann 1979; Abele *et al.* 1988; Holdgate *et al.* 2001).] In the Otway Basin to the west the Clifton Formation (Baker 1944), the basal unit of the Heytesbury Group, is thought to be correlative of the Point Addis Limestone and Jan Juc Marl (Gallagher & Holdgate 2000).

The Jan Juc Marl is a fine-grained silty glauconitic marl with sandy calcarenite interbeds (Abele *et al.* 1988). The unit coarsens upwards and contains a prominent glauconite-rich horizon (Reeckmann 1994) and a number of carbonate cycles capped by well-cemented burrowed horizons (Boreen & James 1995). Gallagher *et al.* (1999) and Li *et al.* (1999) use foraminiferal biostratigraphic data to suggest a Late Oligocene P21b–P22 zonal age (28.4–23.03 Ma) for the Jan Juc Marl and the middle and upper parts of the equivalent Clifton Formation. In the subsurface the Jan Juc Marl may extend to Early Oligocene NP22–NP23 nannofossil and P20 foraminiferal zone and may be as old as 30 or even 32.6 Ma (Siesser 1979).

The Jan Juc Marl appears to be laterally equivalent to the Point Addis Limestone, a shallow nearshore high-energy marine calcarenite and sandy marl facies, with abundant shelly fossils (Abele *et al.* 1988; Holdgate & Gallagher 2003). Nicolaides & Wallace (1997) reported marine hardgrounds in the Point Addis Limestone that correlate with those reported in the Jan Juc Marl. Bioclasts in the Point Addis Limestone consist predominantly of bryozoans with calcareous algae, echinoids and foraminifera also abundant. However, the Point Addis Limestone close to the contact with the underlying Angahook Formation basalts commonly has a different composition. At Eagle Rock, near Aireys Inlet, carbonates directly overlying the basalts have a much greater abundance of oysters, large colonies of calcareous algae, regular echinoid fragments and gastropods (including limpets: Figure 3b). This distinctive assemblage is consistent with the presence of a shallow-water environment above a rocky substrate of the underlying basalt. The shelly calcareous claystone and siltstone of the Puebla Clay conformably overlie the Jan Juc Marl and Point Addis Limestone. This contact is close to the Oligocene–Miocene boundary (Li *et al.* 1999; Holdgate & Gallagher 2003). Siesser (1979) and Li *et al.* (1999) reported an NN1 nannofossil zonal age for the upper 2 m of the Jan Juc Formation suggesting an age range from 23.8 to 22.76 Ma (using the time-scale of Gradstein *et al.* 2004) spanning the 23.03 Ma Oligo-Miocene boundary.

GEOCHRONOLOGIC AND CHRONOSTRATIGRAPHIC CONSTRAINTS

The Eagle Rock sea-stack offshore Aireys Inlet provides an excellent cross-section of the contact between the Angahook Formation basalt and the Point Addis Limestone of the Torquay Group (Figure 3). Here, brachiopod samples were obtained from the Point Addis Limestone, for age determination using strontium-isotope stratigraphy, and the Angahook Formation basalt, for age determination using $^{40}Ar/^{39}Ar$ geochronology. Brachiopod samples of the Jan Juc Marl for strontium-isotope stratigraphy were also taken from Fishermans Steps along Jan Juc beach (Figure 1).

$^{40}Ar/^{39}Ar$ geochronology

Two whole-rock samples of the Angahook Formation basalt, ER1 and ER3, were dated using $^{40}Ar/^{39}Ar$ isotopic analysis. The basalt is composed of bladed euhedral plagioclase phenocrysts as well as less-common olivine phenocrysts. The phenocrysts are enclosed within a fine- to medium-grained intergranular groundmass of approximately equal proportions of plagioclase, augite, opaque minerals and olivine as well as minor interstitial glass. Very minor alteration to kaolinite and/or chlorite is confined to larger olivine and plagioclase phenocrysts.

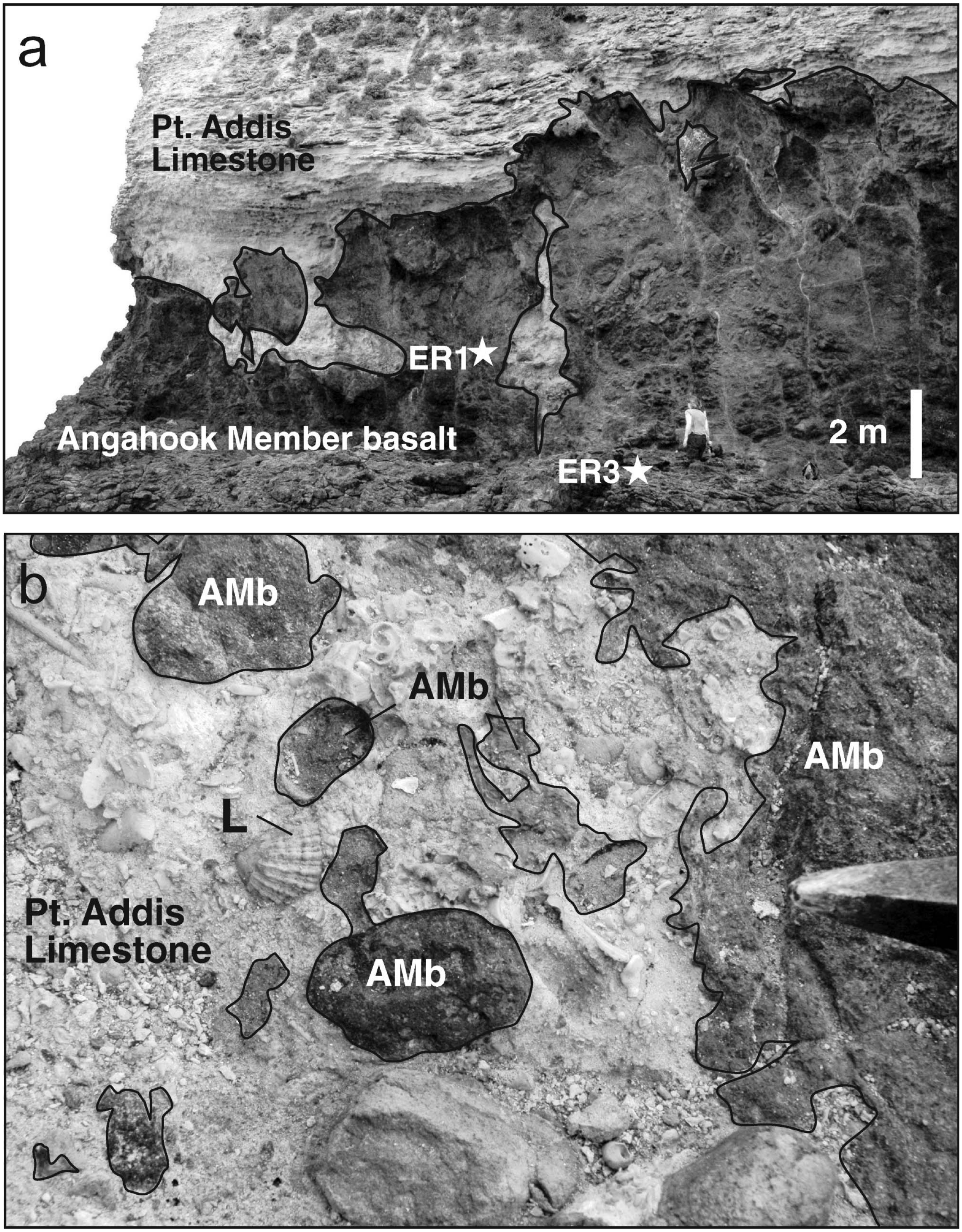

Figure 3 (a) Contact between the Angahook Formation basalt and the overlying Point Addis Limestone, Eagle Rock, Aireys Inlet. Stars indicate the locations of basalt samples ER1 and ER3. (b) Contact shown in detail. AMb, Angahook Formation basalt, showing small basalt clasts within the Point Addis Limestone and rocky substrate dweller bioclasts (such are the limpet shown at L). Pick end of hammer head for scale (at right).

Samples were crushed to a uniform grainsize of 500–1190 μm and cleaned in acetone in an ultrasonic bath. Each clean and dried sample was hand-picked to remove phenocrysts, xenocrysts and glass. Purity of the resulting material is estimated at 99%. Aliquots of the two samples were irradiated in position 5C of the McMaster University Nuclear Reactor, Hamilton, Canada. Irradiation parameters were determined by interpolation using fluence monitor GA1550 biotite (with K/Ar age 98.79 ± 0.54 Ma: McDougall & Roksandic 1974; Renne *et al.* 1998). During the step-heating experiment the temperature was monitored using a thermocouple at the base of a tantalum crucible within a double-vacuum resistance furnace. The heating schedule comprised a series of 16 steps at temperatures between 650 and 1550°C (Table 1). After each heating step, the gas released was exposed to Zr–Al getters for ~10 min to remove all active gases. The isotopic composition of the purified argon was analysed using a VG Isotech MM3600 gas source mass spectrometer at the University of Melbourne. ^{40}Ar/^{39}Ar ages were calculated using the decay constants of Steiger & Jäger (1977).

The resultant laboratory age spectra are shown in Figure 4. Samples ER1 and ER3 are characterised by very similar, slightly 'saddle-shaped' age spectra. Duplicate analyses of both ER1 and ER3 show good agreement. Ages decrease for the first 70% of the gas release before rising slightly in the final 5–10% of the gas release. The older ages in the first two-thirds of the gas release are probably the result of extraneous argon contamination in fluid inclusions or within the glass groundmass. Plateau-like segments, defined as part of the age spectrum where the ages of consecutive steps are within 2σ of one another, corresponding to the last

Table 1 ^{40}Ar/^{39}Ar step-heating data.

Temperature (°C)	^{40}Ar/^{39}Ar	^{38}Ar/^{39}Ar (10^{-2})	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar (10^{-2})	^{39}Ar (mol) (10^{-14})	Cumulative ^{39}Ar (%)	^{40}Ar* (%)	^{40}Ar*/^{39}Ar$_k$	Calculated age (Ma) ± 1σ	Ca/K
ER1 whole-rock basalt, $J = 0.004401 \pm 0.000020$										
650	14.29	0.0153	0.4319	2.21	0.0262	0.05	54.5	7.793	60.8 ± 21.9	0.76
700	16.23	2.6697	0.8187	4.78	0.1475	0.36	13.3	2.157	17.1 ± 4.2	1.4
750	27.92	2.9549	0.8103	8.07	0.6764	1.75	14.8	4.140	32.6 ± 1.5	1.4
800	19.47	2.3218	0.7987	5.17	1.679	5.20	21.9	4.263	33.5 ± 1.0	1.4
850	16.52	2.1206	0.8365	4.29	2.806	10.97	23.7	3.919	30.9 ± 0.7	1.5
900	13.16	1.8948	1.044	3.17	3.873	18.94	29.5	3.884	30.6 ± 0.4	1.8
950	7.7174	1.5422	1.356	1.36	4.697	28.59	49.5	3.824	30.1 ± 0.2	2.4
1000	6.54	1.4425	1.505	0.98	5.288	39.46	57.8	3.786	29.8 ± 0.2	2.6
1050	6.29	1.4332	1.410	0.90	4.595	48.91	59.4	3.737	29.4 ± 0.2	2.5
1100	4.98	1.3655	1.226	0.47	4.583	58.33	74.1	3.691	29.1 ± 0.3	2.2
1150	4.51	1.3394	1.241	0.32	4.804	68.20	81.0	3.661	28.8 ± 0.1	2.2
1200	4.66	1.4024	3.232	0.45	2.056	72.42	76.8	3.585	28.3 ± 0.3	5.7
1250	4.69	1.3887	5.738	0.53	11.23	95.44	76.3	3.588	28.3 ± 0.3	10
1350	6.98	1.5258	9.073	1.37	1.723	98.96	52.3	3.673	28.9 ± 0.7	16
1450	104.87	7.8905	14.69	34.67	0.3351	99.65	3.4	3.623	28.5 ± 4.6	26
1550	34.81	3.2211	19.77	10.45	0.1745	100.00	15.8	5.590	43.8 ± 2.5	35
Totals					48.69			3.745	29.5 ± 0.7	
$\lambda_e = 5.543 \times 10^{-10}$ a^{-1}										
ER3 whole-rock basalt, $J = 0.004422 \pm 0.000014$										
650	34.259	3.302	0.3457	10.102	0.0458	0.07	12.9	4.435	35.0 ± 6.2	0.61
700	18.592	2.151	0.4362	4.895	0.3140	0.59	22.4	4.163	32.9 ± 2.4	0.76
750	17.218	2.269	0.5237	4.529	1.2657	2.65	22.5	3.877	30.7 ± 0.8	0.92
800	12.775	1.931	0.6265	3.017	2.7541	7.13	30.6	3.910	30.9 ± 0.6	1.1
850	11.347	1.805	0.6614	2.569	4.2767	14.10	33.6	3.810	30.1 ± 0.4	1.2
900	8.654	1.617	0.8914	1.664	6.6635	24.95	44.0	3.810	30.1 ± 0.3	1.6
950	5.734	1.411	1.0594	0.700	6.8229	36.06	65.4	3.751	29.7 ± 0.2	1.9
1000	5.655	1.408	1.2828	0.697	6.5703	46.76	65.4	3.701	29.3 ± 0.2	2.3
1050	5.242	1.405	1.3076	0.550	5.9055	56.37	71.0	3.723	29.5 ± 0.2	2.3
1100	4.462	1.358	1.1794	0.300	6.0745	66.27	82.3	3.673	29.1 ± 0.2	2.1
1150	4.490	1.411	1.2090	0.322	5.2390	74.80	80.9	3.637	28.8 ± 0.1	2.1
1200	4.665	1.515	5.0628	0.501	7.8738	87.58	76.9	3.602	28.5 ± 0.3	8.9
1250	4.944	1.492	8.1902	0.672	6.3320	97.84	73.0	3.631	28.7 ± 0.3	14
1300	7.035	1.523	11.3403	1.441	0.9670	99.41	52.3	3.711	29.4 ± 0.6	20
1350	13.526	1.415	12.7386	3.673	0.2017	99.73	27.3	3.720	29.4 ± 2.7	22
1450	22.582	2.444	14.9728	6.697	0.1152	99.92	17.7	4.027	31.8 ± 3.6	26
1550	51.176	4.525	17.5375	16.797	0.0502	100.00	5.7	2.976	23.6 ± 6.6	31
Totals					61.49			3.717	29.4 ± 0.5	
$\lambda_e = 5.543 \times 10^{-10}$ a^{-1}										

Ages calculated using correction factors: (^{36}Ar/^{37}Ar)Ca = 2.70×10^{-4} (±1.68%); (^{39}Ar/^{37}Ar)Ca = 6.79×10^{-4} (±0.7%); (^{40}Ar/^{39}Ar)K = 5.0×10^{-4} (±39%), (^{38}Ar/^{39}Ar)K = 1.23×10^{-2} (±0.17%).

Ages include uncertainty on the irradiation parameter, *J*.

30–40% of the gas release of ER1 and ER3 are closely matched at 28.7 ± 0.2 and 28.8 ± 0.2 Ma, respectively (ages including uncertainty on the irradiation parameter, *J*). This age is slightly older than the whole rock K–Ar ages of 25.7 ± 0.4 and 27.6 ± 0.6 Ma previously reported by Abele & Page (1974) (recalculated for revised decay constants, as noted above).

Strontium-isotope analysis

Documented variation in ^{87}Sr/^{86}Sr value of dissolved strontium in the world's oceans allows the potential for sediments to be dated chronostratigraphically based on their measured strontium-isotopic composition (McArthur 1994; Veizer *et al.* 1997). The method is based on the key assumption that the global oceans are, and have always been, homogeneous in terms of ^{87}Sr/^{86}Sr. The accuracy of the method is dependent on how well this ^{87}Sr/^{86}Sr variation is known (McArthur & Howarth 2004). Although any marine organism will potentially give reliable ^{87}Sr/^{86}Sr data, diagenesis can result in alteration of the primary ^{87}Sr/^{86}Sr composition. Veizer *et al.* (1999) have shown that brachiopods are one of the organisms most resistant to diagenetic alteration and are therefore most useful for strontium-isotope stratigraphy.

In this study, brachiopods were collected from: (i) the base of the Point Addis Limestone, within 1 m of the contact between the limestone and the underlying Angahook Formation basalt at the Eagle Rock locality (Figure 3); and (ii) the Jan Juc Marl from Fishermans Steps at Jan Juc Beach. Brachiopods from the Point Addis Limestone were screened using their δ^{18}O isotopic values as a guide to alteration. Only brachiopods with heavy (near-marine) δ^{18}O composition were selected for Sr analysis. All samples were cleaned of any sediment and washed briefly using dilute hydrochloric acid. Each brachiopod was ground to a fine powder using an agate mortar and pestle. The powdered sample was then leached in 3 mL of 10% acetic acid for 1 h and converted to chloride form. Strontium separation was performed using ion chromatography. Isotopic analysis was performed using a Finnigan MAT262 mass spectrometer, operated in the static mode, at the School of Earth and

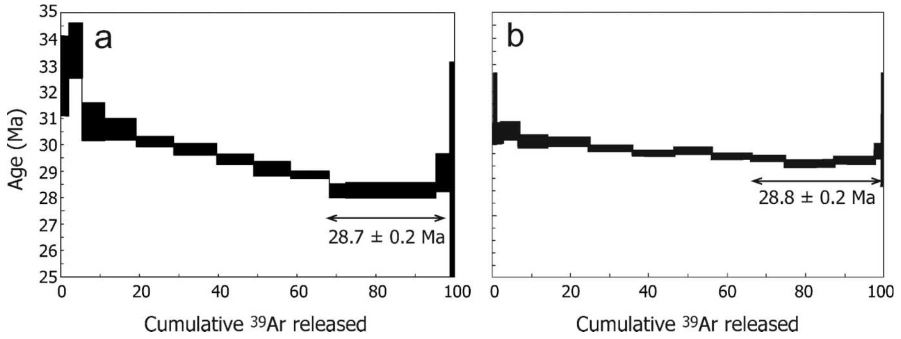

Figure 4 Measured ^{40}Ar/^{39}Ar age spectra for basalt samples (a) ER1 and (b) ER3 from the Angahook Formation of the Demons Bluff Group at Aireys Inlet. Each figure shows the measured age, with 1σ errors, against the fraction of ^{39}Ar released.

Table 2 Strontium-isotope analyses.

		^{87}Sr/^{86}Sr measured	2σ error (10^{-6})[a]	Preferred age (Ma)	Age range[b] (Ma)	∂^{13}C	∂^{18}O
PA1	Point Addis Limestone	0.708149	8	$24.76 + 0.22 - 0.21$	24.18–25.52	2.11	−0.07
PA2	Point Addis Limestone	0.708164	10	$24.43 + 0.20 - 0.17$	23.87–25.14	1.66	−0.10
PA3	Point Addis Limestone	0.708207	9	$23.61 + 0.17 - 0.16$	23.06–24.15	0.97	−0.16
PA4	Point Addis Limestone	0.708178	9	$24.16 + 0.17 - 0.16$	23.62–24.77	1.47	−0.10
SRM987 reference (n = 6)		*0.710233*	*11*	–	–	–	–
Average Point Addis Limestone[c]		–	–	$24.24 + 1.28 - 1.18$	–	–	–
JJ3	Jan Juc Marl	0.708156	14	$24.96 + 0.24 - 0.23$	24.43–25.61	–	–
JJ2	Jan Juc Marl	0.708168	13	$24.66 + 0.22 - 0.19$	24.22–25.23	–	–
JJ1	Jan Juc Marl	0.708086	13	$27.20 + 0.27 - 0.28$	26.49–27.89	–	–
SRM987 reference		*0.710264*	*14*	–	–	–	–

Note: Ages derived from measured isotope ratios corrected for measured SRM987 reference material, as indicated. Preferred age is the age corresponding to the measured ^{87}Sr/^{86}Sr using the measured mean value for SRM987 reference material; this age includes only the error on the strontium seawater curve look-up table (McArthur *et al.* 2001).

[a] 2σ error is 2 × the standard error reported by the mass spectrometer.

[b] Age range incorporates: (i) the analytical error on the measured ^{87}Sr/^{86}Sr; (ii) the error in the strontium seawater curve look-up table (McArthur *et al.* 2001); and (iii) the error on measurement of SRM987 reference material.

[c] The average age is the mean of the preferred ages, with the range in error derived from the maximum and minimum values of the age ranges reported by all samples. This value therefore includes all possible sources of error and is the most conservative estimate of the age of the Point Addis Limestone.

Environmental Sciences at the University of Adelaide. SRM987 reference material was analysed before and after analyses of the unknowns, and, in an effort to maximise precision, 20 blocks each of 10, 16 s scans were collected for each sample. Results of the isotopic analysis are shown in Table 2. Look-up Table Version 4: 08/03 of McArthur *et al.* (2001) was used to derive ages for the samples. Sources of uncertainty in the derived age include: (i) the error on the global $^{87}Sr/^{86}Sr$ seawater curve; (ii) the error in the measurement of the $^{87}Sr/^{86}Sr$ of the reference material; and (iii) the error on the measurement of the $^{87}Sr/^{86}Sr$ of the unknown samples.

Strontium-isotopic data from brachiopods in the Jan Juc Marl give a range of possible ages between 27.9 and 24.2 Ma (Table 2) for two major phosphate and glauconite horizons separated by ~40 cm (Figure 5). The preferred age for the stratigraphically lower sample is 27.20 Ma (+0.27 Ma, −0.28 Ma). The ages for two samples from the higher stratigraphic level are closely matched at 24.96 Ma (+0.24 Ma, −0.23 Ma) and 24.66 Ma (+0.22 Ma, −0.19 Ma), respectively.

All four brachiopods analysed from the Point Addis Limestone show very similar $^{87}Sr/^{86}Sr$ ratios (Table 2). Including all sources of error gives a maximum possible

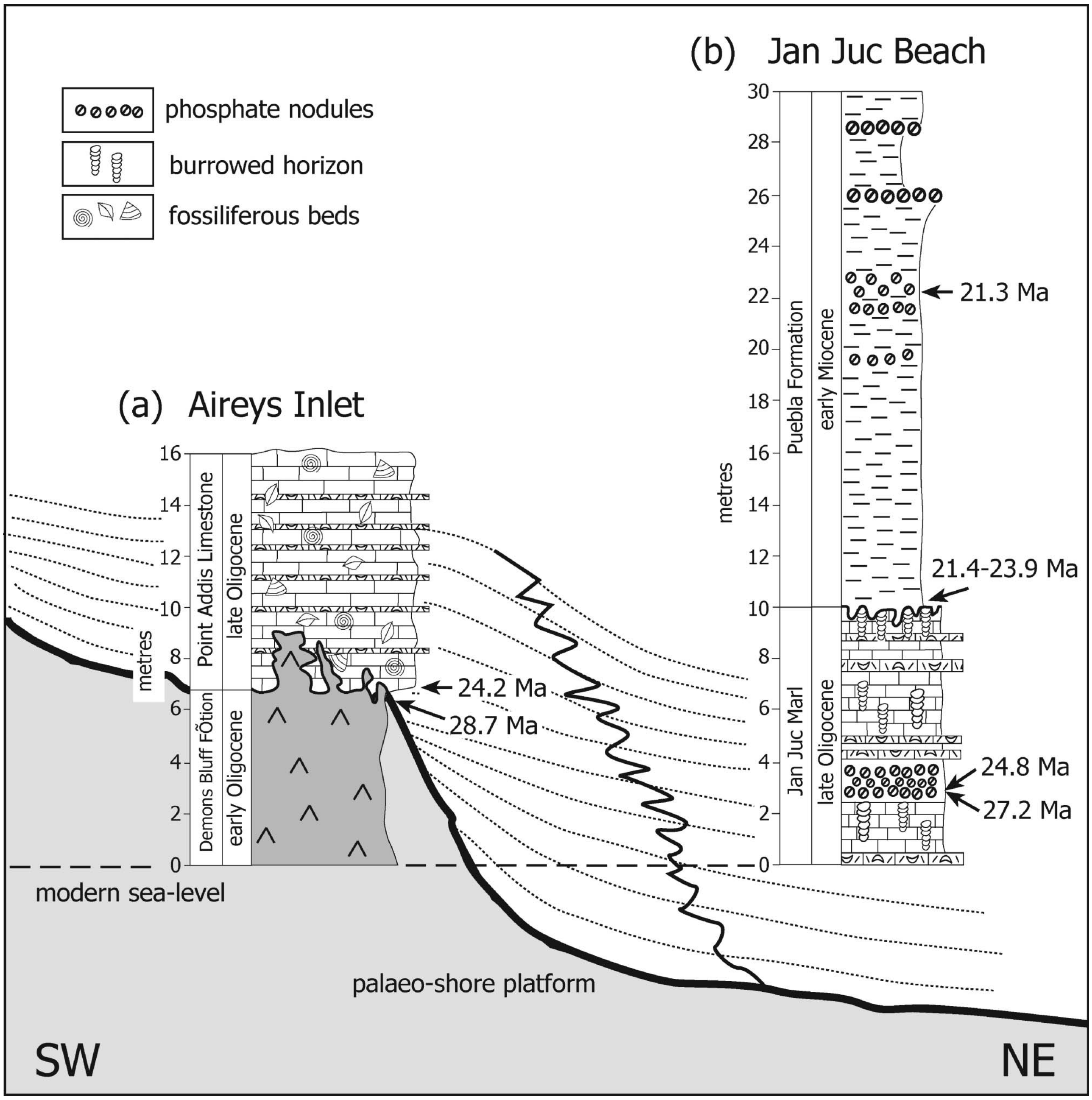

Figure 5 Measured stratigraphic sections for (a) Aireys Inlet and (b) Jan Juc beach, showing ages derived from strontium-isotope stratigraphy and $^{40}Ar/^{39}Ar$ dating. Range of ages for the lower Puebla Clay from Kelly *et al.* (2001); upper Puebla Clay age from Dickinson (2002). Modern sea-level is shown together with schematic, interpreted cross-section showing the basin geometry and facies relationships during deposition of the Torquay Group.

range in ages for the Point Addis Limestone of 25.5 to 23.1 Ma. The preferred age is 24.24 Ma (+1.3 Ma, −1.2 Ma), taken from the mean of the preferred age of each of the four analyses and the range in error derived from the maximum and minimum values of the age ranges of all samples. This age is in close agreement with the upper Jan Juc Marl age from the Fishermans Steps locality. The age of the Point Addis Limestone is significantly younger than the age of 28.7 ± 0.2 Ma for the underlying basalt, demonstrating a significant unconformity between the Demons Bluff Group and the overlying Torquay Group.

CONCLUSIONS

New age data provide constraints on the age and duration of the Janjukian Stage in southeastern Australia. Kelly *et al.* (2001) reported an age of 23.9 Ma for the basal Puebla Clay from Bird Rock, based on measured ^{87}Sr/^{86}Sr ratios from planktonic foraminifera. Using the calibration of McArthur *et al.* (2001) this reported isotopic ratio gives a range of possible ages from 23.89 to 21.39 Ma. Unfortunately the age cannot be further constrained as the measured ^{87}Sr/^{86}Sr ratio is reported with an accuracy of five, rather than six, significant figures. This age together with the new data reported here suggests that: (i) the base of the Janjukian stage (as defined by outcrop of Jan Juc Marl and Point Addis Limestone on the Torquay coast) is around 27.2 Ma, the oldest age of the Jan Juc Formation, and cannot be any older than 28.7 Ma, close to the European Rupelian–Chattian boundary; and (ii) the top of the Janjukian Stage is around 23 or 22 Ma, equivalent to the top of the Chattian and the Oligo-Miocene boundary, as previously suggested by Siesser (1979) and Li *et al.* (1999).

The new data also support suggestions that the Angahook Formation represents a subaerial exposure surface, as originally suggested by Hall (1910). As shown in Figure 5, we therefore interpret the surface of the Angahook Formation as a paleoshore platform representing local high ground over which younger marine sediments were onlapped during subsequent marine transgression. Age data for the Point Addis Limestone and Jan Juc Marl are consistent with the ages of 27.8–26.6 Ma and 23.6–22.4 Ma derived by strontium-isotope stratigraphy for the lower and upper Clifton Formation, respectively (Dickinson 2002), supporting suggestions of stratigraphic equivalence and providing evidence for a major regional transgressive cycle at this time.

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