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A non-marine Lower Cretaceous rift-related epiclastic volcanic unit in southern Australia: the Eumeralla Formation in the Otway Basin. Part I: Lithostratigraphy and depositional environments

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The Early Cretaceous non-marine volcaniclastic Eumeralla Formation accumulated in a rift basin on the southern margin of Australia during the break-up of eastern Gondwana. Wireline-log analysis and a range of sedimentary data have helped to discriminate three major basin-wide informal lithostratigraphic units in the formation. From the base of the formation they are: Eumeralla I: siltstone/mudstone/sandstone/coal; Eumeralla II: siltstone/mudstone/thin lithic sandstone; and Eumeralla III: volcaniclastic sandstone. A fourth unit — Eumeralla IV: siltstone/sandstone/coal — occurs throughout the western Otway Basin, but is absent, probably because of erosion, from the central and eastern parts of the basin. The bases of all four lithostratigraphic units are probably diachronous.

The succession of lithostratigraphic units Eumeralla I–IV is interpreted as representing coal swamps and flood plains of low-energy streams; shallow and deep freshwater lakes; channel tracts and flood plains of high-energy streams; and channel tracts, flood plains and coal swamps of low- energy streams respectively. Sedimentary facies analysis of outcropping Eumeralla II and Eumeralla III in the eastern Otway Basin confirms the interpretations for these units.

The basin-wide extent of the three lower lithostratigraphic units implies that a single integrated drainage system for the entire basin was established at the onset of Eumeralla Formation deposition, and persisted at least until the late Albian. This inference is supported by the close correlation between variations in lithology and depositional environments and the Aptian–Albian sea-level changes. However, intrabasinal volcanism significantly influenced sedimentation and was probably the primary control on basin drainage.

Introduction

The Eumeralla Formation, part of the Lower Cretaceous Otway Group, was deposited in a variety of non-marine environments in the Otway Basin, one of several extensional sedimentary basins which developed along the southern margin of Australia (Fig. 1) before and during the break-up of eastern Gondwana (Falvey 1974; Yu 1988). The formation overlies ?Upper Jurassic–Lower Cretaceous sedimentary and basaltic rocks deposited during an earlier rift phase in the basin, and pre-Mesozoic basement (Fig. 2). It occurs throughout the basin, mainly in the subsurface, where it has been intersected in more than 100 petroleum exploration wells (both onshore and offshore) and water-bores.

The only onshore outcrops of the Otway Group are in the Otway Ranges and Barrabool Hills near the eastern Otway Basin margin and in western Victoria (Fig. 3). Coastal exposures in the Otway Ranges along 100 km of shoreline southwest of Melbourne probably represent most of the upper 2000 m of the Eumeralla Formation (Felton 1992). The exposed thickness of the Otway Group in western Victoria is not known. Maximum thickness of the Eumeralla Formation is estimated at 3500 m (Gleadow & Duddy 1981; Megallaa 1986).

The formation has been described as mainly chloritic mudstone and shale with subordinate thinly bedded lithic sandstone and coal (Reynolds 1971; Morton 1986). However, coastal outcrops in the eastern Otway Basin consist principally of thick-bedded sandstone forming rugged cliffs up to 70 m high. The sandstone consists mainly of first-cycle epiclastic volcanic detritus of unknown provenance, and interbedded

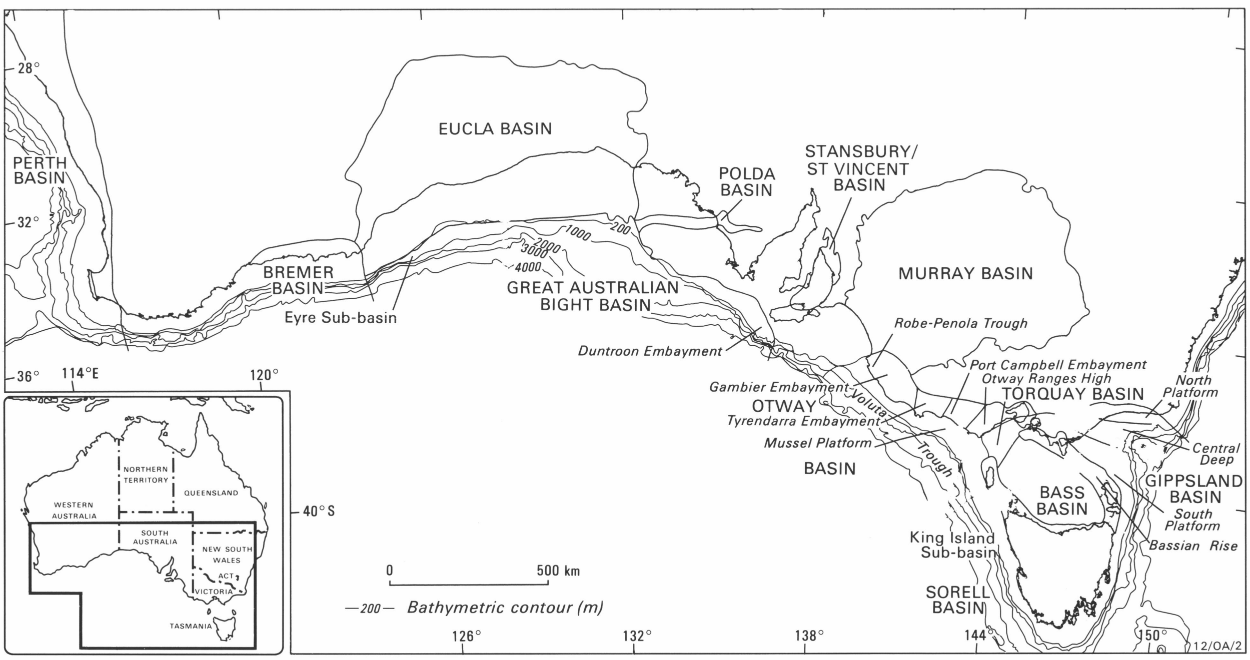

Figure 1. Location and regional setting of the Otway Basin (after Willcox & Stagg 1990).

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AGE		STAGE	PALYNOLOGICAL ZONE (L. & basal U. Cret. only)	STRATIGRAPHIC NAME	
Tertiary		Miocene Oligocene		Heytesbury Group	
Tertiary		Eocene Palaeocene		Wangerrip Group	
Cretaceous	Upper	Maastrichtian Campanian Santonian Coniacian Turonian Cenomanian	*A. distocarinatus*	Sherbrook Group	
Cretaceous	Lower	Albian	*P. pannosus*	Eumeralla Formation	Otway Group
Cretaceous	Lower	Albian	*U.C. paradoxa*	Eumeralla Formation	Otway Group
Cretaceous	Lower	Albian	*L.C. paradoxa*	Windermere Sst Member	Otway Group
Cretaceous	Lower	Albian / Aptian	*C. striatus*	Windermere Sst Member	Otway Group
Cretaceous	Lower	Aptian	*U.C. hughesi*	Windermere Sst Member / Crayfish Subgroup	Otway Group
Cretaceous	Lower	Aptian	*L.C. hughesi*	Crayfish Subgroup	Otway Group
Cretaceous	Lower	Barremian	*F. wonthaggiensis*	Crayfish Subgroup	Otway Group
Cretaceous	Lower	Neocomian	*C. australiensis* ?	Casterton Formation ?	
Jurassic	Upper				
Pre-Mesozoic				Basement	

Figure 2. Stratigraphy of the Otway Basin (after Morton 1990).

siltstone, minor conglomerate, mudstone, and coal. Finer-grained rock types predominate in the subsurface (Felton 1992). Prevailing opinion concerning the 'uniformity' or 'monotony' of the Eumeralla Formation (Edwards & Baker 1943; Reynolds 1971; Gleadow & Duddy 1981; Morton 1986) does not withstand detailed scrutiny from the perspectives of petrology (Duddy 1983; Felton 1992), depositional style (Duddy 1983; Felton 1989a, 1989b, 1992), or lithological variety (Felton 1992).

The character and evolution of Eumeralla Formation deposition in the basin is presented as a two-part paper. Part I, herein, describes the informal lithostratigraphic units and interpreted depositional environments which successively dominated sedimentation throughout the basin, and the sedimentology of lacustrine and fluvial deposits of parts of the sequence. Part II applies the geometry and relationships of sedimentary facies associations in the eastern Otway Basin to discriminate two discrete fluvial systems: an older proximal to medial alluvial fan and a younger braid plain to distal fan. Palaeocurrent directions of the fluvial systems indicate that the source(s) of the volcaniclastic sediment which dominates the Eumeralla Formation lay to the south and southeast of the present coast. Elevated Palaeozoic and Proterozoic basement blocks contributed non-volcanic quartz-lithic detritus locally.

Previous sedimentary studies

Early work in the Otway Basin mainly focused on establishing basin stratigraphy and regional correlations to assist with petroleum exploration. The stratigraphy erected in the late 1960s and early 1970s was based largely on contrasts in sandstone petrology. Changes in depositional facies were noted in several formations in the basin (James 1968; Eyles 1974), and their importance to regional correlation recognised (Morton 1986; 1990). From petroleum exploration drilling and seismic data, Kopsen & Scholefield (1990) and Morton (1986, 1990) presented depositional models for the lower Otway Group in the western Otway Basin (in South Australia). These models, based on seismic stratigraphic analysis and a limited study of sandstone provenance according to the methods of Dickinson & Suczek (1979), are continuing to evolve (Morton & Drexel 1995).

Published information on the Eumeralla Formation records few details of its sedimentary facies and depositional environments. The Otway Group, including the Eumeralla Formation, has been interpreted —mainly from macrofloral evidence — as reflecting deposition in a variety of fluvial and lacustrine environments (Douglas 1969; Dettmann 1986). Duddy (1983) described the character of Eumeralla Formation river channels as braided, and described palaeosols from their flood plains. Felton (1989b; 1992) also identified braided-stream systems in the Eumeralla Formation. Struckmeyer & Felton (1990) linked studies of organic and sedimentary facies to refine palaeoenvironmental interpretations in the Otway Group. Biomarker studies of hydrocarbons have suggested a variety of subenvironments in the lower parts of the Otway Group (Padley et al. 1995).

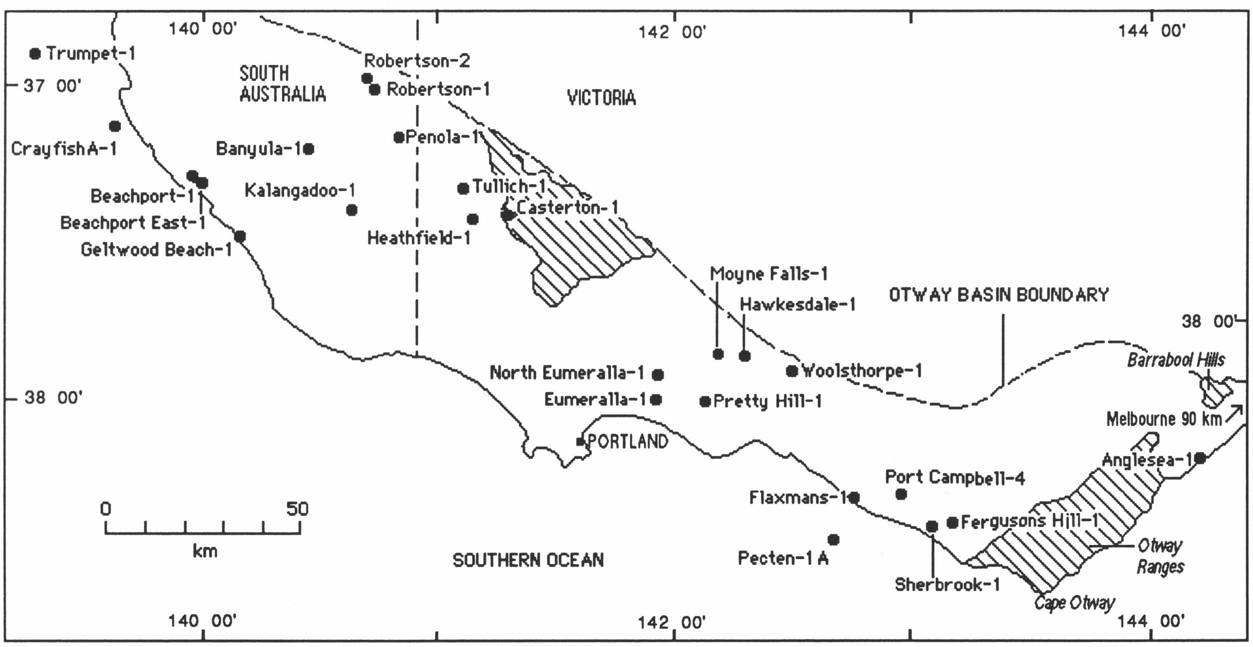

Figure 3. Otway Group outcrops (hachured) and petroleum exploration wells examined in this study.

Several authors have attempted to account for the source of the abundant volcanic detritus in the Eumeralla Formation. They have proposed both extra- and intrabasinal sources, such as Palaeozoic basement volcanics (Edwards & Baker 1943) and contemporaneous volcanic flows, despite the absence of primary volcanic rocks of Cretaceous age within or near the basin (Reynolds 1971). Applying fission-track dating of detrital apatite grains to a study of the thermal history of the basin, Gleadow & Duddy (1981) dated two pulses of Cretaceous volcanism and deposition at 126 and 106 Ma. They considered that this volcanism occurred within the basin. Duddy (1983) carried out comprehensive work on the petrology and geochemistry of the Eumeralla Formation, and mapped its burial metamorphic facies. Felton (1992), who also studied the petrology of Otway Basin sandstones, linked variations in Eumeralla Formation sandstone framework composition with palaeocurrent data, and with lithological and sedimentary facies changes, to present an argument for contemporaneous intra-basinal volcanism southwest to southeast of Cape Otway.

Methods and data

Selected wireline logs, cores, and cuttings from wells throughout the basin were used to identify associations of sedimentary rock types comprising distinct lithostratigraphic units, and to delineate their lateral and vertical distribution in the basin. Interpretation of the depositional environments represented by each unit relied on a range of sedimentary data derived mainly from cores and cuttings, supplemented by observations of age correlatives in outcrop, and of wireline-log characteristics.

A seismic-facies analysis was not included in this study because the quality of the older data is generally poor, particularly in the eastern onshore part of the basin, and recently acquired non-proprietary data are scant. The lack of structural control afforded by good-quality seismic data precluded construction of structurally correct regional cross-sections. Identification, description, and correlation of lithostratigraphic units may still proceed as presented here, but the relative thicknesses of the units across the basin may bear little relationship to original depositional thicknesses, even if compaction corrections are applied.

Twenty-five petroleum exploration wells, each penetrating a substantial thickness of the Otway Group and Casterton Formation, most with good palynological age control and reasonable wireline-log quality, were selected for study (Table 1). Digitised wireline-log data were unavailable for these wells, so self-potential (SP), gamma-ray, and resistivity logs for these wells were redrawn by hand and reduced to a common scale. These logs were selected from the range of wireline logs available for each well because they were considered to have the most value in contributing to lithological and facies interpretation.

Sedimentary rock types (sandstone, siltstone/mudstone, coal) in the wells were reinterpreted from the wireline logs, and checked against cores and cuttings, from which additional observations of composition, grainsize, fossils, and sedimentary structures were made. The rock types were closely cross-checked against their corresponding log responses, to ensure consistent interpretation of rock types in intervals poorly represented by core-and-cutting material.

Comparison of palynological ages with the lithostratigraphic boundaries interpreted during this study gives an indication of any diachroneity of the units. The apparent thicknesses of biostratigraphic zones in wells are affected by the structure, and cannot be used to calculate or infer relative rates of deposition. The palynological data recorded from wells, including those of Morgan (1985), relate to the zonation of Helby et al. (1987); however, recent changes to zonation (Morgan et al. 1995) affect the interval at the boundary of the Crayfish Subgroup and overlying Eumeralla Formation, and are discussed below. Changes to the apparent ages of lithostratigraphic units, while affecting assessments of their diachroneity, does not alter their spatial distribution or environmental interpretation.

The stratigraphic nomenclature in this paper is that proposed by Morton (1990). The recent elevation of the Crayfish Subgroup to group status (Morton et al. 1994) invalidates the term

Table 1. Otway Basin petroleum exploration wells selected for this study

West	*Northwest*	*Centre*	*East*
Trumpet 1	Banyula 1	North Eumeralla 1	Pecten 1A
Crayfish A1	Penola 1	Eumeralla 1	Flaxmans 1
Beachport 1	Robertson 1	Pretty Hill 1	Port Campbell 4
Beachport East 1	Robertson 2	Hawkesdale 1	Fergusons Hill 1
Kalangadoo 1	Tullich 1	Woolsthorpe 1	Sherbrook 1
Geltwood Beach 1	Heathfield 1	Moyne Falls 1	Anglesea 1
	Casterton 1		

Table 2. Key features of Eumeralla lithostratigraphic units

Lithofacies	*Distribution*	*Age and palynological zones*	*Relationships with other Eumeralla lithofacies*
Eumeralla IV			
Siltstone/sandstone/coal	Mainly west and northwest; may be present elsewhere	Albian (–?Cenomanian); upper *C. paradoxa–P. pannosus*	Overlies E III, its time equivalent in W and NW
Eumeralla III			
Volcaniclastic sandstone	Basin-wide; best developed in centre and E	Middle–late Albian; near base lower *C. paradoxa–P. pannnosus*	Overlies E II; overlain by E IV. Partial time equivalent of E II and E IV
Eumeralla II			
Siltstone/mudstone/thin lithic sandstone	Basin-wide	Late Aptian–early to mid-Albian; upper *P. notensis–C. striatus*; extends into upper *C. paradoxa* in W and NW	Overlies E I, overlain by E III; a time equivalent of both
Eumeralla I			
Siltstone/mudstone/sandstone/coal	Basin-wide; not recognised in Pecten 1A	?Late Barremian–Albian; ?upper *F. wonthaggiensis–C. striatus*	Overlain by E II. Overlies top Pretty Hill unconformity

Otway Group as a consequence. Morton et al. (1994) also suggested that the term Otway Supergroup would be inappropriate owing to the angular unconformity at the base of the Eumeralla Formation in the western Otway Basin. As stratigraphy and relationships within the Otway Group below the Eumeralla Formation in the central and eastern Otway Basin are uncertain, and no subgroups have been proposed for the 'Crayfish Group', the terms Crayfish Subgroup and Otway Group are retained here.

Lithostratigraphic units

During the lithological study, seven major lithostratigraphic units were recognised in the Otway Group and Casterton Formation — three within the section below the Eumeralla Formation. These lower units are not dealt with here. Three informal units comprising the Eumeralla Formation, termed Eumeralla I to III, can be correlated throughout the basin; a fourth unit, Eumeralla IV, is extensive in western and northwestern parts of the basin, but sparse in central and eastern parts, from which it has probably been removed by erosion (Figs. 4–7; Table 2).

Eumeralla I. Siltstone/mudstone/sandstone/coal

Description and interpretation

Siltstone is the main rock type, but mudstone, lithic (mainly volcaniclastic) fine-grained sandstone, and coal beds which in places contain much mineral matter (dull coal) are interbedded with it. In several wells in the northwest, the proportion of sandstone increases towards the top of Eumeralla I; in Heathfield 1 well the unit is sandy throughout.

This unit was probably deposited by low-energy meandering streams in one or more fluvial flood basins; coal swamps were common, and shallow ponds or lakes well developed. These depositional conditions appear to have prevailed throughout the basin.

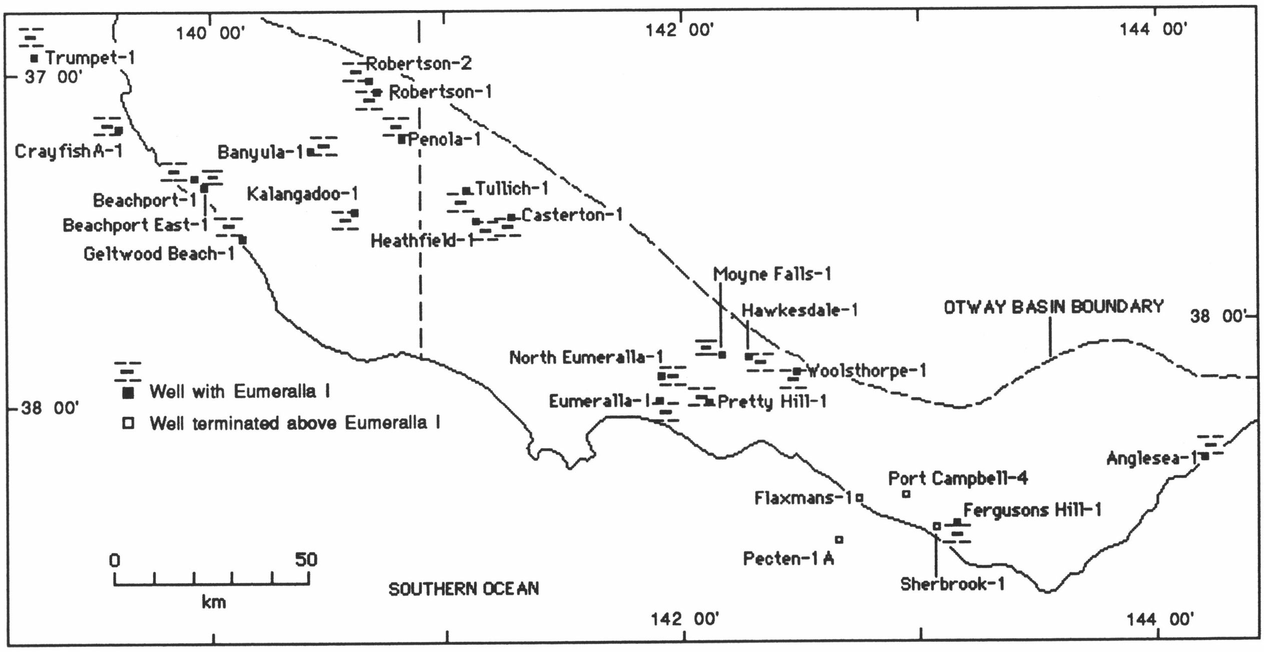

Figure 4. Distribution of Eumeralla I.

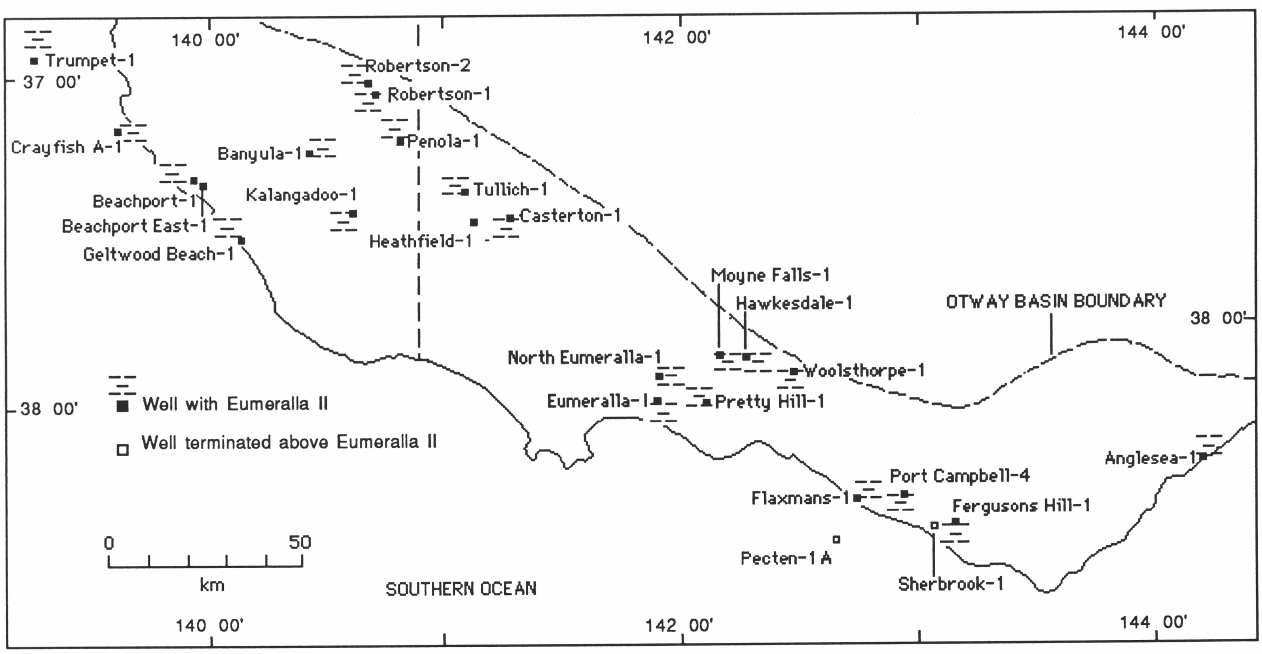

Figure 5. Distribution of Eumeralla II.

Coal beds are characteristic of Eumeralla I, but are absent from the lower part of the unit in the northwest, and in Hawkesdale 1, Woolsthorpe 1, and Moyne Falls 1 wells, near the central northern basin margin. A possible lacustrine environment is interpreted for the lower part of the unit in these areas, where lakes eventually filled with sediments and evolved into coal swamps more characteristic of Eumeralla 1 (Figs. 8, 9). Coaly facies are particularly well developed at the top of Eumeralla I in wells in the centre.

Discussion

The base of Eumeralla I appears to correspond to the seismic unconformity recognised by Rochow (1971) and Williamson et al. (1990; their 'top Pretty Hill' seismic horizon) at the base of the Eumeralla Formation. The base of Eumeralla I is therefore interpreted as the base of the Eumeralla Formation.

Felton (1992) suggested that the base of Eumeralla I (i.e., the Eumeralla Formation) might be diachronous. However, Morgan et al. (1995) considered that the base of the Eumeralla Formation lies at the base of their lower *P. notensis* Zone and is synchronous in at least the western (South Australian) part of the Otway Basin. Different ranges have been reported for *P. notensis* (Morgan et al. 1995), so the question of diachroneity remains unresolved (cf. Figs. 8 and 9).

Tupper et al. (1993) recognised a siltstone/mudstone/coal sequence in the lower Eumeralla Formation in wells on the Chama Terrace, in the western Otway Basin. Oils in the central-eastern Otway Basin are probably sourced from Eumeralla Formation peat swamp environments (Padley et al. 1995) which may be part of Eumeralla I.

A basal Eumeralla I sandstone corresponding to the Windermere Sandstone Member of the Eumeralla Formation (Morton 1990) has not been recognised in the wells studied.

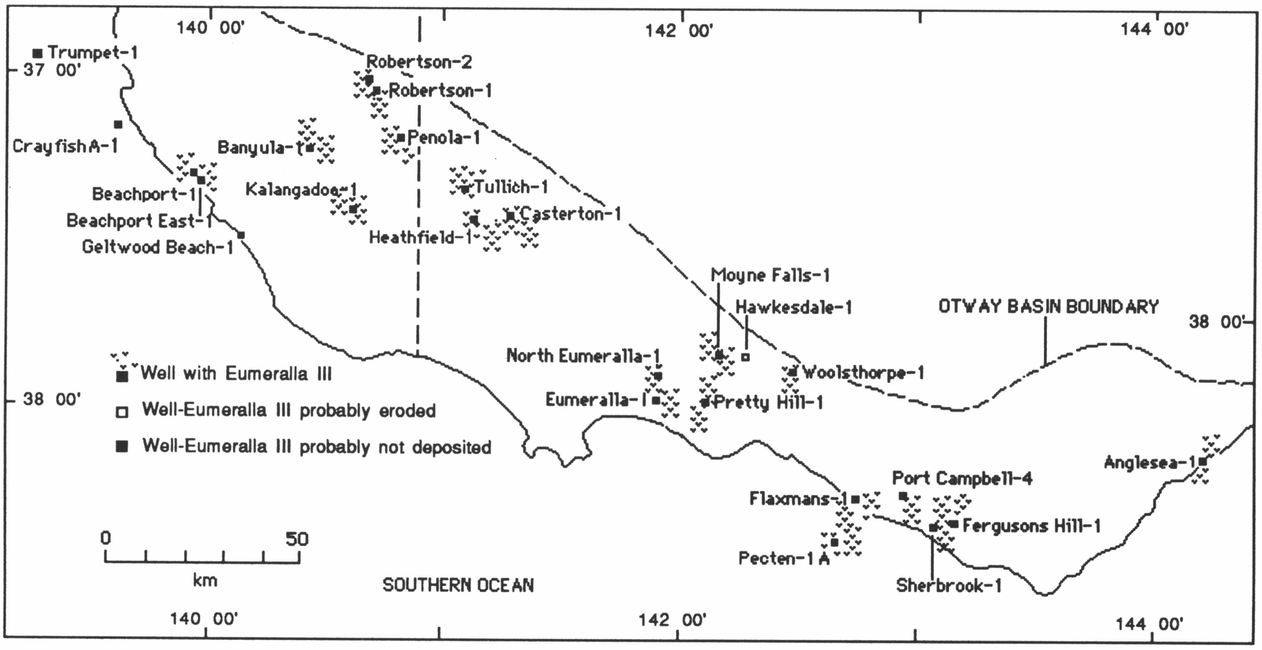

Figure 6. Distribution of Eumeralla III.

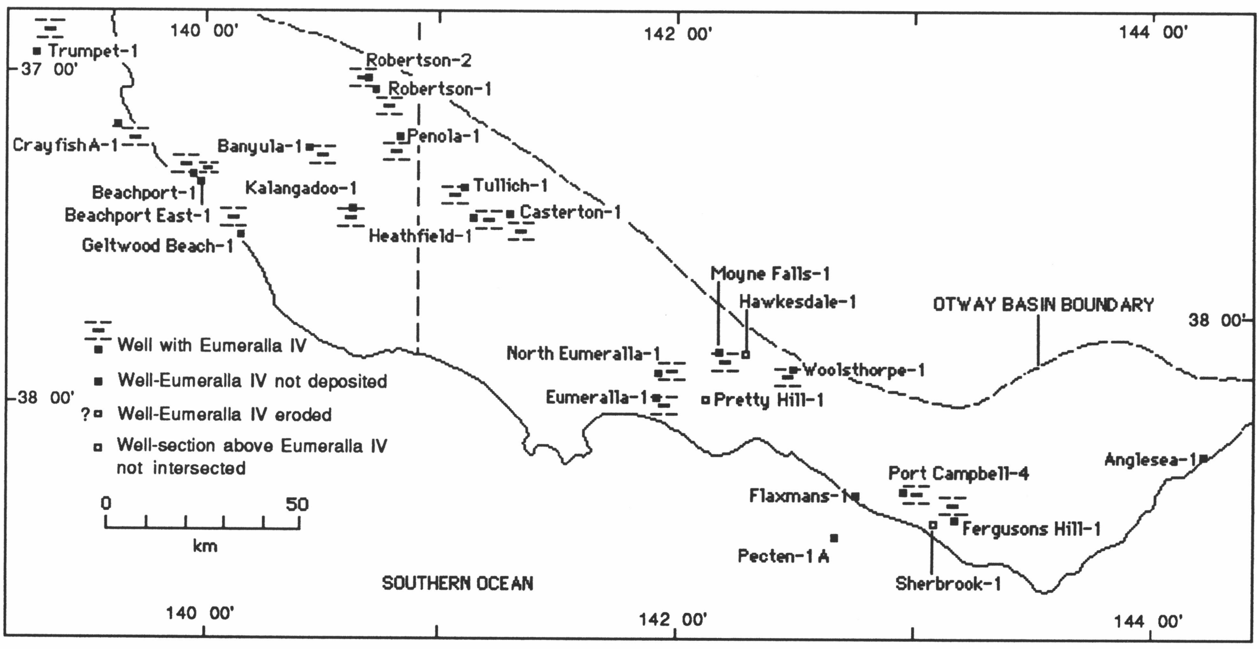

Figure 7. Distribution of Eumeralla IV.

Eumeralla II. Siltstone/mudstone/thin lithic sandstone

Description and interpretation

Eumeralla II consists mainly of fine-grained sedimentary rocks (siltstone and mudstone). Thin fine- to very fine-grained lithic (volcaniclastic) sandstone beds are common to abundant. Lack of abundant coal distinguishes Eumeralla II from Eumeralla I.

Eumeralla II is developed throughout the Otway Basin. It is interpreted as mainly lacustrine in origin. In a study of organic and sedimentary facies in the basin, Struckmeyer & Felton (1988, 1990) correlated an organic facies characteristic of a deep-freshwater lacustrine origin with this unit. Freshwater lakes succeeded and drowned the coal swamps of Eumeralla I over most of the basin.

A mainly fine-grained clastic section exposed in a road-cutting in the eastern Otway Basin has been interpreted as lacustrine in part (Felton 1992), and probably corresponds in part to Eumeralla II. The sedimentology of the cutting is described below.

Discussion

The base of Eumeralla II may be diachronous: it appears to lie within the *C. hughesi* Zone in the northwest (Robertson 1, ?Robertson 2, Tullich 1, and Casterton 1) and parts of the central area (Pretty Hill 1, Hawkesdale 1, ?Woolsthorpe 1, and possibly Moyne Falls 1), whereas elsewhere it lies at the base of or within the *C. striatus* Zone.

Eumeralla II is not recognised in Heathfield 1, in which a mainly siltstone unit containing several coal beds correlated with the *C. hughesi* Zone is interpreted as Eumeralla I.

Eumeralla III. Volcaniclastic sandstone

Description and interpretation

Eumeralla III consists mainly of fine- to coarse-grained volcaniclastic sandstone, and subordinate interbedded volcaniclastic siltstone and minor conglomerate containing intraclasts and/or exotic clasts. Its thickest and coarsest development is in the east, notably on- and offshore southwest of Cape Otway. Sandstone bodies in Pecten 1A and Fergusons Hill 1 are interpreted from wireline logs to be up to 60 m thick, but are mostly less than 25 m thick and separated by siltstone a few metres thick in other wells in the east. Gamma-ray-log signatures of these sandstones have a blocky character, defined by sharp flat bases and inclined tops, which indicate gradational fining upwards of the sandstone bodies. Blocky gamma-ray-log signatures of non-marine sequences are commonly interpreted as braided-stream-channel sandstones (Selley 1988).

Outcropping sandstone and siltstone in the eastern Otway Basin are considered to be part of Eumeralla III because they are similar in sandstone thickness and grainsize, incidence of siltstone partings, and age to Eumeralla III in the subsurface in nearby wells. These rocks are interpreted from their sedimentary facies as the deposits of high-energy braided fluvial channels and their adjacent flood plains (see below and part II of this paper).

The sandstone:siltstone ratio in the east is 80:20. Although the ratio is lower elsewhere, a change from siltstone- to sandstone-dominated deposition is apparent throughout most of the basin, and defines the Eumeralla II–Eumeralla III boundary. In the west and northwest, a marked increase in sand deposition corresponds to the base of the unit elsewhere

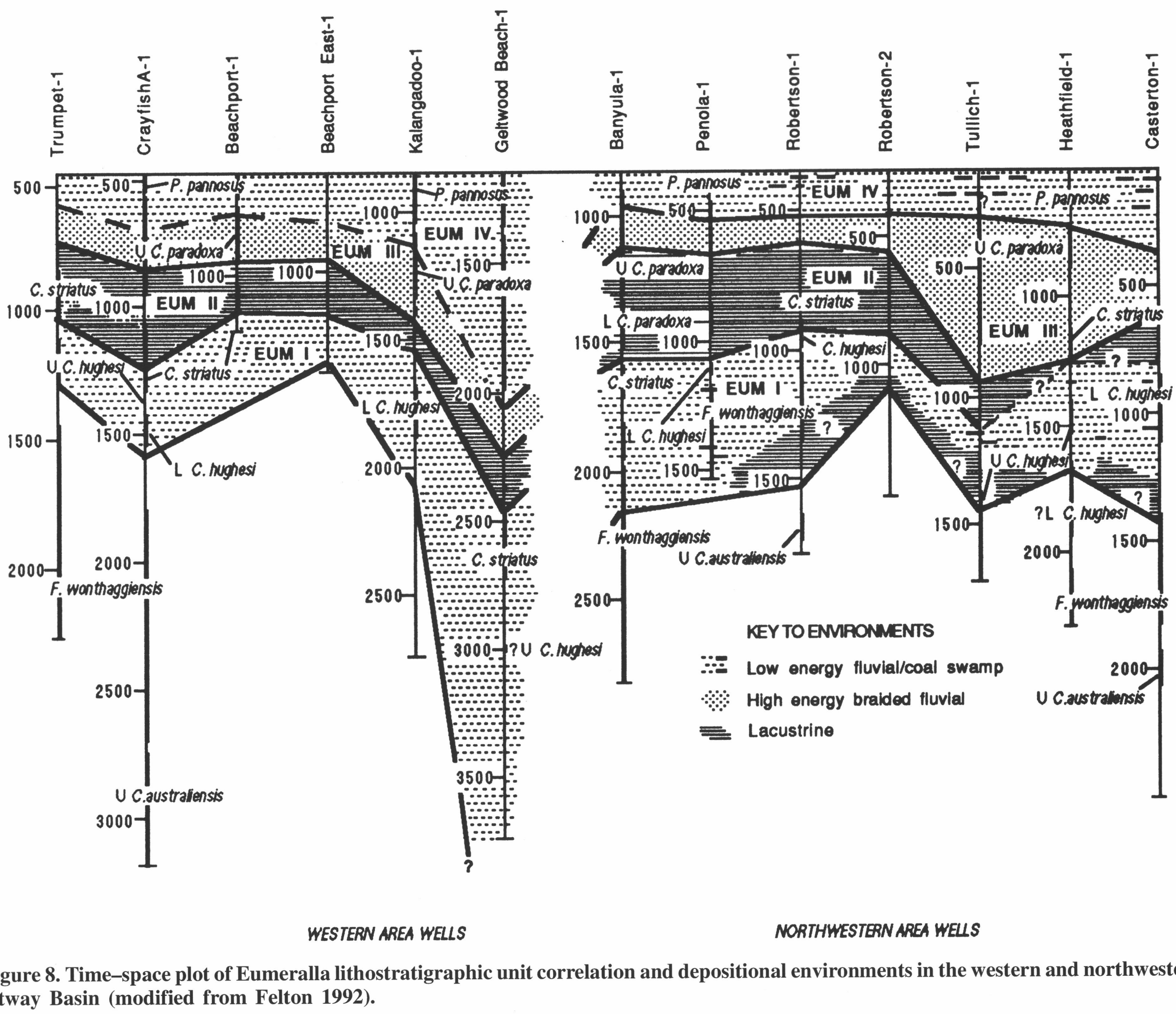

Figure 8. Time–space plot of Eumeralla lithostratigraphic unit correlation and depositional environments in the western and northwestern Otway Basin (modified from Felton 1992).

(Felton 1992). Even so, the sandstone:siltstone ratio in these areas is less than 40:60, a feature that could be applied to discriminating a lithostratigraphic unit correlative with but distinct from Eumeralla III.

Discussion

Eumeralla III marks a substantial change in the prevailing depositional regime from low-energy stream systems and large freshwater lakes to high-energy streams which transported large amounts of sand. The dominance of contemporaneous medium-grained volcanic detritus in the sand, and the spread of sand-dominated sediment throughout the basin apparently from southeast to northwest, (Figs. 8, 9) are indications either that major volcanic eruptive activity began, that its locus changed, or that dormant or extinct volcanic terrains were newly uplifted. The base of Eumeralla III is a major sequence boundary within the Eumeralla Formation.

Volcanic eruptions and/or uplift of volcanic source areas were accompanied by rejuvenation of drainage in the basin. Rain and/or snow precipitation might have increased, or the pattern of precipitation changed, as a consequence of the rapid growth of large active volcanoes. Tectonic and eruptive activity, with or without increased precipitation, would account for both the rapid erosion and redeposition of loosely consolidated volcanic products and high-energy stream flow in the newly established drainage systems.

The very thick sandstones in Pecten 1A and Fergusons Hill 1, and their coarse to medium grainsize, relative to other areas of the basin (Felton 1992) may indicate that this area lies closest to a volcanic sediment source. The character and palaeocurrent directions of correlative Otway Group outcrops near Cape Otway support this interpretation (see part II of this paper).

From palynological evidence, the base of this unit is probably diachronous. It lies close to the *C. striatus*–lower *C. paradoxa* Zone boundary in the centre and east, and near the base of the upper *C. paradoxa* Zone in many wells in the west and northwest. This observation is consistent with the spread of sandy volcaniclastic sediment through the basin from sources in the southeast. The pick of the base of Eumeralla III in Heathfield 1 is difficult in the overall sandy sequence that it intersected. As the base of Eumeralla III is no lower than the *C. striatus*–lower *C. paradoxa* Zone boundary elsewhere in the basin, the pick at the base of the *C. striatus* Zone in Heathfield 1 (Fig. 8) may be too low.

Eumeralla IV. Siltstone/sandstone/coal

Description and interpretation

Eumeralla IV consists largely of siltstone. Subordinate sandstone is volcaniclastic, thinner, and finer than in the underlying Eumeralla III. The siltstone lacks distinctive gamma-ray- and SP-log signatures, but its lower electrical response helps distinguish it from the sandstone. In general, although the sandstone in Eumeralla IV is similar in composition and grainsize to the siltstone, it shows up distinctly on the SP logs as sharp kicks to the left (e.g., Heathfield 1).

Coal beds are present in Robertson 1, Casterton 1, and Tullich 1 — all located near the northern margin of the basin. Coal beds, fragments of which are evident in well-cutting samples, may be indicated on the resistivity log by sharp kicks to the right, but, in 'dirty' coals (i.e., containing much mineral matter) characteristic of the Otway Group (e.g., table 7.6 of

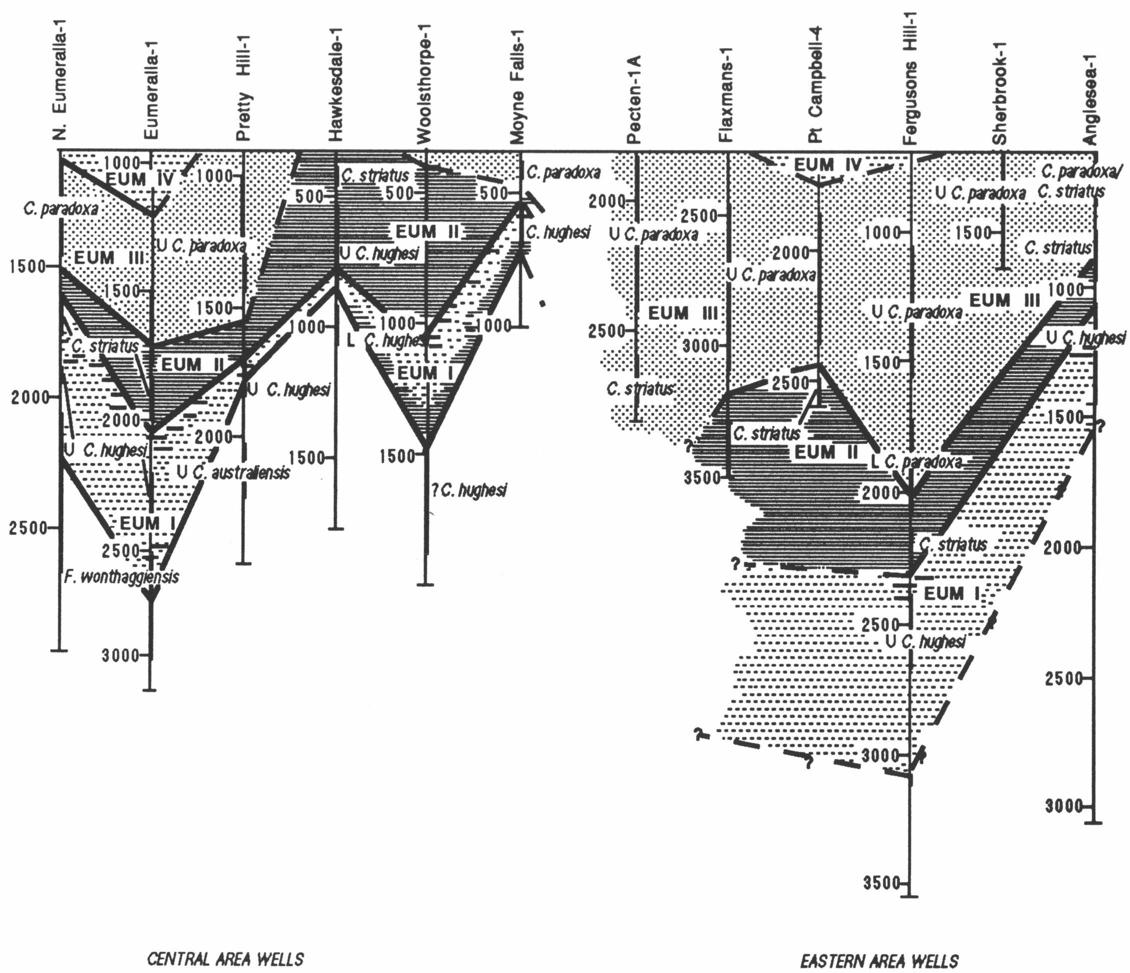

Figure 9. Time–space plot of Eumeralla lithostratigraphic unit correlation and depositional environments in the central and eastern Otway Basin (modified from Felton 1992). The pattern symbols are explained in Figure 8.

Kenley 1976), this log response is commonly suppressed.

Eumeralla IV is absent from most wells in the centre and east (Figs. 7, 9). Its presence in Port Campbell 4 and Fergusons Hill 1 is equivocal. Some wells in these areas were collared in the Eumeralla Formation below this unit. Others were collared in the Upper Cretaceous marine sequence overlying the formation below Eumeralla IV, whose absence is probably due to erosion before the younger sediments were deposited.

Eumeralla IV represents flood-plain, lake, and local coal-swamp environments with low-gradient meandering streams.

Discussion

The change from high- to low-energy depositional conditions is thought to result from a diminution of the sediment supply, and a loss of flow competence in streams draining volcanic sources as active volcanism waned, volcanic edifices subsided, and erosion further reduced elevation of the source areas. Basin drainage systems also might have been truncated by rising base levels due to rising sea level or tectonic subsidence, causing drainage to pond and favouring mainly fine-grained sedimentation.

Sedimentology of Eumeralla II and III in outcrop

Methods

Fresh natural and man-made exposures include sections up to several hundred metres parallel and transverse to depositional strike along the coast in the eastern Otway Basin. The depositional data for a number of long profiles, including details of inaccessible cliff outcrops examined with binoculars, were superimposed onto photographs. A number of vertical profiles were logged in detail to supplement the long profiles. Although vertical profiles are limited in their usefulness when characterising fluvial styles (Miall 1985), they are a convenient means of summarising the scales and relative abundances of sedimentary facies, and may have particular value for comparison with the subsurface. The vertical profiles presented here (and located in Fig. 10) are representative of the range of facies in Eumeralla II and III in the eastern Otway Basin.

The sedimentary facies recognised in outcrop can be grouped into a number of genetically distinct facies associations, described in part II. The relationships and thicknesses of facies associations compared for different parts of Eumeralla II and III outcrops in the eastern Otway Basin, and integrated with other sedimentary data, provide the basis for interpreting and characterising at least two local fluvial systems in the outcrop area.

Outcrop descriptions

Eumeralla II

Skenes Creek Road vertical profiles. Three vertical profiles recorded in Skenes Creek Road summarise the evolution of a 270-m coarsening-upwards section which is interpreted as a flood-plain and lake sequence recording fluctuating water levels in a flood-basin lake (profiles SCR1 and 2; Figs. 11–14), and gradual filling of the lake and migration of a fluvial channel across its flood plain (profile SCR3; Fig. 12). Higher in the section (not illustrated), lacustrine silty mudstone succeeds the fluvial interval, and a lake-beach sandstone is apparent (Felton 1992).

Most coal seams in the profiles are enclosed by lacustrine deposits (laminated and thinly bedded siltstone, mudstone, and fine to very fine sandstone), have no associated seat earths, and may be allochthonous.

Seat earths underlie some of the coal beds in the Skenes Creek Road section. One, at the top of unit 6 in profile SCR1 (Fig. 11), is 40 cm thick and forms the upper part of a discrete fining-upwards sequence capped by a thin coal bed. Units 7–9 in profile SCR 2 (Fig. 12) are similar but lack a well-developed seat earth. Such sequences are interpreted as the fill of abandoned lacustrine delta-distributary channels in which ponded water lay. Ponds eventually filled with fine sediments; buried vegetation formed thin coal beds.

Eumeralla III

Cat Reef vertical profile. A vertical profile at Cat Reef records aggradation and abandonment (units 1–11; Fig. 15) of a broad channel tract in which fining-upwards sheet sand accumulated repeatedly over intraclast gravel-filled scour hollows (bases of units 3 and 4, Fig. 15) in the bases of channels. Clasts range from boulders (1 m in diameter) to granules (Fig. 16). The cobble to granule size fraction consists of a mixture of intraclast siltstone and dark, altered glassy volcanic rocks. The boulders are intraclasts of (1) plane- and cross-bedded sandstone and (2) sandy conglomerate whose clasts are similar in size and composition to the cobble and granule fraction of the host conglomerate.

Sedimentary structures in the channel-tract sandstone are dominated by plane-bedding; minor backset cross-bedding and low-angle bedding indicate high-stage flows (Figs. 15, 16). Ripple and climbing-ripple laminations occur near the tops of

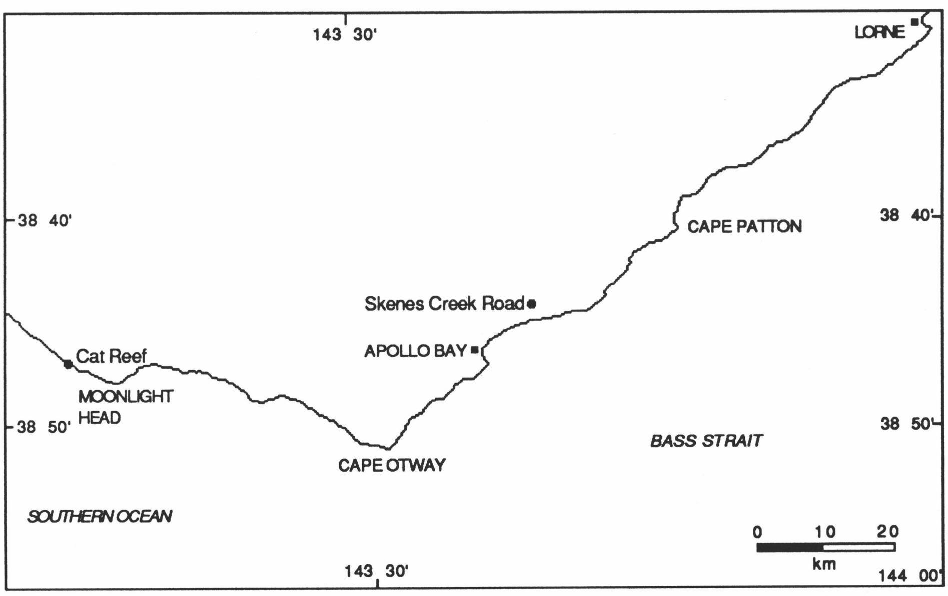

Figure 10. Outcrop locations, eastern Otway Basin (after Felton 1992).

thick multistorey sandstones as sandy beds pass upwards into finer-grained sediments (e.g., Figs. 15). Palaeocurrent directions in the sheet sandstone vary, but have an overall northwesterly to northeasterly trend.

The channel tract was abandoned a number of times, sometimes long enough for soils to develop and plants to grow (Figs. 15, 17). Much of the fine-grained part of the section is interpreted as suspension fall-out from turbid floodwater entering a flood-plain pond.

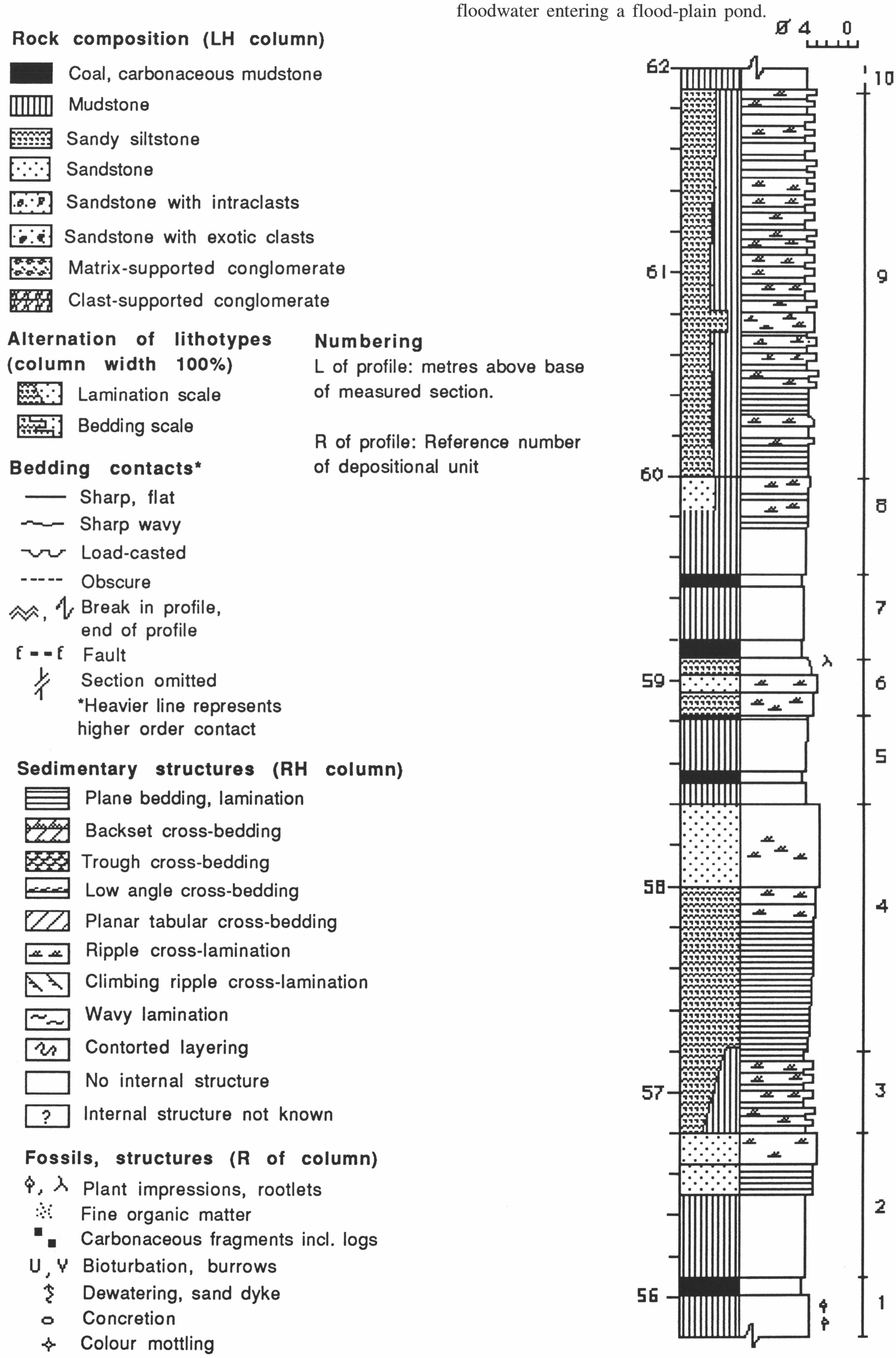

Figure 11. Skenes Creek Road, profile SCR1, and key to vertical profiles.

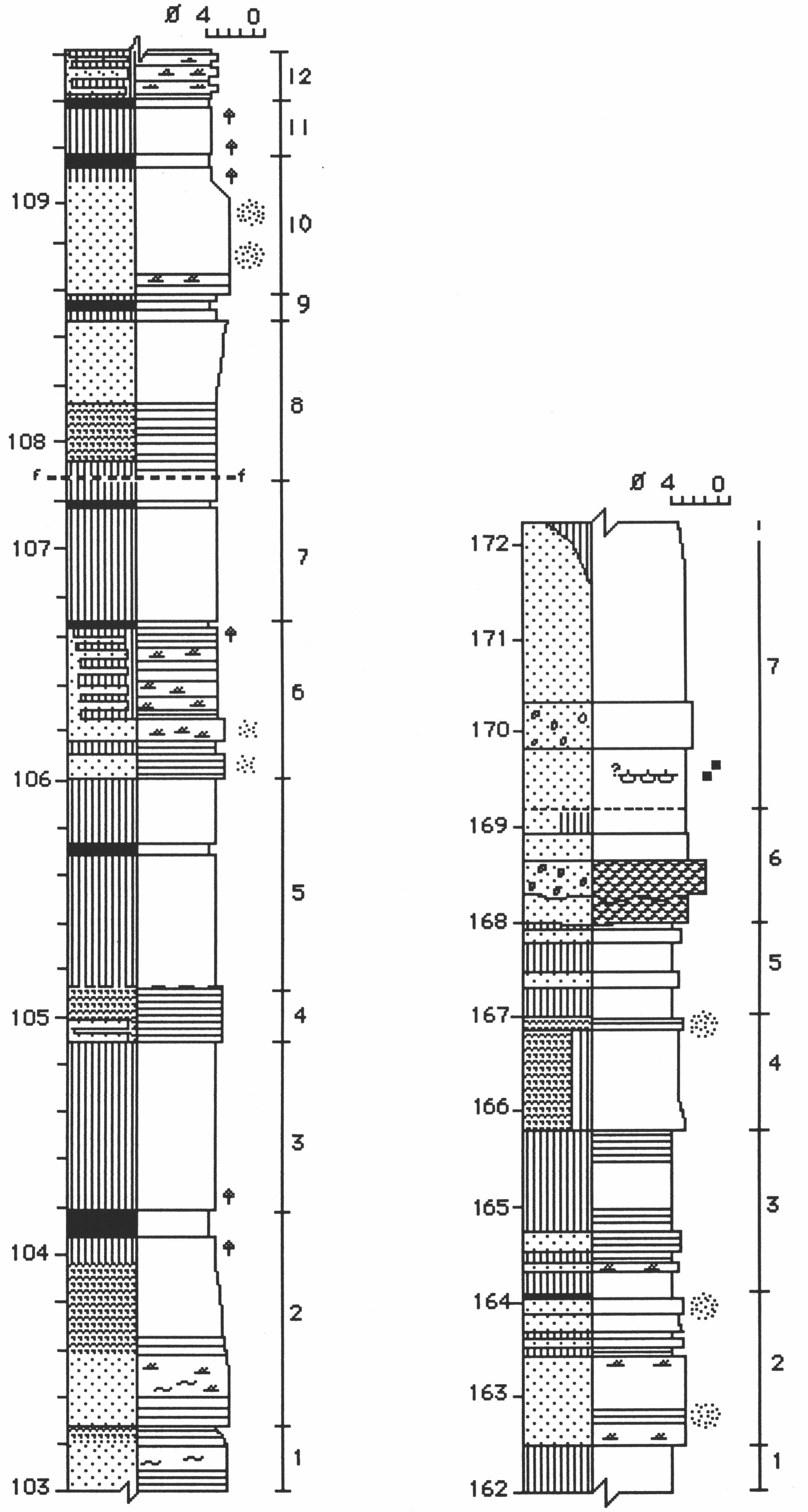

Figure 12. Skenes Creek Road, profiles SCR2 (left) and SCR3 (right).

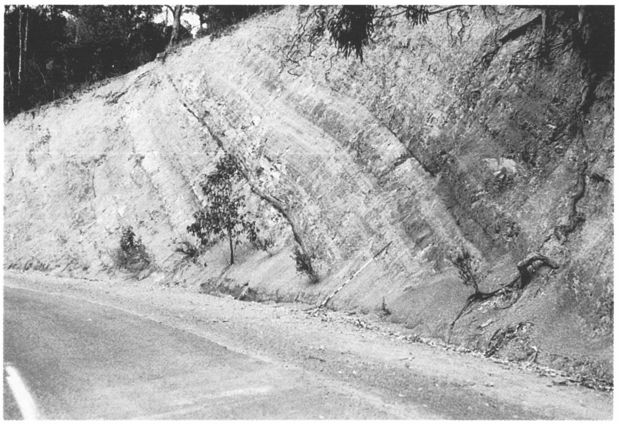

Figure 13. Skenes Creek Road. Flood-plain and lake sequence. The coal seam near the base of the measuring staff is the lowest seam (top of unit 1) in profile SCR1. The top of the staff rests on rippled fine-grained sandstone at the top of unit 4. The staff is 2 m long.

Figure 14. Skenes Creek Road. Flood-plain swamp sequence; the top is 10.5 m below the base of profile SCR2. Several coal seams up to 50 cm thick overlie structureless carbonaceous mudstone (grey), some of which contain plant rootlets. Interseam rocks are composed of thinly bedded siltstone, mudstone, and fine sandstone. The staff is 2 m long.

Sedimentary evolution of the Eumeralla Formation

By the mid-Barremian, older depositional sub-basins were largely filled with sediment before the onset of Eumeralla Formation deposition. The basin-wide extent of Eumeralla I suggests that the basin was acting as a single depositional entity, and reflects the establishment of a single, integrated basin-wide drainage system. The succession of distinct litho-stratigraphic units across the basin can be interpreted as products of evolution of such a system, which persisted to the end of the Albian.

More than one drainage system may have existed early in the history of Eumeralla Formation deposition. Felton (1992) presented evidence for the existence of two major fluvial systems — in the northwest and centre — before Eumeralla Formation deposition. She suggested that lakes developed in these areas at the onset of Eumeralla Formation sedimentation because renewed tectonism in the basin had caused the two systems to pond; lake development is a consequence of interior drainage in rift basins (Leeder & Gawthorpe 1987). The change from lacustrine to extensive flood-plain and swamp deposition in the northwest and centre may indicate that through-basin drainage had developed. Leeder & Gawthorpe (1987) described through-basin drainage in rifts as being characterised by a meandering fluvial system. Alexander & Leeder (1987) noted that both lakes and meandering systems tend to be developed close to the hanging walls of rift grabens (i.e., close to the bounding fault of a basin). This fits the lithological succession observed in Eumeralla I in the northwest and north-centre, close to the former basin-bounding fault.

If the basin had supported more than one drainage system, they must have been closely connected because the depositional conditions throughout the basin were quite uniform, particularly during the deposition of Eumeralla II and III; any changes to depositional controls would have affected all systems similarly in order to maintain that uniformity. Factors controlling/affecting fluvial drainage and sediment deposition are related to tectonics and climate and are not reviewed here, but include — among others — sediment supply, base level, precipitation, relief, and vegetation.

Ponding of drainage along the northern basin margin and establishment of widespread flood-plain and swamp environments in Eumeralla I may have been a consequence of a rising base level. The coincidence of these environments with a major marine transgression during the Barremian (Haq et al. 1987; Morgan 1980) and a maximum on the marine flooding curve derived by Struckmeyer & Brown (1990) is strong evidence that base level for drainage in the basin may have been controlled by sea level at this time. A rise in base level is also consistent with an increased rate of subsidence across the basin during a second phase of rifting (Williamson et al. 1990).

The change in sandstone composition from mainly quartz-lithic in the Crayfish Subgroup (Felton 1992; Little & Phillips 1995) to volcaniclastic in the Eumeralla Formation (Duddy 1983; Felton 1992) reflects the onset of major volcanism in the basin, which accompanied the second stage of rifting. This event may be the pulse of volcanism dated at 126 Ma by Gleadow & Duddy (1981). Subsidence in the central part of the rift could have been offset by elevation of the rift floor, driven by increased heat flow and expansion of magma; subsequent volcanic eruptions along the axis of the rift produced a substantial edifice. Evidence presented in part II of this paper suggests that a major source of the epiclastic volcanic detritus comprising the Eumeralla Formation was located in the axial part of the extensional basin resulting from the second stage of rifting. The coincidence of the Barremian marine transgression (Haq et al. 1987; Morgan 1980) with the changes in depositional conditions in the Otway Basin therefore might be entirely circumstantial; drainage in the basin could have been controlled entirely from within.

The widespread development of freshwater lakes (Eumeralla II), and a restriction of the flood-plain and coal-swamp environments represented by Eumeralla I, imply that the base level continued to rise. However, a model of facies relationships in continental half-grabens proposed by Schlische & Olsen (1990) predicts that — under conditions of constant water volume and sediment input, uniform subsidence, and a fixed outflow level from the half-graben — initially fluvial conditions will be replaced in time by lacustrine conditions. The lakes eventually fill and fluvial/alluvial conditions return throughout the half-graben system.

Deposition in the basin seems to accord with Schlische & Olsen's (1990) model. Fluvial conditions were re-established in the basin, whose central and eastern parts were blanketed by thick volcaniclastic sands (Eumeralla III) deposited by large active rivers during the early Albian (*C. striatus*–lower *C. paradoxa* Zone). However, the 106-Ma Cretaceous volcanic event identified by Gleadow & Duddy (1981) may have been the major influence on Eumeralla III sedimentation (Felton 1992).

Early development of Eumeralla III in the east, especially in Pecten 1A and Anglesea 1, and in Heathfield 1 and Kalangadoo 1 in the northwest and west respectively, suggest that these sites were adjacent to active volcanic centres or located on major distributaries from such centres. Other sedimentary and petrographic data offer some support for this (Felton 1992). The later appearance of Eumeralla III elsewhere in the west and northwest might indicate that those sites were remote from source volcanoes or distributaries and/or that topographic highs were reactivated or maintained, such as Beachport High, which existed in the Aptian (Reynolds 1971).

The deposition of Eumeralla III apparently coincided with a late Aptian marine regression (Haq et al. 1987); this observation again suggests that the marine base level wielded an influence on non-marine sedimentation in the basin. The lowering of base level due to the marine regression could have contributed to the expansion of Eumeralla III across the basin, particularly westwards, where the first marine connection with the basin is thought to have been established (Morgan 1980; Mutter et al. 1985). Eumeralla III is less well developed in the west and northwest, areas which apparently were

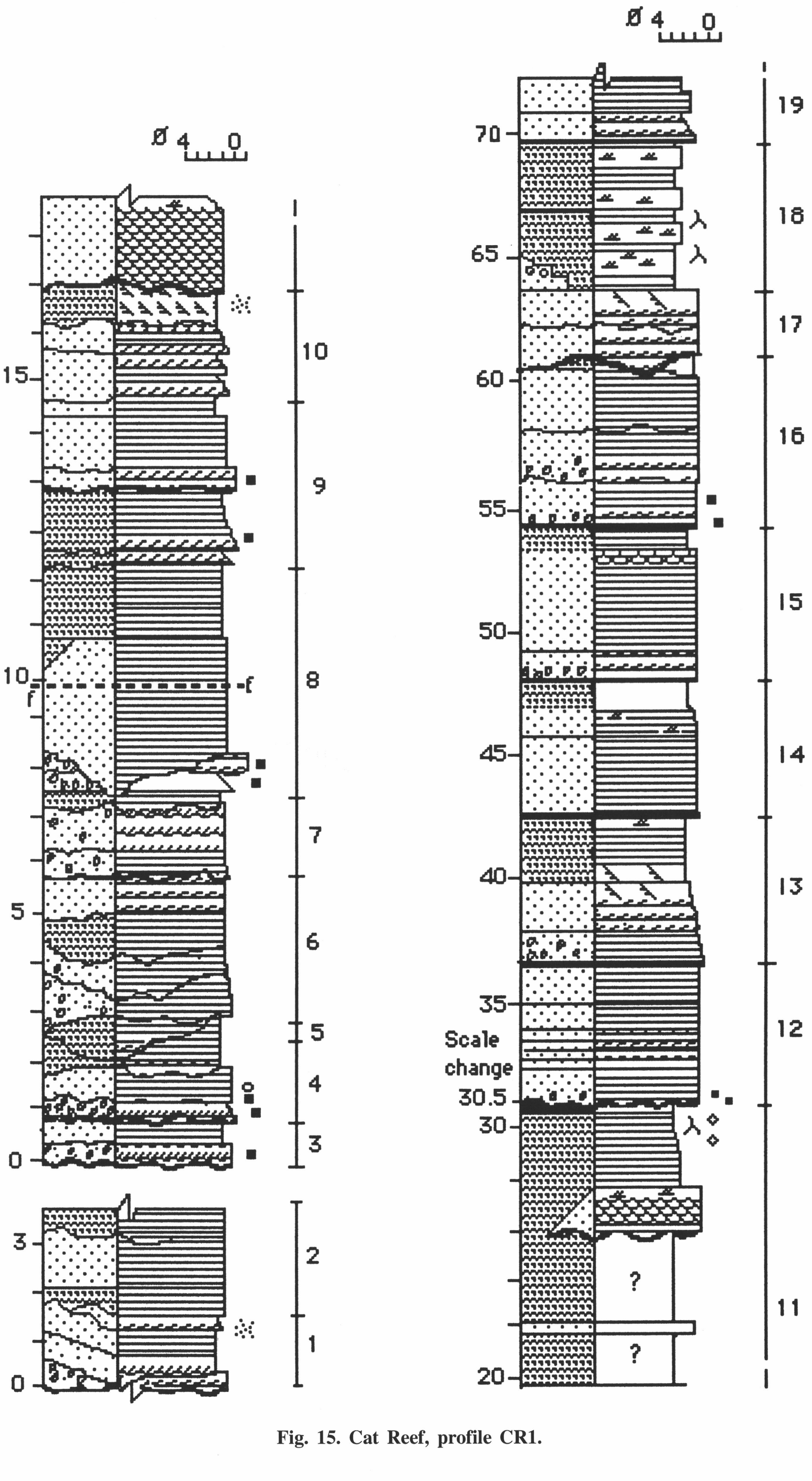

Fig. 15. Cat Reef, profile CR1.

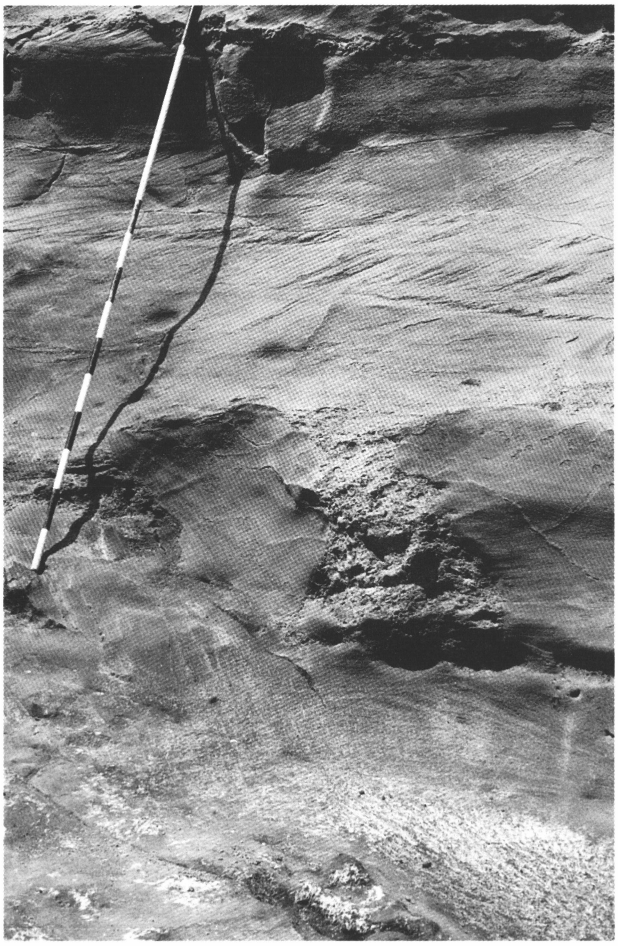

Fig. 16. Massive intraformational conglomerate at the base of unit 3, profile CR1, comprises sandstone-intraclast boulders in an intraclast-supported small-pebble conglomerate filling a scour hollow. The pebbles are siltstone and devitrified glassy volcanic rocks. The overlying channel-fill consists of backset cross-bedded sandstone with a plane-bed set near the top of the photograph. The circular structure in the plane-bed set is a broken carbonate concretion. Short intervals on the measuring staff are 10 cm long.

Fig. 17. Soil profile overlain by a coal bed and the scoured base of a channel sandstone in unit 11, profile CR1. Mudstone at the top of the soil profile is reddened and bleached, and peds are developed. Rootlets demonstrate that the coal formed in situ.

bypassed by the major trunk rivers. Palaeocurrent data from Eumeralla III outcrops (see part II of this paper) imply that mainly westerly flowing rivers drained the basin at this time.

The expansion of Eumeralla IV and restriction of Eumeralla III towards the end of the Early Cretaceous suggest that sedimentation was responding to the late Albian marine transgression (Haq et al. 1987; Morgan 1980) and/or continued subsidence. Waning and cessation of volcanism, and a resultant reduction in sediment supply and lower relief in the source area(s), perhaps contributed to the restriction of Eumeralla III.

Conclusions

It seems likely that the non-marine sedimentation in the basin was influenced, at least in part, by changes in sea level from the Barremian onwards, as Morgan (1980) first suggested, since several sedimentary events apparently coincide with sea-level changes. Volcanism was also a major influence on sedimentation, and dominated the sediment supply from the Barremian to the end of the Albian (Felton 1992). However, the relative importance of volcanism, sea-level change, and tectonic subsidence on basin sedimentation from the Barremian onwards cannot be fully evaluated on present sedimentary evidence. The models for rift sedimentation were developed for rift systems without major infra-rift volcanic activity, and may be of limited use in interpreting the Eumeralla Formation.

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