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Jurassic volcaniclastic–basaltic andesite–dolerite sequence in Tasmania: new age constraints for fossil plants from Lune River

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Jurassic plants excavated from a 12 × 5 m site, at Lune River, southern Tasmania, include an araucarian tree and numerous pteridophytes, belonging to the orders Osmundales, Filicales and Bennettitales. The fossils occur in 2–3 m of immature volcanilithic sandstone beds. The sandstone consists primarily of clasts from granitic basement rocks underlying much of southeast Tasmania and mafic clasts containing feldspathic microliths, and primary, phreatomagmatic quartz crystals. Detrital zircons from the sandstones are mostly Early Jurassic (Toarcian) in age (182 ± 4 Ma) with minor Triassic (226 Ma), Devonian (380–360 Ma) and Proterozoic populations. Basaltic andesite, hereafter referred to as andesite, caps the volcanilithic units and displays similar ratios of fluid-immobile trace elements (e.g. Zr/Nb, Ti/V), to the Jurassic dolerite found in Tasmania, indicative of a common source. The andesites are correlated with the Jurassic Kirkpatrick Basalts (Trans-Antarctic Mountains, Antarctica) based on their field relationships with bounding strata, age, and distinctive similarities in major-element composition and fluid-immobile trace-element ratios. The andesite is interpreted as an extrusive equivalent of the Tasmanian dolerite. Importantly, drillcore from Lune River contains stoped clasts of andesite in fine-grained dolerite, indicating that the andesite pre-dates the dolerite. Thermal alteration index of microfossils (3–3.3) and reflectance of organic material within the sediments (0.54–0.77 Ro) resulted from contact metamorphism associated with the emplacement of this basalt. The sedimentology and stratigraphy of the depositional environment, plus the presence of hydrophilic pteridophytes and gymnosperms, indicates that the Toarcian environment was temperate to warm and humid, with an abundant supply of water.

KEY WORDS: andesite, Antarctica, dolerite, Jurassic, plants, Pteridophyta, Tasmania.

INTRODUCTION

Silicified plant macrofossils found in shallow pits or on the regolith surface have long been known from the Lune River area of southern Tasmania (Gould 1972; Tidwell 1987, 1991; Tidwell *et al.* 1991). These are much prized by lapidarists, but they have not been found *in situ*, and dating has been by general taxonomic comparison with a mid-Mesozoic age suggested (White 1986). These scattered plant fossils are spatially associated with basalt flows that were originally assumed to be representative of the commonly occurring Cenozoic basalts, before it was suggested that they are volcanic equivalents of widespread Jurassic hypabyssal dolerite sheets (Banks *et al.* 1989).

In this paper, we report the discovery of *in situ* plant remains in close association with volcanics and volcanilithic sediments, and we show that the volcanic sediments were deposited late in the Early Jurassic (Toarcian). These are the first Jurassic *in situ* sedimentary and extrusive volcanic rocks available for study in Tasmania and give the first precise date for the fossil plants from Lune River.

The small study area contains a suite of rocks that confirm Tasmania's close links to Antarctica prior to the rifting of Gondwana. The basalt at Lune River has a close geochemical affinity with the Kirkpatrick Basalts of Antarctica, which are extrusive equivalents of the Ferrar Igneous Complex (Siders & Elliot 1985). Further, the volcanilithic sandstone from the site has characteristics and physical components similar to widespread phreatomagmatic deposits linked to the groundwater-rich basin associated with the Jurassic rift zone of the Trans-Antarctic Mountains (Hanson & Elliot 1996).

Site location

The location of the site was reported to staff at the University of Tasmania by Nigel Ellis after he and his partner discovered a silicified fallen conifer while fossicking for gem stones. The site lies in the southeastern sector of the Tasmania Basin, near the western boundary of the basin, on an east-facing slope. It is ~5 km south of Lune River and 6 km north of Leprena, on the western side of the Leprena Track, close to Tasmania's southeast coast (Figure 1). The site falls

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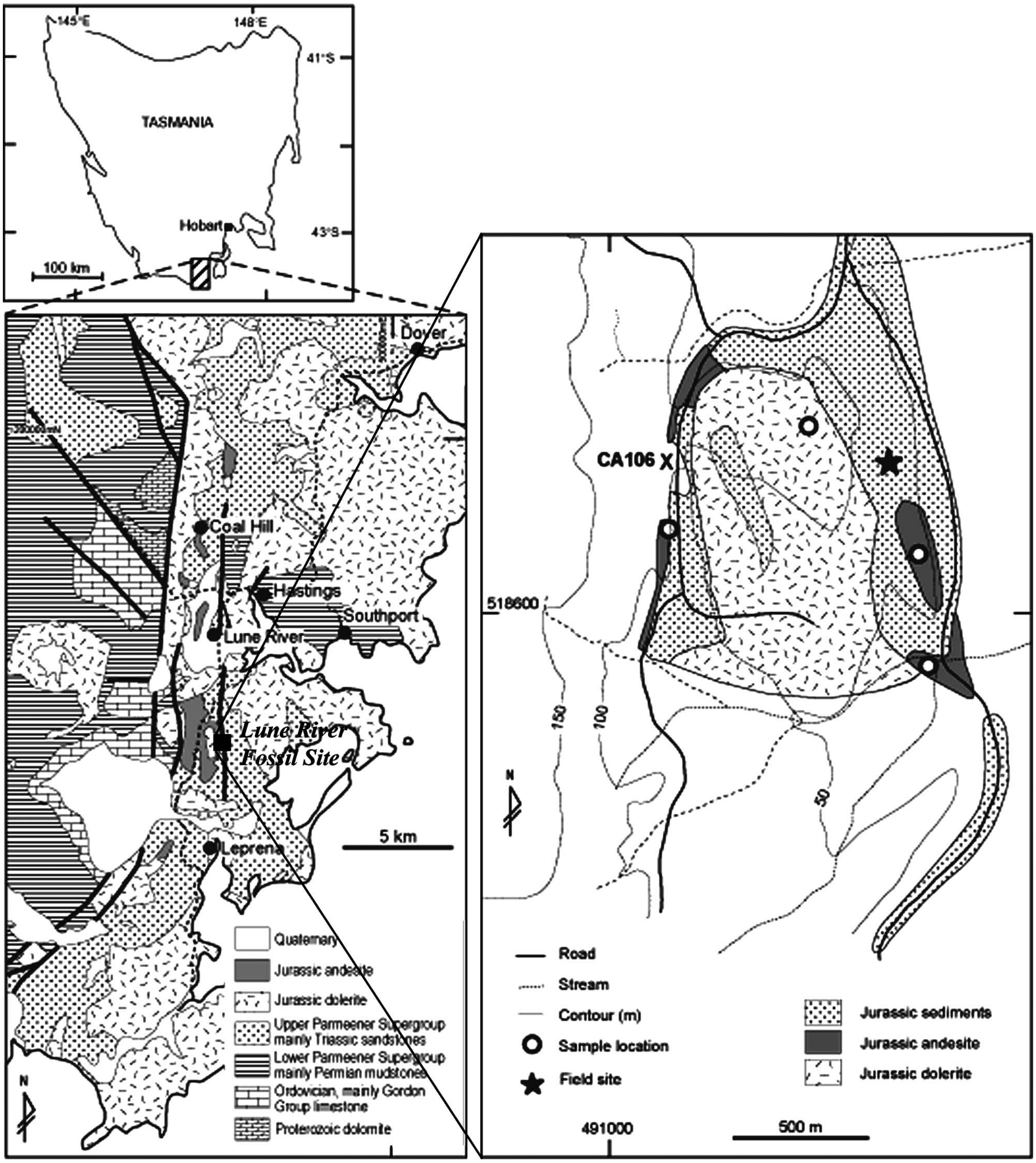

Figure 1 Location of the Lune River fossil site and associated geology of southeastern Tasmania, together with a detailed geological map of the region surrounding the fossil site, showing the location of drillcore CA 106, sample locations and field relationships between basaltic andesite and dolerite (adapted from unpublished work by C. Sharples).

within the bounds of the public fossicking site at Lune River. However, Mineral Resources Tasmania amended the dimensions of the public area on the 17 December 2003, such that under section 163(1) of the Mineral Resources Development Act 1995, a 50 m^2 area surrounding the site itself is now a protected fossil site and is no longer open to amateur fossickers. The area is covered in thick regrowth which severely restricts mapping and obscures the few outcrops of basalt.

Geological setting

The Lune River fossil site lies in the Tasmania Basin, near a fault scarp which defines the western wall of a north-northwest–south-southeast-trending graben that possibly formed in the Cenozoic. It is adjacent to an outcrop of Jurassic dolerite and is associated with andesite flows and volcanic sandstone.

The upper Parmeener Supergroup (Leaman 1975; Farmer 1985; Williams 1989; Forsyth 1989a, b; Langford

1992; Bacon *et al.* 2000; Reid & Burrett 2004; Stacey & Berry 2004) consists of latest Permian to latest Triassic terrestrial siliciclastic and volcaniclastic beds and contains basalt flows and intrusives dated at 233 ± 5 Ma in the northeast of the state (Calver & Castledon 1981). Rhyolitic tuffs are widespread in the Late Triassic, and one has an age of 214 ± 1 Ma (Bacon & Green 1984).

During the Jurassic (177.3 ± 3.5 Ma), the upper Parmeener Supergroup and older rocks were intruded by dolerite (Hergt & Brauns 2001) forming sheets up to 600 m thick of mafic igneous rocks consisting mainly of dolerite with granophyre and quartz diorite differentiates (McDougall 1962). These shallow-level intrusives, their cause and their modes of intrusion have been discussed by Compston *et al.* (1968), Leaman (1975, 1995), Baillie (1989) and Stacey and Berry (2004). According to Siders and Elliot (1985), the primary source region of the magmas was probably contaminated upper mantle, as with the correlative Ferrar Igneous Province, Victoria Land, Antarctica, although interaction with crustal lithologies during ascent probably resulted in significant contamination.

METHODS

A 12 × 5 m pit was excavated using a mechanical excavator and shovels. Trowels were used in the final stages of uncovering large plant material. Details of analytical procedures are given in Appendix 1.

Maceral descriptions were largely provided by Keiraville Konsultants (Cook 2004), with additional descriptions from Knowles (2004). Individual zircon crystals were separated using a hand-pan and magnet, and analysed using an HP4500 quadrupole ICPMS equipped with a 213 nm Nd-YAG New Wave. Palynomorphs were prepared by Laola Pty Ltd and identified by G. Playford at the University of Queensland. They were compared with standards in North (1985) to determine the Thermal Alteration Index (TAI). Plant identifications were made, where possible, by comparison to holotypes held at the Tasmanian Museum and Art Gallery.

RESULTS

Site stratigraphy

The fossils at Lune River occur in very fine-grained silicified siltstone found at the base of the stratigraphic section measured in the pit (Figure 2). Three beds of normally graded, fossiliferous quartz-rich volcanilithic sandstone overlie it. Much of the sandstone unit is extremely weathered and has a high clay content, but the rock in the lowermost 10 cm is unaltered. A reverse-graded horizon of mudstone with medium to coarse-grained sandy lenses occurs between the second and third clay-rich sandstone beds. Thinly laminated silicified tuff separates the sandstone from andesite now weathered to ferruginous clay with cherty amygdales.

Much of the site consists of horizontal beds, up to 1 m thick, of moderately to very well-sorted, immature, quartz-rich volcanilithic sandstone with 50–60% lithic clasts, probably derived from granitic basement rocks underlying much of south and southwest Tasmania (Gunn *et al.* 1997). The upper beds have been altered to clay. Similar lithologies appear in drillcore CA106 (Figure 3), drilled close to the site by Marathon Petroleum (Figure 1), so lateral continuity is likely. Local scour-and-fill structures, infilled with pebble-size clasts of quartz and carbonaceous matter are present. The major components are quartz with angular, curviplanar margins and rounded and angular lithic clasts, many of which are mafic and contain feldspathic microliths. The composition of other lithic clasts is variable: some are carbonaceous shale, while others appear granodioritic. Clumps of tabular sodic plagioclase are common, as well as large, angular isolated potassium feldspar crystals with sieve texture cores. Minor components include primary, euhedral hornblende (*sensu lato*), angular strained quartz crystals with polygonal recrystallisation fabrics, decrepitated biotite partially replaced by chlorite, zoned apatite, euhedral zircons and rare garnets. Ilmenite and titanomagnetite are common. Two forms of devitrified glass occur between clasts: recrystallised axiolitic black-brown glass, and fine golden-orange bubble-wall shards. Secondary quartz cement infills pore spaces. Some grains have silica overgrowth rims. The volcanilithic sandstones are rhyolitic in composition (76.2–80.5 wt% SiO_2).

The sandstone grades up into very fine- to fine-grained, pale-grey, silicified sediments with lenses of fine- to very fine-grained quartz sandstone, reworked mudstone clasts, lithic and glass fragments, bubble-wall shards, and euhedral black Fe–Ti oxides. Rare angular quartz crystals occur in the matrix. Montmorillonite crystals up to 2 mm occur in pockets 1–2 cm in diameter in the sediment. These sediments are thinly laminated, and there is no evidence of ripple- or cross-lamination at the site. The contact between the top of the fine sediments and the bottom of coarse overlying beds is knife-sharp. Plant fragments are common, with a mean size ranging from 0.5 to 5.0 cm, although many examples are much larger. Carbonaceous fragments 2–5 mm in length are common. Bubble-wall shards, the angular quartz and lithic components indicate that this unit is a fine tuff, derived from volcanic ash.

U–Pb dating using zircons

Sandstone and the volcanic ash deposits contain both rounded and euhedral zircons. The youngest euhedral zircons (8 out of 24 zircons) have a weighted mean age of 182 ± 4 Ma (Toarcian stage of the Early Jurassic: Gradstein *et al.* 2004) (Figure 4). These are probably derived from the quartz-phyric felsic volcanics clasts within the sandstone. Older euhedral zircons were also present (228–223, 256–247 and 389–353 Ma) indicating that zircons were weathering directly out of Triassic, Permian and Devonian igneous rocks. The Triassic and Late Permian zircons (256–223 Ma) are probably from the intrusives and rhyolitic sediments from the upper Parmeener Group (Bacon & Green 1984; Calver & Castledon 1981). The Devonian zircons and granite

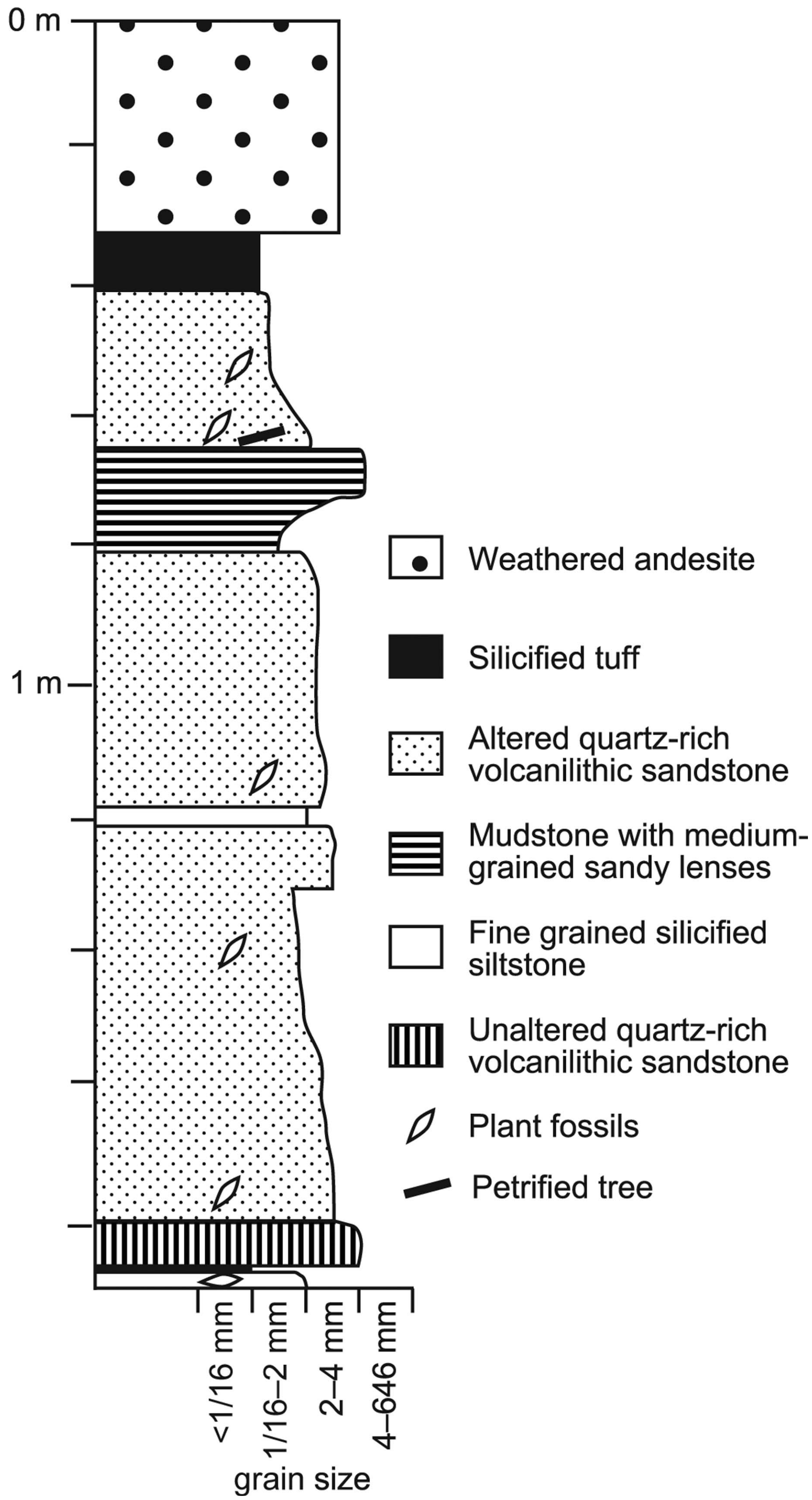

Figure 2 Stratigraphic section of the Lune River fossil site (see Figure 1 for location).

clasts were probably derived directly from the 399–350 Ma Devonian granites present throughout Tasmania (Black *et al.* 2004). The rounded zircons were mostly Proterozoic in age and were probably ultimately derived from the Proterozoic basement of Tasmania or the South Tasman Rise. For example, the 625–585 Ma zircons are typical of eastern Australian Paleozoic sedimentary rocks (Sircombe 1999). The 1150–1105 Ma zircons

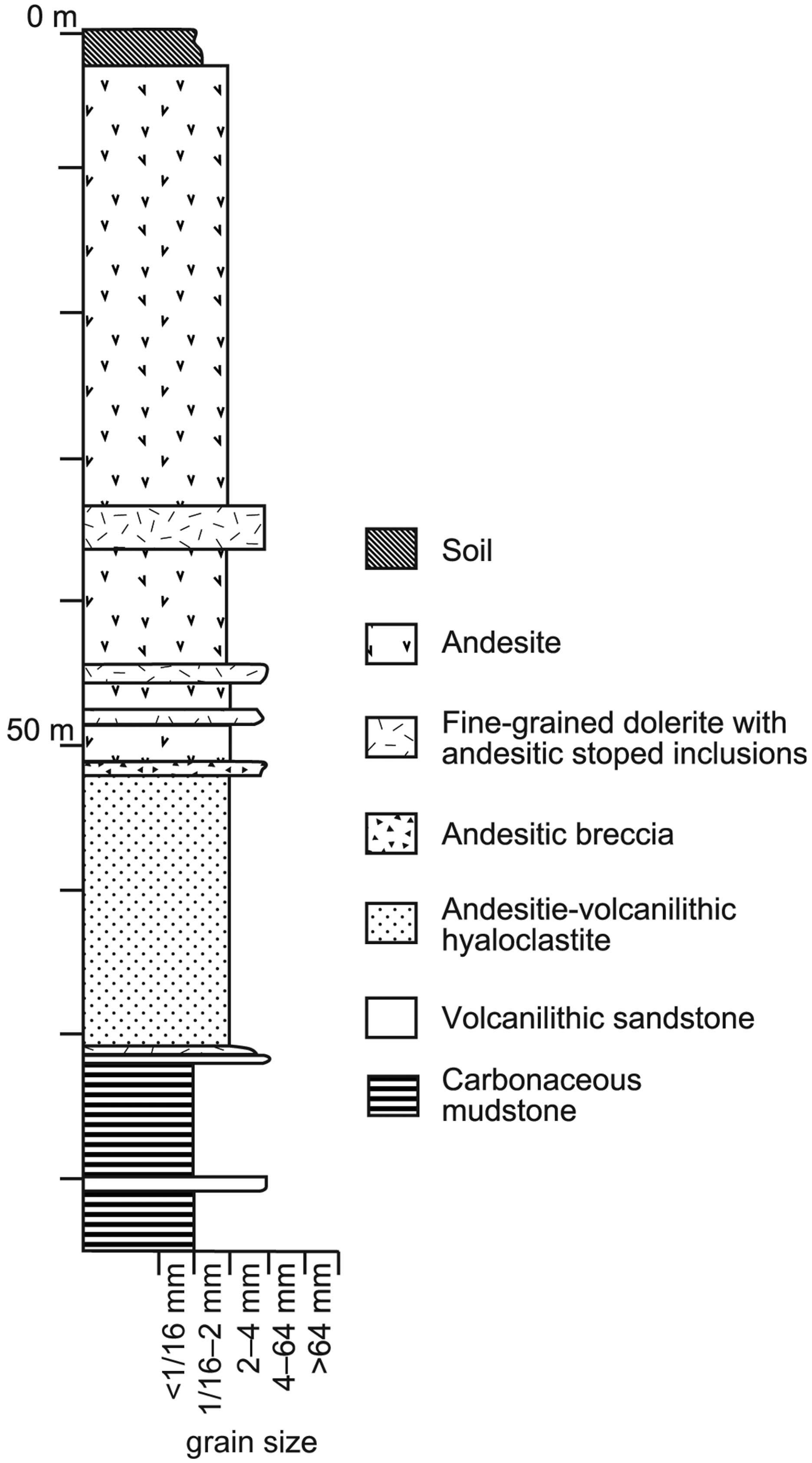

Figure 3 Stratigraphic section of core CA 106 (see Figure 1 for location).

ultimately are derived from Grenvillian magmatism known, for example, from the South Tasman Rise (Fioretti *et al.* 2005) or from recycled sources in older Tasmanian sandstones such as the Mathinna Group (Black *et al.* 2004).

Andesite and dolerite

Basaltic andesite (here referred to as andesite) samples from the Lune River site have a restricted composition, varying between 5.4 and 5.6 wt% MgO and 55.1–55.5 wt% SiO_2 (Table 1). They are quenched, sparsely

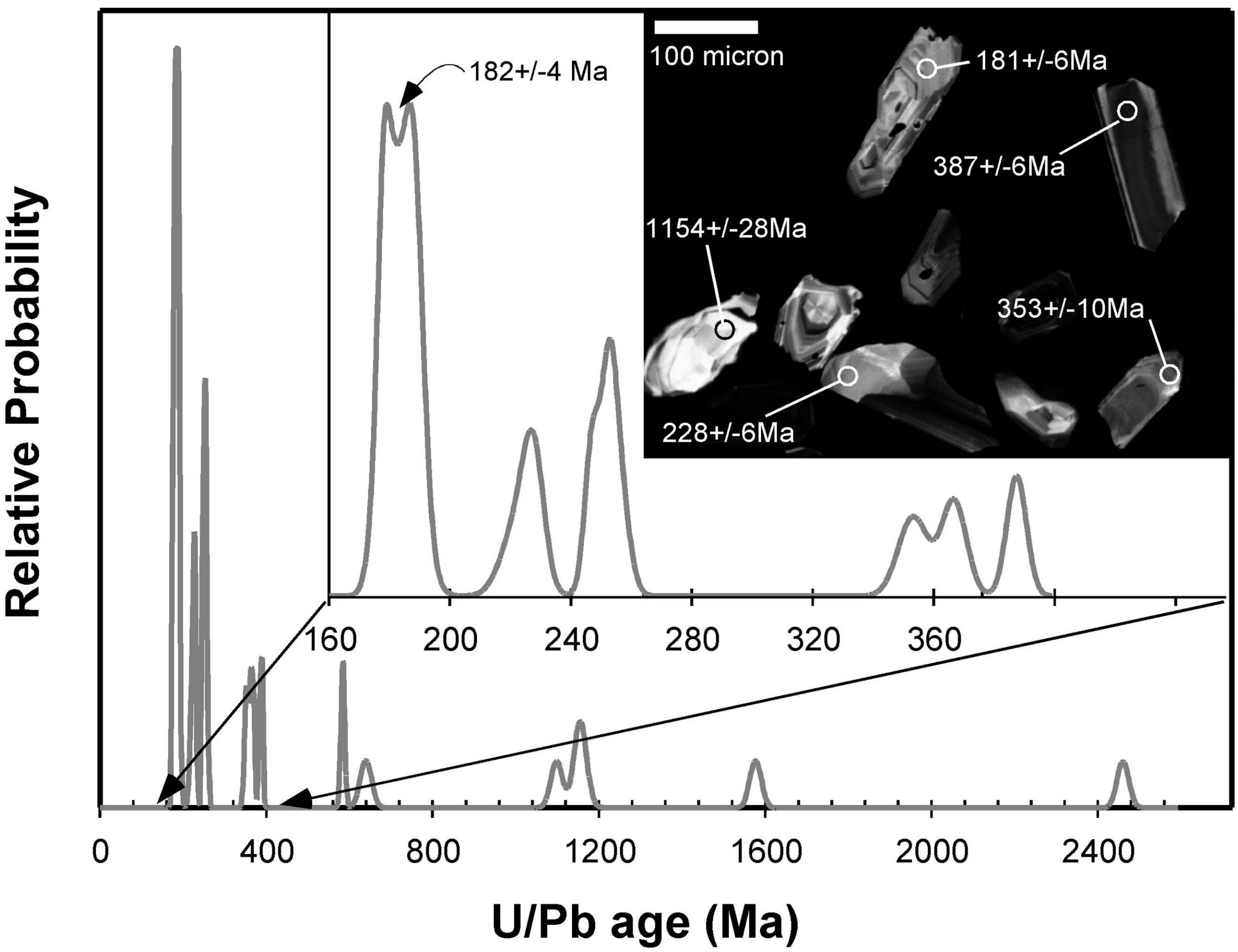

Figure 4 Probability age distribution of zircons derived from volcanilithic sandstone and ash deposits. Inset shows morphology and internal structure of zircons from cathodoluminescence and the locations of the analyses.

plagioclase–clinopyroxene-phyric and weakly vesicular. The groundmass is texturally variable, from dendritic crystallites in glass associated with quench crystallisation, to glass completely altered to brown clay. Relict phenocrysts of plagioclase occur in the glass in multicrystal clots. Larger clinopyroxene phenocrysts occur, although many have altered to smectite. Abundant altered tiny Fe–Ti oxide crystals are scattered in the groundmass.

Pillow andesite outcrops near the site. These exhibit classical radial joints, which define polygonal pillow structures. These pillows are separated by very fine-grained, laminated volcanic ash. Fractures between the pillows acted as conduits for groundwater movement, and quartz veins have replaced the inter-pillow spaces. Rare, thin veins of pure montmorillonite also occur.

Drillhole CA106, located close (<1 km) to the Lune River fossil site has carbonaceous mudstone from 70 m to the base of the core at 84 m. Two thin beds of quartz and crystal-rich volcanilithic sandstone occur above the mudstone, and above these, a thick bed of jigsaw-fit texture, intrusive, andesitic breccia with a sedimentary matrix occurs. The textures suggest that the andesite intruded into wet volcanilithic sediment and that this unit is an intrusive hyaloclastite. Andesitic clasts show both thready and curviplanar margins, resulting from quenching during wet sediment interaction. A thin bed of andesitic breccia with minimal sedimentary matrix overlies the hyaloclastite. The hyaloclastite proved important in providing geochronological constraints for the timing of the andesite in relation to the volcaniclastic deposits found at the site. Between 51 and 71 m, the volcanilithic matrix of the hyaloclastite is very similar petrographically and texturally to the sandstone sampled at the fossil site, demonstrating that the andesite erupted into unconsolidated wet sediment.

The upper part of the core is andesite, intruded in at least three places by a very fine-grained to glassy basic, igneous rock with no vesicles. The intruding magma is interpreted to be a chilled-phase dolerite. Dolerite at the contact between the two is very fine grained and glassy. Margins of the andesite show embayment by intruding magma, and angular stoped inclusions of andesite lie within chilled dolerite. The Lune River andesites have a geochemical affinity with both the Tasmanian Jurassic dolerite and with the Kirkpatrick Basalts from Victoria Land, Antarctica (Figure 5). These rocks display an arc signature, with high Zr/Nb and low Ti/V (Pearce 1982), in contract to the Tasmanian Cenozoic basalts which

Table 1 Geochemical data comparing the Lune River andesite with the Kirkpatrick Basalt in Antarctica, Tasmanian Tertiary Basalt and Tasmanian Dolerite.

	Andesite, Lune River		Dolerite, Lune River		Andesitic clay, Lune River	Kirkpatrick Basalt[a]	Tasmanian dolerite[b]	Tasmanian Tertiary basalt[c]
	154345	154337	154344	154346	154343	$n=12$	$n=8$	$n=10$
Major element (%)								
SiO_2	55.20	55.11	55.52	54.95	51.46	54.50	54.39	45.22
TiO_2	0.74	0.74	0.73	0.76	0.96	0.62	0.59	2.39
Al_2O_3	14.36	14.34	14.30	14.42	19.40	15.16	14.95	12.98
Fe_2O_3	10.20	10.42	10.36	10.99	7.29	9.11	9.42	12.66
MnO	0.17	0.17	0.19	0.18	0.06	0.17	0.16	0.20
MgO	5.57	5.42	5.66	5.67	3.61	7.14	6.84	9.71
CaO	9.99	9.89	10.14	9.26	0.67	10.88	11.07	10.39
Na_2O	1.97	1.93	1.89	1.87	1.36	1.79	1.47	3.97
K_2O	0.44	0.77	0.48	0.98	3.16	0.54	0.78	1.56
P_2O_5	0.13	0.13	0.12	0.11	0.04	0.09	0.07	0.92
Loss	0.90	0.70	0.77	0.66	11.81	–	0.26	–
Total	99.66	99.61	100.16	99.86	99.82	100.00	100.00	100.00
S	0.04	0.04	0.03	<0.01	<0.01	–	–	–
Trace elements (ppm)								
Nb	6	6	6	6	9	5	5	87
Zr	120	122	120	113	166	94	88	348
Sr	145	137	162	124	72	120	122	945
Cr	64	58	60	79	82	154	116	303
Ba	298	255	276	266	1457	174	209	399
Sc	41	41	40	41	54	–	42	–
V	258	257	249	286	343	221	238	186
Y	32	29	27	26	21	23	22	28
Rb	34	81	29	46	36	28	24	28
Ni	63	59	61	59	60	89	87	182

Sample numbers are University of Tasmania Geology Department numbers.
All iron as Fe_2O_3.
Data sources: [a]Siders and Elliot (1985); [b]Everard (1987), Brauns *et al.* (2000); [c]Compston *et al.* (1968), Sutherland (1989): analyses are averages.

have an intra-plate geochemical signature (Sutherland 1989) with lower Zr/Nb and high Ti/V.

Maceral properties and interpretation

The macerals were collected from the fossil site itself, and were confined to the fossiliferous mudstone units. The only palynomorph from Lune River reliably identified as potentially Jurassic is a trilete reticulate spore referable to *Retetriletes* found in sample UTGD 154353. It is brown to dark brown and has a TAI of 3–3.3. Other organic matter was mainly diffuse and structureless, with very low amounts of vitrinite, inertinite and/or algal matter. Two occurrences of textinite, a brown coal maceral, occur in sample UTGD 154353. Other than the palynomorph, macerals are dark-brown-black, and where present, the cell structure is intact.

Vitrinite and associated cutinite fluorescence intensity is relatively low, and the fluorescence colour is dull orange (Cook 2004). Two samples, UTGD 154354 and UTGD 154353, contain very rare algal bodies, and these fluoresced with a dull-yellow colour, suggesting a maturity of 0.43–0.65 Ro (Knowles 2004). In some samples, the vitrinite is associated with dull-orange fluorescing liptinite, some of which is cutinite. The vitrinite also occurs in smaller intraclasts not associated with liptinite. The liptinite shows dull-orange fluorescence colours and low fluorescence intensity in relation to the vitrinite reflectance values obtained (A. C. Cook pers. comm. 2004).

Analysis of vitrinite reflectance defines the level of maturity of a sample, and displays a strong depth or temperature, rather than time, dependency. The maturity of the volcanilithic sandstone, sample UTGD 154353 (0.54–0.64 Ro), is slightly lower than the maturity of the underlying volcanic ash, UTGD 154354 (0.63–0.77 Ro). The ranges of vitrinite reflectance are relatively high; a mean vitrinite reflectance range of 0.54–0.77 Ro is representative of the site.

Lune River plants

Plants unearthed at Lune River are preserved as a result of cellular replacement by microcrystalline quartz. The assemblage includes a diverse range of plants, from a fallen araucarian tree, to a number of gymnosperms and pteridophytes (Table 2). The fossils are encased in fine-grained fossiliferous tuff and are generally confined to the volcanilithic sandstone unit. Phylogenetic relationships among some species of the Lune River assemblage led Tidwell (1987) to interpret the age of plants

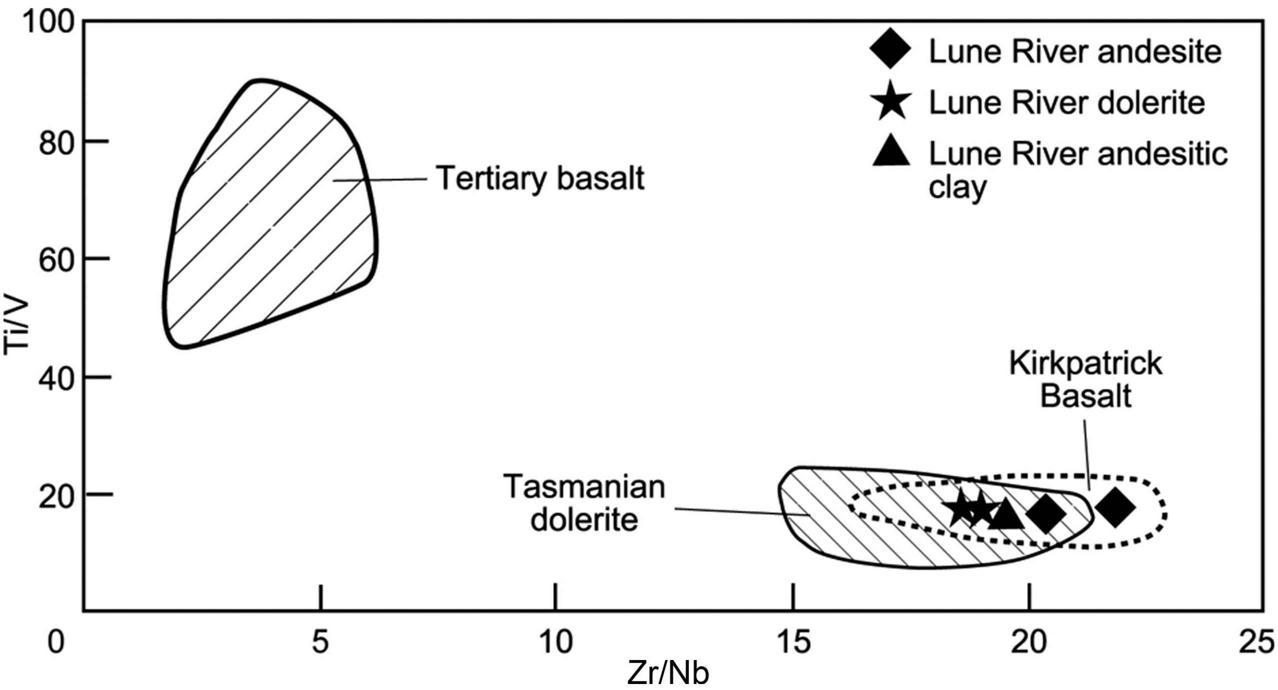

Figure 5 Ti/V *vs* Zr/Nb plot showing the Tasmanian dolerite field (adapted from Everard 1987 and Brauns *et al.* 2000), the Tertiary basalt field (adapted from Sutherland 1989) and the Kirkpatrick Basalt field (adapted from Siders & Elliot 1985). The igneous rocks from Lune River, and the clay derived from weathered andesite capping the site clearly lie within the Kirkpatrick Basalt/Tasmanian dolerite fields.

Table 2 Classification of plant fossils from the fossil site at Lune River.

Order	Family	Genus and species
Pinales	Araucariaceae	*Agathis* cf. *australis*
Peltaspermales	Umkomasiaceae	*Pachypteris* cf. *indica*
Bennettitales	Bennettitaceae	*Otozamites* sp.
Osmundales	Guaireaceae	*Lunea jonesii*
Osmundales	Osmundaceae	*Osmundacaulis pruchnickii*
Osmundales	Osmundaceae	*Osmundacaulis nerii*
Filicales	Matoniaceae	*Tasmanopteris richmondii*
Filicales	Osmundaceae	*Cladophlebis indica*
Equisetales	Equisetaceae	*Equisetum* sp.

Identified by K. Bromfield.

previously discovered at Lune River to be Late Jurassic to Early Cretaceous.

DISCUSSION

If maturation resulted from regional coalification associated with deep burial, Cook (2004) suggested that a maximum cover of about 2000 m might be inferred, assuming average geothermal gradients. This inference implies that deposition of Jurassic sediments was originally much more widespread than the graben in which they are now preserved. However, contact alteration from proximal doleritic and andesitic emplacement is more likely to be the cause of high vitrinite reflectance recorded in samples from Lune River. A range of temperature and time combinations could produce the degree of coalification found and an episode of mild contact alteration is consistent with the weak fluorescence intensity and red shift found for the liptinite (A. C. Cook pers. comm. 2004) and with the field relationships. From the TAI, it seems likely that the coalification of organic material at Lune River is due to contact alteration.

The fossil plant-bearing volcaniclastic deposits from Lune River share many characteristics with the pyroclastic deposits of the Hanson Formation, Trans-Antarctic Mountains, Antarctica. Both contain felsic, immature volcanic crystals, 50–60% lithic fragments, and grains derived from the underlying strata (basement rocks and Triassic sediments) (Hanson & Elliot 1996). The volcanic and sedimentary textures indicate derivation from a subaqueous eruption. The zircons and the volcanic quartz in the sediments most likely derive from this eruption, and the age of the zircons (182 $\pm$ 4 Ma) records the timing of this event.

The Lune River andesite overlying the fossiliferous volcanilithic sandstone is similar geochemically to the Kirkpatrick Basalts, Antarctica. It shares the apparent arc-like signatures of these Jurassic flood basalts. It erupted through the sandstone, creating a hyaloclastite texture as it interacted with the wet sediment, and much of the andesite erupted directly into water, creating pillow textures. Field relations such as stoped andesitic clasts included in the glassy dolerite margin, and the embayment along the margin of the andesite, demonstrate that the andesite was in place prior to the intrusion of the dolerite or that these events were geologically contemporaneous. The Tasmanian dolerites are dated at 175 $\pm$ 5 Ma (Hergt & Brauns 2001), giving a minimum age for the Lune River sequence. The fossil plants recovered from Lune River were therefore deposited sometime between the eruption of the volcanilithic sandstone (182 ± 4 Ma) and the intrusion of the dolerite and andesite (175 ± 5 Ma). This has a significant impact on the interpretation of the evolution of these plant families, which previously had only been dated phylogenetically.

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APPENDIX 1: ANALYTICAL PROCEDURES

Maceral descriptions

Alan Cook, from Keiraville Konsultants, using a Leitz MPV1.1 photometer equipped with separate fluorescence illuminator, performed Vitrinite Reflectance analysis. Whole-rock samples were mounted in cold-setting polyester resin and polished using chromium sesquioxide and MgO polishing powders. Wayne Knowles from Mirror Image also performed the VR analysis.

Zircon analyses

U–Pb geochronology was performed at the University of Tasmania. Heavy minerals were separated using a hand-pan and a magnet. Individual zircon crystals were hand-picked from the concentrate and mounted in epoxy resin. Cathodoluminescence images of the zircons were obtained to characterise the morphology of the zircons. Thirty-micrometre spots, mostly on igneous rims of zircons, were analysed using a HP4500 quadrupole ICPMS equipped with a 213-nm Nd-YAG New Wave. The Temora standards of Black *et al*. (2004) were used as a primary standard. The 91500 zircons of Wiedenbeck *et al*. (1995) were used as a secondary standard.

XRF analyses

Mineral compositions were analysed using a CAMECA SX100 electron microprobe located in the Central Science Laboratory, University of Tasmania, Hobart. The instrument is equipped with five wavelength-dispersive spectrometers and a Rontec Xflash energy dispersive detector. The instrument was operated at an accelerating voltage of 15 kV with a nominal beam current of 20 nA (faraday cup) and beam size of 3 μm. X-ray lines were calibrated using a suite of well-characterised natural minerals, synthetic simple oxides and pure metals. Measurement conditions were tailored to avoid analytical artefacts.