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Provenance of Palaeozoic turbidites in the Lachlan Orogenic Belt: strontium isotopic evidence

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The sedimentary provenance of Palaeozoic turbidites in the southern Lachlan Orogenic Belt is determinable by comparing the mean Sr isotopic ratios of the turbidites with those of potential provenance areas at the time of sedimentation. The possible provenances encompass rocks of Precambrian to Cambrian age extending from central South Australia to western Tasmania and estimates of their isotopic compositions are obtainable by pooling data in the geochronological literature. Sr isotopic data exist for turbidites of Early Ordovician, Late Ordovician and Devonian age located in northeastern Victoria, southeastern New South Wales and northeastern Tasmania, respectively. All Precambrian provenance areas have mean $^{87}Sr/^{86}Sr$ ratios that are too high to be equated with those of the turbidites. The turbidites contain Sr with a relatively 'juvenile' isotopic composition and the only possible equivalent sediment sources are Cambrian sedimentary rocks, such as the Kanmantoo Group in South Australia, and igneous rocks as in western Tasmania. The palaeogeography of turbidite deposition involved a mountain belt developed during the Late Cambrian–Early Ordovician Delamerian Orogeny, which acted as a barrier to sediment transport from the continental interior, and shed detritus into the turbidite basin of a passive continental margin.

Key words: Lachlan Orogenic Belt, palaeogeography, Palaeozoic, sedimentary provenance, strontium isotopic tracing, turbidites.

INTRODUCTION

The tectonic interpretation of the Lachlan Orogenic Belt continues to be beset with fundamental uncertainties. The regional tectonic setting has been considered in terms of numerous variations on passive continental margin, marginal sea and convergent plate boundary themes (e.g. Cas *et al.* 1980; Powell 1983; Crawford *et al.* 1984). The geometry is also debated, with present tectonic zones regarded as having their original configuration or being in part allochthonous (e.g. Powell 1983; Powell *et al.* in press). Even the palaeogeography and sedimentary provenance are imperfectly understood: how was the huge volume of Ordovician turbidites generated? This paper is an attempt to address some of these issues by placing constraints on the sedimentary provenance of turbidites by Sr isotopic means, and through this on the likely palaeogeography and tectonic setting.

ISOTOPIC PROVENANCE TRACING

The application of the Rb–Sr isotopic system to provenance tracing is based upon the three following propositions: (i) that a particular provenance can be characterized by a mean Sr isotopic composition; (ii) that this isotopic signature is transferred to the sediment derived by weathering the provenance area; and (iii) that subsequent deposition results in this isotopic composition becoming the initial value of the derivative sedimentary rock.

The characterization of the overall isotopic composition of a potential provenance can be achieved by pooling many Sr isotopic analyses from the different rock types exposed within the provenance area. Pooling isotopic data is also geologically reasonable as it mimics the blending of detritus during sedimentation. Two factors can lead to distinctive $^{87}Sr/^{86}Sr$ values for specific provenances. First, provenances may differ greatly in geochemistry (for example as a function of tectonic setting) and this is expressed in the Rb/Sr ratios that govern isotopic growth. Second, variation in the age of provenances is reflected in the extent of isotopic growth. The development of distinctive mean isotopic compositions in diverse geological settings is illustrated by the mean $^{87}Sr/^{86}Sr$ ratios of three Proterozoic examples at 500 Ma (Table 1): Adelaide Orogenic Belt (0.730), Willyama Complex (0.782), and Tyennan Nucleus (0.807). In the context of the present paper, Precambrian areas often have substantial internal isotopic variation and average values may be quite uncertain. However, in the above cases the means are so distinct that uncertainties are probably unimportant in the context of provenance tracing, and in the following discussion it is only significant that the values are high. Palaeozoic settings, being younger, are more coherent and $^{87}Sr/^{86}Sr$ ratios often have a pronounced peak in their distribution which strengthens any pooled mean.

Consider, for example, the first stage of a sedimentary cycle involving the weathering of a quartz–feldspar protolith to form a sediment. During the alteration of feldspar to clay, crystal chemistry will result in preferential incorporation of Rb in the clay lattice and some Sr release into solution. As a result, most sediments will have higher Rb/Sr ratios than the parent rocks, so their isotopic

Table 1 Rb-Sr isotopic data for Palaeozoic turbidites and potential provenances. The isotopic ratios of the turbidites at the time of sedimentation are given in bold type. A provenance match is located by following down the column containing the bold type entry.

Geological unit	Age (Ma)	No. samples	Mean modern system				Mean ^{87}Sr/^{86}Sr for set age (Ma)				
			Rb ppm	Sr ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	500	485	455	400	Span*
Palaeozoic turbidites											
Gundowring Terrain	500?	22	121	119	2.94	0.7383	**0.7174**	0.7180	0.7193	0.7216	0.0005
Lockhart Terrain	485	8	197	79	7.28	0.7626	–	**0.7123**	0.7154	0.7212	0.0011
Cooma High Grade	455	12	229	131	5.08	0.7495	–	–	**0.7166**	0.7206	0.0007
Cooma Low Grade†	455	9	173	75	6.75	–	–	–	**0.713?**	–	–
Mathinna (Ord)†	485	6	215	44	14.4	–	–	**0.712?**	–	–	–
Mathinna (Dev)	400	12	225	78	8.41	0.7676	–	–	–	**0.7197**	0.0006
Provenance areas											
Precambrian											
(1) Carnot gneiss	2600	20	103	144	2.08	0.7800	0.7652	0.7656	0.7665	0.7681	0.0051
(2) Eyre Peninsula granites	1600	20	195	173	3.27	0.7798	0.7565	0.7572	0.7586	0.7612	0.0087
(3) Willyama Complex	1700	56	227	165	4.02	0.8106	0.7819	0.7828	0.7845	0.7877	0.021
(4) Houghton Diorite	850	11	43	105	1.19	0.7368	0.7283	0.7286	0.7291	0.7300	0.0038
(5) King Island granite	820	5	294	77	11.2	0.8523	0.7723	0.7747	0.7796	0.7884	0.016
(6) Tyennan Nucleus	800	58	103	20	15.4	0.9163	0.8066	0.8099	0.8165	0.8286	0.022
(7) Adelaide Orogenic Belt	750	16	143	82	5.05	0.7660	0.7300	0.7311	0.7333	0.7372	0.0035
Early Palaeozoic											
(1) Normanville Group	540?	4	126	221	1.66	0.7240	0.7121	0.7125	0.7132	0.7145	0.0010
(2) Kanmantoo Group	540?	57	169	187	2.62	0.7349	0.7163	0.7168	0.7179	0.7200	0.0007
(3) SA syntectonic granites	500	8	167	241	2.00	0.7243	–	0.7105	0.7113	0.7129	0.0052
(4) SA post-tectonic granites	485	5	184	60	8.92	0.7643	–	–	0.7064	0.7134	0.0023
(5) Mt Reid Volcanics	540?	29	104	153	1.97	0.7248	0.7108	0.7112	0.7120	0.7136	0.0006
(6) Queenstown Porphyry	540?	7	132	170	2.25	0.7324	0.7164	0.7169	0.7178	0.7196	0.0031
(7) All Tasmania igneous	540?	43	134	163	2.38	0.7279	0.7110	0.7115	0.7125	0.7144	0.0007
(8) Victorian greenstones	540?	10	6	147	0.12	0.7066	0.7057	0.7057	0.7058	0.7059	0.0004
(9) Mt Stavely dacites	540?	11	56	238	0.69	0.7120	0.7071	0.7073	0.7075	0.7081	0.0006

* The extent of the distribution of isotopic ratios (span) is estimated as one standard error of the mean (see text) for ratios at 400 Ma.

† Data handling described in text.

systems cannot be used to calculate the protolith age. While geochemical fractionation of Rb from Sr can be considerable, the provenance signature may be retained in the isotopic compositions of sediments because isotopic ratios are unaffected by purely chemical processes like weathering reactions. However, the isotopic effects of weathering may be complex. Differential weathering of minerals with differing primary isotopic compositions may produce isotopically distinct sedimentary derivatives. Furthermore, there can be distinct isotopic heterogeneity between grain size fractions in transported (Douglas 1993) and deposited (Biscaye & Dasch 1971) sediment. Nonetheless, the situation can be simplified empirically: a detailed study of size fractions of suspended sediment in the continental drainage of the Murray-Darling river system by Douglas (1993) demonstrates that the $> 25\ \mu m$ suspended fraction has acceptable Sr isotopic matches with provenances. For example, the $> 25\ \mu m$ suspended sediment fraction in the upper Murray River has a measured ^{87}Sr/^{86}Sr ratio of 0.748 and the estimated mean ratio for the exposed rock in the catchment is 0.748 (obtained by pooling data for 75 rocks in the catchment). Equivalent results for the McIntyre River show that the $> 25\ \mu m$ sediment has a ratio of 0.7107, which is similar to source Palaeozoic granitic (0.7126, 53 samples) and sedimentary rocks (0.7109, 23 samples).

It is presumed that sedimentary deposition does not involve any isotopic change. Significant isotopic equilibration between the silicate component and seawater has been discounted and silicates do carry a provenance signature (Dasch 1969). Necessarily, the sediment considered must not contain additional marine components, particularly carbonate (this can be established petrographically or geochemically, and the rocks considered below are carbonate-free). The isotopic systems established during sedimentation may vary in nature. In the case of shales an isochron system may develop (e.g. Bofinger & Compston 1967) and the initial ratio of the isochron will give the mean isotopic composition of the provenance. With coarser sediment in which primary mineral grains survive from the source and coexist with new mineral grains formed during weathering, it is more likely that a partially inherited isotopic system rather than an isochron will result (Peterman *et al.* 1981). Such a sediment can be characterized by a mean isotopic composition estimated by pooling numerous samples.

Disturbance of the isotopic system after sedimentation by the movement of Rb and/or Sr during diagenesis or metamorphism may invalidate this technique. However, if the disturbance involves limited redistribution within lithologies, say on a scale of metres as is common in much regional metamorphism, isotopic pooling of samples can recover a reasonable approximation of the mean system. (The analogy is with metamorphic isotopic homogenization whereby the weighted mean of data on a metamorphic isochron will approximate a point on the primary pre-metamorphic isochron.) More extensive open systems with net gain or loss of Rb and/or Sr cannot be treated; some may be detected when an increase in Rb/Sr ratio results in Sr isotopic ratios calculated for the time of sedimentation which are unrealistically low for the Earth system.

In summary, there are considerable differences between many geological terrains in Rb/Sr ratios and age, and therefore in Sr isotopic compositions; sediments derived from weathering of these terrains will have different mean $^{87}Sr/^{86}Sr$ ratios leading to the possibility of matching distinctive or unique isotopic compositions from sediment to provenance. Given the variables associated with each stage of sedimentation and limitations on the numbers of samples that can be handled, exact provenance matches are not to be expected. However, it is proposed that the Sr isotopic system may permit broad, but convincing provenance assignments to be made. The provenance signature will be best preserved in detrital sediments like siltstones, which are fine grained enough to contain a representative sample of grains of weathered minerals from the protolith, and sufficiently coarse grained to contain primary detrital mineral grains. The mean Sr isotopic ratios for provenance and sediment are estimated by pooling of numerous Rb-Sr data obtained either for the purpose, or from published chronological studies. The pooling procedure weights the isotopic compositions of individual samples as a function of Sr concentration, as the effective contribution of each sample is proportional to its Sr content. The calculation determines the amount of ^{87}Sr and ^{86}Sr contributed by each sample, totals each isotope for the population, and by division obtains the pooled $^{87}Sr/^{86}Sr$ ratio. The pooled concentrations of Rb and Sr are arithmetic means and are used to calculate the overall $^{87}Rb/^{86}Sr$ ratio. An age of sedimentation is determined for the stratigraphic unit under consideration and mean isotopic compositions for the sediment and potential provenances are then calculated for that time. Normal lithological variation means that provenance areas can vary internally in isotopic composition to a considerable degree. There are likely to be some individual provenance samples that by chance have similar isotopic compositions to a tested sediment even when the mean compositions differ greatly; hence comparison must employ the means rather than the distributions. For this reason, and because the spread of individual isotopic ratios in the provenance is unlikely to be gaussian, statistical estimates of uncertainties for the mean isotopic compositions are of limited value. However, some indication of the spread of data is given by the standard error of the weighted mean of isotopic ratios. More elaborate means of data handling are unwarranted at the present reconnaissance stage of this study.

Other isotopic techniques of provenance tracing are reviewed by Heller and Frost (1988). The Sm–Nd method utilizes projection of the isotopic system of a sediment to equivalence with a model mantle system to obtain a source model age, which may then be equated with the geochronology of provenance areas. This approach is of particular value in the case of single-stage sedimentation from Precambrian crystalline basement (e.g. Zhao *et al.* 1992). Another method, the direct measurement of the age of detrital grains (e.g. ion microprobe U-Pb ages of zircons, Ireland 1992; K–Ar ages of white mica, Heller *et al.* 1992), is a powerful technique, the youngest age obtained being equal to, or older than, that of the provenance. However, neither of these approaches is likely to detect a second cycle provenance that inherits its isotopic characteristics from a sedimentary precursor. The Sm–Nd technique, because of limited fractionation of the Sm/Nd ratio during sedimentation, will only identify the model age of the first stage precursor; mineral ages will not be reset during the second phase of sedimentation. In this case the Rb–Sr method may have the advantage because the high Rb/Sr ratios of many clay-rich sediments mean that a sedimentary terrain may develop a distinctive isotopic composition after deposition (different from that of the original provenance) and this will label any sediment derived from it.

PALAEOZOIC TURBIDITES WITHIN THE LACHLAN OROGENIC BELT

Quartz-rich turbiditic sequences of Early Palaeozoic age are the dominant sedimentary component of the southern Lachlan Orogenic Belt and are found in the majority of tectonic zones over a total strike width of 600 km (Figure 1). Within much of Victoria and southern New South Wales the most widespread sedimentary succession is a lithologically uniform sequence of Ordovician siliciclastics (Cas & VandenBerg 1988). These strata are at least several kilometres thick, and consist of interbedded grey quartz-rich sandstone and black mudstone and slate. Many of the quartz grains in the sandstones are rounded, and although originally of plutonic or metamorphic origin, probably represent a recycled sedimentary provenance (Cas & VandenBerg 1988). Well-preserved sedimentary structures within the sandstones identify them as turbiditic in origin, deposited within an extensive deep water basin. Palaeocurrent directions are predominantly from the west in central Victoria (Cas & VandenBerg 1988) and from the south in eastern Victoria and southeastern New South Wales (Cas *et al.* 1980; Fenton *et al.* 1982).

Following the Late Ordovician–Early Silurian Benambran Orogeny, the palaeogeography of the southern Lachlan Orogenic Belt changed considerably as substantial areas were uplifted. Nevertheless, the Melbourne Trough, which extended from north-central Victoria through northeastern Tasmania (Powell *et al.* in press), continued to receive quartz-rich turbiditic sediments, which accumulated largely in deep water. The western margin of the trough migrated eastwards with time, so that by the earliest Devonian, shoreline facies

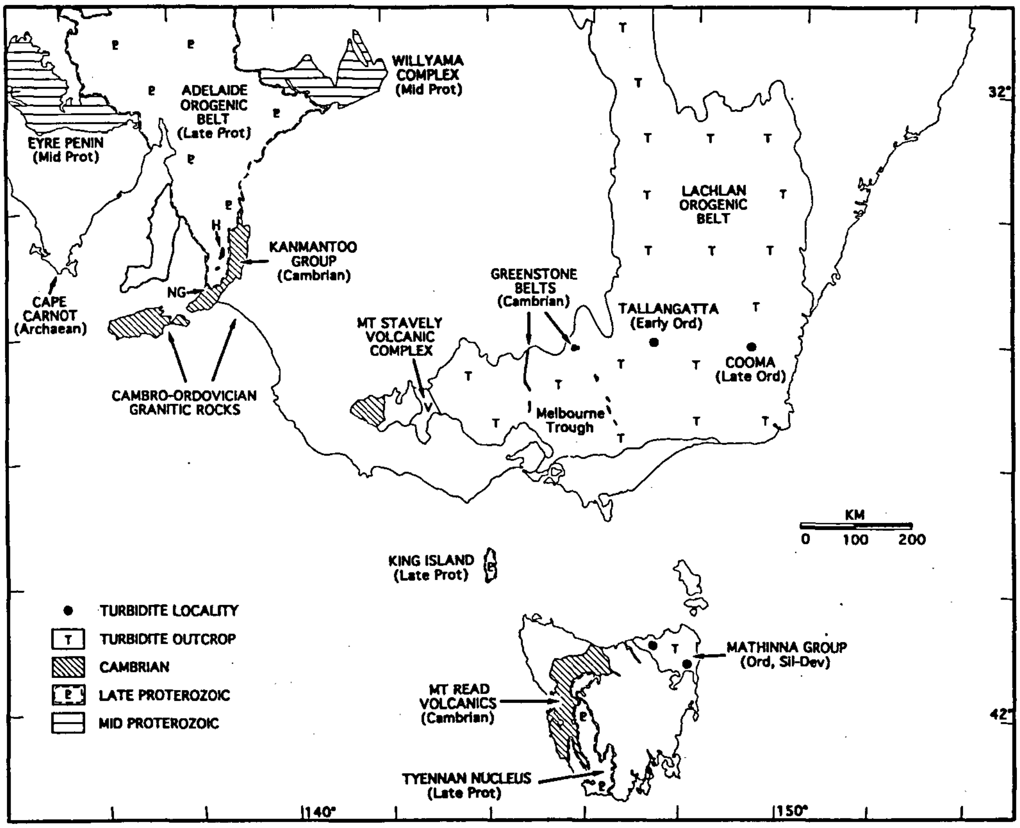

Figure 1 Outline map of southeastern Australia indicating the extent of Palaeozoic turbidites in the Lachlan Orogenic Belt and the location of possible provenance areas to the west and southwest. The sites of Sr isotopic data in northeastern Victoria (near Tallangatta), the Cooma district, New South Wales, and northeastern Tasmania are indicated by solid circles. The three main tectonic entities are the Archaean to Middle Proterozoic craton of Eyre Peninsula in the far west, the Late Proterozoic to Early Palaeozoic Adelaide Orogenic Belt in the Adelaide–Flinders Ranges region, and the Lachlan Orogenic Belt in centre and east. The letter symbols in the Adelaide area are: H, Houghton inlier (Late Proterozoic); NG, Normanville Group (Early Cambrian). The Delamerian mountain belt extended from the north of the Adelaide Orogenic Belt (Flinders Ranges) through the outcrop area of the Kanmantoo Group to far western Victoria and continued southward to the west of Tasmania into the contiguous section of Antarctica.

were accumulating in the Melbourne district. The eastern portion of the trough remained deep marine until the mid-Devonian, when a major regression (due to uplift?) resulted in a relatively sudden change to fluvial and lacustrine environments (Ryan 1992). Palaeocurrent directions in the Melbourne Trough are predominantly from the west and southwest in both Victoria and Tasmania, except for the uppermost (Emsian) part of the sequence along the eastern side of the trough (Walhalla Group), which was derived from the east (Powell *et al.* in press). Petrologically, the Siluro–Devonian sediments of the Melbourne Trough are similar to the underlying Ordovician strata, and have a large component of well rounded (recycled?) grains. In addition they may contain a small amount of feldspar and occasional fragments of silicic volcanics (Powell *et al.* 1993).

ISOTOPIC COMPOSITIONS OF POSSIBLE PROVENANCES

Given the palaeocurrent directions and the nature of the sediment, the provenance of the bulk of the Palaeozoic turbidites can be placed in the adjacent continental area of Gondwana to the west. In Australia, the geological components of this provenance region are presently exposed in a belt from south-central South Australia to Tasmania and are generally elongate parallel to the broadly north–south tectonic grain of eastern Australia. However, given the varied geology of this region, the specific provenance could have any age from Archaean to earliest Ordovician. Webby (1978) postulated that the sediment was derived from a mountain chain developed during the latest Cambrian–earliest Ordovician Delamerian Orogeny, and which extended from the Flinders Ranges through western Tasmania into Antarctica. Cas and VandenBerg (1988) concurred, suggesting that the Precambrian and Cambrian metasedimentary rocks forming this mountain range were the sediment source of the Lachlan Orogenic Belt. Fenton *et al.* (1982) considered the Proterozoic of western Tasmania, or Cambrian to Precambrian sediments of the Ross Orogen in Antarctica, to be potential sources. Turner *et al.* (1993b) noted that Nd isotopic data for three samples of the Ordovician turbidites from central Victoria were consistent with derivation from Late Proterozoic to Cambrian sedimentary rocks of the Adelaide Orogenic Belt. Powell *et al.* (1993; in press) suggested that the Siluro–Devonian sediments of the Melbourne Trough in Victoria and Tasmania were largely of stable platform-cratonic provenance, but the Early Devonian strata could have a component derived from silicic igneous rocks in southeastern Australia.

All of the potential provenance areas are dominated by quartzofeldspathic or pelitic rocks; the majority of the isotopic data available for these areas refer to the former lithologies. As the provenance of the turbidites was quartz-rich these measurements are appropriate for provenance tracing. All isotopic results for potential provenance areas east of the Adelaide region will now be discussed; the more remote Precambrian rocks further west will be considered only in terms of typical associations. The isotopic data are presented in Table 1 and locations indicated on Figure 1; sources are cited below and most include further descriptions of lithology and geological context.

Precambrian provenance areas

(1) Archaean gneisses at Cape Carnot, Eyre Peninsula (~2600 Ma; Cooper *et al.* 1976): quartzofeldspathic augen, layered and leucogneisses.

(2) Middle Proterozoic granites and acid volcanics of the Stuart Shelf (1600 Ma; Creaser 1990) are representative of their extensive relatives in the Gawler Range Volcanics of central Eyre Peninsula.

(3) Middle Proterozoic quartzofeldspathic gneisses and granites of the Willyama Complex (1600–1700 Ma; Pidgeon 1967; Shaw 1968).

(4) Late Proterozoic metamorphic rocks of the Houghton inlier in the Mt Lofty Ranges (850 Ma; Cooper & Compston 1971). These rocks form basement to the Adelaide Orogenic Belt and from the limited data available are isotopically heterogeneous, hence pooling is unrealistic. Seven quartzofeldspathic gneisses are very radiogenic and had $^{87}Sr/^{86}Sr$ ratios greater than 0.85 in the Palaeozoic. As they may be unrepresentative and because such radiogenic rocks are inappropriate sediment sources (see below), they are not considered further. Only the 'Houghton Diorite', itself an unusual and minor lithology, is included in Table 1 to serve as a peculiarly unradiogenic limiting case for the Proterozoic.

(5) A Late Proterozoic granitic intrusion on King Island, Tasmania (820 Ma; McDougall & Leggo 1965).

(6) Late Proterozoic quartzites, phyllites and mica schists of the Tyennan Nucleus, Tasmania (800 Ma; Raheim & Compston 1977)

(7) Late Proterozoic sedimentary rocks of the Adelaide Orogenic Belt (Turner *et al.* 1993b).

Early Palaeozoic provenance areas

(1) The Early Cambrian Normanville Group of the Mt Lofty Ranges contains shales, though the group is volumetrically minor and unlikely to be important in itself (Compston *et al.* 1966; Turner *et al.* 1993b).

(2) The Early Cambrian Kanmantoo Group of the Mt Lofty Ranges has been isotopically sampled at numerous localities and stratigraphic levels (Compston *et al.* 1966; White *et al.* 1967; Milnes *et al.* 1977; Turner *et al.* 1993b; Gray, unpubl. data); the lithologies are primarily immature metasandstones and metapelites.

(3) 485–500 Ma syntectonic and post-tectonic granites of southeastern South Australia (White *et al.* 1967; Milnes *et al.* 1977; Gray 1990; Turner *et al.* 1992; Turner *et al.* 1993a, 1993b). Note that there are silicic volcanics associated with the post-tectonic granites.

(4) Dacites to rhyolites of the Cambrian Mt Read Volcanics of western Tasmania (Adams *et al.* 1985).

(5) A combined Cambrian igneous provenance of western Tasmania (data from Adams *et al.* 1985) incorporates the Mt Read Volcanics, Murchison Granite and quartz–feldspar porphyries from Queenstown. The Murchison Granite is isotopically similar to the Mt Read Volcanics. The Queenstown porphyries are distinctly more radiogenic and are also treated as a special case.

(6) Cambrian greenstones of central Victoria from the Heathcote and Howqua belts (Nelson *et al.* 1984) are included for completeness though their metabasic mineralogy makes them an unlikely sediment source.

(7) Cambrian(?) dacites of the Mt Stavely Volcanic Complex which, as the most radiogenic rocks from this setting, provide an upper limit to the $^{87}Sr/^{86}Sr$ ratios likely for this complex (Gray 1990).

ISOTOPIC COMPOSITIONS OF THE PALAEOZOIC TURBIDITES

Rubidium–strontium isotopic data for Palaeozoic turbidites are available for four widely separated geographical areas, two in northeastern Victoria (latest Cambrian? and Early Ordovician), and one each in southeastern New South Wales (Late Ordovician) and northeastern Tasmania (Ordovician and Siluro-Devonian), providing a first-order coverage of the Lachlan Orogenic Belt (Figure 1). The large-scale turbidity currents implied by the vast extent of these deposits should have resulted in extensive mixing of sediment, the best circumstance for the use of mean sediment compositions. The isotopic data are compiled in Table 1. Ages of sedimentation have been assigned by linking local palaeontological data to stratigraphically and analytically well-defined isotopic age determinations used in the assembly of the geological time, scale (Snelling 1985). Uncertainty in the age of sedimentation at the ± 10 Ma level is unimportant as the isotopic ratios of sediment and provenance change in the same sense with time, and relativities are reasonably maintained. Table 1 permits provenance testing at several ages other than those quoted here, and later conclusions are independent of the assigned ages.

Northeastern Victoria

The Early Palaeozoic metasedimentary rocks of the area around Tallangatta, Victoria have been subdivided into two terrains by Fleming *et al.* (1985); the isotopic data are unpublished results of that study.

GUNDOWRING TERRAIN

The Gundowring Terrain outcrops in the vicinity of Tallangatta, Victoria to the north and west of the Yabba Adamellite and comprises quartzofeldspathic gneiss, migmatite and minor calc-silicate. The rocks were metamorphosed in the upper amphibolite facies and have been exposed to six deformations. As a result a turbiditic origin cannot be proved, but the preserved coarse bedding and the massive quartzofeldspathic lithologies are comparable to those in lower grade, unequivocal turbidite sequences elsewhere in southeastern Australia. Because of its more complex history the Gundowring Terrain is regarded as being older than the Lockhart Terrain described below, and could be latest Cambrian in age (Fleming *et al.* 1985); an age of 500 Ma is adopted. Individual initial ratios at 500 Ma range from 0.715 to 0.720 with a well-defined peak at ~ 0.717.

LOCKHART TERRAIN

The Lockhart Terrain extends southward from the Yabba Adamellite as metasandstone and metapelite mainly of biotite grade, which exhibit graded bedding and Bouma sequences (Comacho 1982). An Early Ordovician age is proven by the rare presence of Bendigonian graptolites (Kilpatrick & Fleming 1980). A Rb–Sr total rock age of ~ 470 Ma is reasonably compatible with Early Arenig (Bendigonian) sedimentation, indicating that the isotopic system is not greatly affected by metamorphism. At the assigned age of 485 Ma the eight reconnaissance samples have a small span of isotopic ratios between 0.709 and 0.714.

Cooma district

Within the Cooma Complex it is convenient to distinguish the low and high grade areas of metasedimentary rocks, which although compositionally very similar (Munksgaard 1988), differ in both mean Sr content and the spectrum of isotopic compositions. It has been suggested by Flood and Vernon (1978) that the high-grade rocks may have been transported diapirically from a deeper part of the section during the emplacement of the Cooma Granodiorite and might therefore be older than the low-grade metamorphics. Isotopic data are from Pidgeon and Compston (1965) and Munksgaard (1988).

LOW METAMORPHIC GRADE

The low-grade rocks have been subdivided into the Binjura and Coolringdon beds (Joplin 1942). However, Hopwood (1969) considers their boundary to be faulted rather than stratigraphic, and the two units are combined here. The lithologies are thinly bedded sandstone and shale, and massive sandstone and shale units metamorphosed at chlorite and biotite grade. Locally, graptolites give a Late Ordovician (Gisbornian–Eastonian) age (Hopwood 1969). The Coolringdon beds are now incorporated in a very widespread unit, the Adaminaby beds, from which graptolites give Eastonian and Gisbornian to Llandoverian ages (White *et al.* 1977). A Late Ordovician age of 455 Ma is adopted. The turbidite origin of rocks in the region is discussed by Crook *et al.* (1973). Two of the samples analysed by Munksgaard (1988) have unrealistically low $^{87}Sr/^{86}Sr$ ratios at 455 Ma (< 0.700), hence there is evidence for isotopic disturbance; the remainder fall between 0.707 and 0.715 and may approximate the mean isotopic system.

HIGH METAMORPHIC GRADE

The high-grade area comprises quartzofeldspathic and metapelitic banded and mottled gneiss and migmatite manifesting three generations of folds, and is regarded as a continuation of the low-grade succession; the sedimentary interpretation is presumed to be similar. The possibility that the high-grade rocks are older than the low grade cannot be quantified, so their age is also taken as 455 Ma. The $^{87}Sr/^{86}Sr$ ratios of these rocks at 455 Ma are quite varied, ranging from 0.711 to 0.721.

Northeastern Tasmania

The Mathinna Group of northeastern Tasmania (Baillie 1989; Powell *et al.* 1993) comprises a conformable sequence of at least 7 km of turbidites spanning the Early Ordovician to the Early Devonian, and is overlain by Emsian volcanics. The basal units are confined to the northwestern part of the outcrop area, and have yielded Darriwillian graptolites. The eastern three-quarters of the Mathinna Group outcrop belt comprises Siluro–Devonian strata, which are probably equivalent to the Melbourne Trough sequence of this age.

Isotopic data are available for both the Ordovician and Siluro–Devonian parts of the succession (Cocker 1982). The isochron relationships discussed by Cocker (1982) indicate that the Ordovician rocks were significantly isotopically disturbed at ~ 420 Ma. At the assigned primary age of 485 Ma two samples have unrealistic $^{87}Sr/^{86}Sr$ ratios (< 0.704). However, the three least radiogenic samples have isotopic systems consistent with an Early Ordovician age, having $^{87}Sr/^{86}Sr$ ratios at 485 Ma in the range 0.7111–0.7124, and might be representative. Data from Siluro–Devonian sandstone and siltstone samples indicate that the isotopic systems are intact with an isochron age of 401 ± 7 Ma; the primary age adopted is 400 Ma, at which time the isotopic ratios span 0.717 to 0.723.

PROVENANCE ASSIGNMENT

Similar isotopic compositions of potential provenance areas and Palaeozoic turbidites at the times of sedimentation (Table 1) indicate a possible provenance match. Matches can also be assessed graphically using the Sr isotopic evolution diagram (Figure 2). The potential provenance areas are now assessed for a numerical match, with subsequent discussion of additional geological constraints.

The Precambrian areas are isotopically very variable from one to another and some are also variable internally. In addition, the sampling may not be comprehensive in some cases and the mean systems uncertain. Nonetheless, for the present purpose it is possible to generalize, in that all Precambrian areas had $^{87}Sr/^{86}Sr$ ratios in excess of 0.728 in the Early Palaeozoic and most were much more radiogenic. At the time of sedimentation all turbidites had $^{87}Sr/^{86}Sr$ ratios less than 0.720. On Figure 2 the isotopic growth paths for the Precambrian systems are significantly removed from the turbidite systems. It is immediately apparent that the Precambrian areas were far too radiogenic to be considered as sediment sources.

The turbidites contained relatively unradiogenic Sr on deposition, indicative of a comparatively 'young' source containing relatively 'juvenile' Sr. A young orogenic setting is the most likely provenance. Of the exposed rocks in southeastern Australia only the Cambrian lithologies of South Australia and Tasmania are possible sources; on Figure 2 their isotopic growth paths move through the body of turbidite data.

It is convenient to distinguish two groups within the turbidite data. The more radiogenic turbidite localities give good $^{87}Sr/^{86}Sr$ matches with the Kanmantoo Group (KG):

(1) latest Cambrian (?) Gundowring Terrain 0.717 (KG 0.716, at 500 Ma)

(2) Late Ordovician Cooma high grade rocks 0.717 (KG 0.718, at 455 Ma)

(3) Siluro-Devonian Mathinna Group 0.720 (KG 0.720, at 400 Ma).

Other areas are compatible with the less radiogenic Cambrian igneous rocks of Tasmania (TAS), and the Early Cambrian Normanville Group (NG) and latest Cambrian-earliest Ordovician syntectonic granites (STG) of South Australia:

(4) Early Ordovician Lockhart Terrain 0.712 (TAS 0.712; NG 0.713; STG 0.711, at 485 Ma)

(5) Ordovician Mathinna Group, if the figure of ~0.712 is reliable (TAS 0.712; NG 0.713; STG 0.711, at 485 Ma)

(6) Late Ordovician Cooma low grade rocks, if the figure of ~0.713 is reliable (TAS 0.713; NG 0.713; STG 0.711, at 455 Ma).

At a first approximation good provenance assignments can be made. However, there are qualifications on specifics both with regard to mixed sources and geological constraints on whether potential source areas were actually exposed to erosion at the appropriate time. First, note that an overall South Australian provenance of earliest Palaeozoic age, incorporating the Normanville Group, the Kanmantoo Group and granitic rocks, amalgamates lithologies of quite different isotopic character. At 455 Ma, for example, the Kanmantoo Group is relatively radiogenic (0.718), the Normanville Group (0.713) and syntectonic granites (0.711) intermediate, and the earliest Ordovician post-tectonic granites least radiogenic (0.706), but rapidly evolving (Table 1). With changes in the proportions of these rock types contributing to the sediment, considerable variation in isotopic composition is possible, and a match might be made with any of the turbidites.

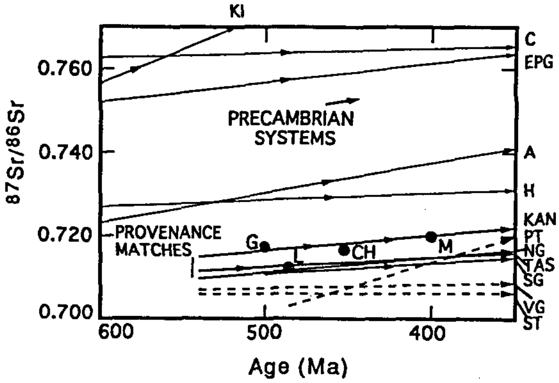

Figure 2 Rb–Sr isotopic evolution diagram depicting the growth trajectories of isotopic systems. The solid black circles locate the turbidite localities at the time of sedimentation: G, Gundowring Terrain (latest Cambrian?, northeastern Victoria); L, Lockhart Terrain (Early Ordovician, northeastern Victoria); CH, Cooma high grade rocks (Late Ordovician, southeastern New South Wales); M, Mathinna Group (Siluro-Devonian, northeastern Tasmania). Growth lines for Precambrian provenance areas are solid thin lines and are much more radiogenic than the turbidite systems: KI, King Island (Late Proterozoic); C, Cape Carnot gneisses (Archaean); EPG, Eyre Peninsula granites (Middle Proterozoic); A, Adelaide Orogenic Belt (Late Proterozoic); H, Houghton Diorite (Late Proterozoic). The Willyama Complex (Middle Proterozoic) and Tyennan Nucleus (Late Proterozoic) are more radiogenic and plot outside the diagram at higher $^{87}Sr/^{86}Sr$. Growth lines for Early Palaeozoic systems having good provenance matches with the turbidites are shown as solid thick lines: KAN, Kanmantoo Group (Early Cambrian); NG, Normanville Group (Early Cambrian); TAS, Tasmanian Cambrian igneous rocks; SG, syntectonic Cambro-Ordovician granites of South Australia. Early Palaeozoic systems less radiogenic and distinct from those of the turbidites are depicted with dashed lines: PT, post-tectonic Cambro-Ordovician granites of South Australia; VG, Victorian greenstones (Cambrian); ST, Mt Stavely Volcanic Complex (Cambrian?).

Second, the majority of the Tasmanian Cambrian igneous rocks are relatively unradiogenic with a narrow range of isotopic compositions which does not overlap the mean values for, and cannot be equated with, the more radiogenic turbidites, (1) to (3). The quartz-feldspar porphyries of Queenstown (given separately on Table 1) are distinctly more radiogenic than the mean. If such rocks are much more abundant in western Tasmania than represented in the isotopic data, a Tasmanian source for the more radiogenic turbidites is possible. However, while numerically consistent with the provenance, these rocks are most likely excluded on geological grounds, because during the time of turbidite sedimentation they were probably buried beneath the extensive Early Palaeozoic alluvial fan to shallow marine sediments that covered much of central Tasmania (Banks & Baillie 1989).

The Cambrian greenstones of Victoria are implausible sediment sources due to a lack of quartzose lithologies and low $^{87}Sr/^{86}Sr$ ratios (~0.706). Dacites of the Mt Stavely Volcanic Complex are lithologically more realistic, but again too unradiogenic ($^{87}Sr/^{86}Sr \sim 0.708$). Both isotopic growth trajectories are significantly removed from the turbidite systems (Figure 2). Furthermore, the lack of greenstone detritus within the turbidites, except in the Early Devonian strata in the southeastern corner of the Melbourne Trough, strongly implies that the greater part of the present greenstone belts was not exposed during turbidite deposition.

It is possible that the younger turbidites were derived by erosion of the older as the Siluro-Devonian component of the Mathinna Group (0.720 at 400 Ma) matches the three older, well-defined mainland areas (~ 0.721; Table 1). However, palaeocurrent directions in the Mathinna Group (Powell *et al.* 1993) clearly indicate that the predominant sediment source lay to the west. Hence, the Ordovician turbidites to the north on the present mainland that were uplifted during the Benambran Orogeny cannot have been more than a minor component of the provenance area. Furthermore, at the time of deposition of the Mathinna Group (Siluro-Devonian), central and western Tasmania were largely covered by a shallow sea, as shown by the accumulation of shallow marine siliciclastics and carbonates (Banks & Baillie 1989), and older Palaeozoic rocks there were probably not exposed. Thus none of the Ordovician or Silurian rocks of southeastern Australia can be invoked as the major provenance area of the Mathinna Group.

Powell *et al.* (1993) suggested that erosion of Late Silurian–earliest Devonian silicic igneous rocks in southeastern Australia might have supplied some detritus to the Early Devonian turbidites of the Mathinna Group. However, these igneous rocks are insufficiently radiogenic to have been a major source and are also excluded on palaeocurrent evidence (see above). For example, the mean $^{87}Sr/^{86}Sr$ ratio at 400 Ma of 33 plutons from the Kosciusko, Berridale and Murrumbidgee Batholiths is 0.7097, as against 0.7197 for the Siluro-Devonian Mathinna Group, with distinctly different data distributions.

The case for a Cambrian (to earliest Ordovician) provenance is conclusive. A Kanmantoo Group or equivalent source is very likely for the more radiogenic turbidites. The less radiogenic turbidites could be of 'South Australian' or 'Tasmanian' derivation and it is premature to assign specific geographic sources. Their unradiogenic signature is indicative of a significant igneous-derived component in the sediment. The source is more plausibly 'Tasmanian', because that setting predominantly contains rocks with low $^{87}Sr/^{86}Sr$ ratios. However, as noted above, the source cannot literally be placed in Tasmania, but might involve equivalent rocks exposed during the time of sedimentation of the turbidites. The Dundas Trough, in which the Tasmanian volcanics were erupted, may have been continuous southward into Antarctica during the Cambrian as the Bowers Terrane (Laird *et al.* 1977). However, the predominant eastward palaeocurrent directions within the turbidites of the Lachlan Orogenic Belt would appear to make this southerly extension of the Tasmanian volcanics an unlikely source.

On the other hand, for the unradiogenic provenance to be 'South Australian' it has to be dominated by sediment from acid igneous rocks, which while possible, seems unlikely, given the present extensive and intermingled distribution of metasedimentary and igneous lithologies. However, equivalents of the Kanmantoo Group, along with 480-500 Ma granitic rocks, are widespread in South Victoria Land, Antarctica (Wilson Terrane, Laird 1991), and probably on tectonic continuity also underlie the ice of George V Land and its offshore extension on the continental shelf, though outcrop is lacking. The latter region lay to the west of Tasmania in the Early Palaeozoic, along the western edge of the turbidite basin, and could conceivably provide a 'South Australian' style provenance with a higher igneous component.

An Early Palaeozoic provenance is also demonstrated by ion microprobe U–Pb analysis of zircons in Ordovician sandy mudstones from four localities adjacent to the Bega Batholith in the far east of the Lachlan Orogenic Belt (Williams *et al.* 1991). The youngest population of detrital zircon ages at 650–450 Ma provides a rigorous older limit to the age of the provenance, and because it extends to the time of sedimentation must give the actual age of the provenance. In addition, the ages most probably record magmatic crystallization, confirming the postulated igneous component in the sediment. A Sm-Nd model age of 1230 Ma (CHUR) from a paragneiss in the Cooma Complex (McCulloch & Chappell 1982) could be construed to indicate an ultimate Precambrian derivation for this material. A sedimentary source age is not registered in the Sm-Nd system because Sm and Nd did not geochemically fractionate during the weathering and sedimentation processes involved in the formation of the source. Resistance to fractionation by the rare earth elements is common and results in a limitation in the use of the Sm-Nd model ages for provenance tracing.

PALAEOGEOGRAPHIC IMPLICATIONS

The Cambrian (to earliest Ordovician) provenance assignment has several palaeogeographic implications. The Proterozoic to Archaean rocks adjacent to the turbidite basin and forming the continental interior did not provide significant volumes of sediment to the basin. It is unlikely that these rocks were entirely sub-surface during deposition or that the sediment they supplied to shallow marine environments was trapped on extensive shelf areas and not transported into the adjacent deep-water turbidite basin. Instead the drainage systems across the Precambrian terranes must have been prevented from entering the basin, presumably by the physical barrier of the Delamerian mountain belt. This extended from central South Australia through western Victoria and into Antarctica to the west of Tasmania. These mountains were uplifted at the end of the latest Cambrian–earliest Ordovician Delamerian Orogeny, at around 500 Ma, and were composed predominantly of metasedimentary and granitic rocks.

Two lines of evidence suggest that the Delamerian mountain range had significant topography, probably of the order of several kilometres. First, the Sr isotopic data discussed previously show clearly that erosion of the Delamerian mountains supplied the bulk of sediment deposited throughout the area now covered by Victoria and northeastern Tasmania from the Early Ordovician to the Early Devonian. This enormous volume of sediment could only have been sourced by a major mountain belt (Webby 1978). Second, the highest metamorphic grade presently exposed in the Kanmantoo Group indicates a pressure of ~4 kb (Offler & Fleming 1968) implying 10–15 km of denudation. In order to cause this much erosional denudation, a major topographic high must have been present.

Additional palaeogeographic insights concern the Tyennan Nucleus in Tasmania (Figure 1). This Precambrian terrane was exposed in the Early Ordovician when it shed siliciclastic sediment across a shallow shelf that occupied a large part of western Tasmania (Banks & Baillie 1989). However, little, if any, of this Precambrian detritus was transported into the turbidite basin to the north and east, as shown by the lack of a significant Precambrian $^{87}Sr/^{86}Sr$ signature in the Ordovician turbidites. By the Devonian, the Tyennan Nucleus may have been at least partly concealed beneath a newly deposited sediment cover; the Siluro-Devonian part of the Mathinna Group, which lies to the east and was predominantly derived from the west, also lacks any evidence of a Precambrian source. It is likely that the supply of detritus from the Delamerian highlands to the west, of Tasmania was sufficiently great to swamp any contribution from erosion of the Tyennan Nucleus.

TECTONIC IMPLICATIONS

For the greater part of Late Precambrian and Phanerozoic time, southeastern Australia formed part of a long-lived interface extending from Australia through west Antarctica between Gondwana and the global ocean. To simplify the following discussion, the region considered is mainly restricted to the southeastern mainland of Australia, the origin of which can be traced to the Late Proterozoic development of the Adelaide Orogenic Belt. This rift-like structure (Von der Borch 1980) developed on continental basement, presumably in response to limited extension of the continental margin, and was filled with a thick sequence of shallow-water detrital sediments and carbonates.

During the Early Cambrian extension probably became more pronounced, giving rise to a continental shelf and adjacent deep-water basin where the partly turbiditic Kanmantoo Group was deposited. Contemporaneous subduction-related island arc volcanism is recorded in the greenstone belts of central Victoria (Crawford *et al.* 1984). Hence, the tectonic setting is plausibly one of continental margin-expanding marginal sea-volcanic arc.

The Cambrian phase of development reached its tectonic culmination at the Cambrian-Ordovician boundary with the compressional deformation, regional metamorphism and igneous intrusion of the Delamerian Orogeny. The cause of the orogeny is unclear. In the context of the above tectonic setting, the plausible model invokes closure of the marginal sea by subduction, until collision of the volcanic arc with the continental margin causes the Delamerian Orogeny. The volcanics of the Mt Stavely Volcanic Complex in western Victoria may represent andean-type volcanism during this phase (as evidenced by the $^{87}Sr/^{86}Sr$ ratios of dacites [Table 1], which are too high for an oceanic arc).

However, to properly appreciate the Delamerian Orogeny it is necessary to consider its continental context and continuation within the adjoining section of west Antarctica. For example, in Victoria Land poly-deformed amphibolite facies schists and gneisses of the Wilson Group are intruded by the Cambro-Ordovician Granite Harbour granitic bodies. Related geology characterized by a culminating Cambro-Ordovician orogeny defines a belt extending across Antarctica (e.g. review by Elliot 1975). Most importantly, in Antarctica the thermal effects of the orogeny extend well beyond the outcrop area of Cambro-Ordovician rocks over a huge area of older Precambrian basement (Krylov 1972), where the resetting of mineral ages was achieved with little other effect on the rocks. Hence, not only did the Cambro-Ordovician orogeny terminate an elongate orogenic belt spanning Antarctica and part of Australia, but it is more generally manifested in a continent-wide thermal disturbance. These same features are repeated elsewhere, for example, over much of the African continent, where orogenic structures which developed in the Late Proterozoic came to an end in the Cambro-Ordovician Pan-African thermal event (e.g. Cahen & Snelling 1984). The global extent of the Cambro-Ordovician culmination indicates an origin in global mantle dynamics rather than the local specifics of plate motions.

The outcome of the Delamerian Orogeny was the production of a transcontinental mountain belt. In the new Lachlan Orogenic Belt of southeastern Australia, erosion of the Delamerian mountains during the Ordovician fed sediment offshore as turbidites, as clearly shown by the Sr isotopic data. The deep-sea submarine fans built up by the turbidites covered a vast area, but formed a single system as evidenced by the regional similarity of sedimentary facies (Fergusson & VandenBerg 1990), internal consistency in palaeocurrent directions, and uniformity of Sr isotopic provenance. This indicates that the tectonic setting was most likely a passive continental margin. It is also deduced from this coherency that the present configuration of tectonic zones within southeastern Australia broadly matches the geometry in the Ordovician.

The nature of the substrate to the turbidites is of great importance to tectonic models of the region. The initial Sr isotopic compositions of mid-Palaeozoic granitic rocks in southeastern Australia demonstrate that there is no Precambrian continental crust present, at least at the depth of the granite source regions (Gray 1990). The oldest known components of the crust are the Cambrian basalt to andesite volcanics of the Victorian greenstone belts. However, the granite isotopic data for this same area are interpreted in terms of a source containing substantial arc-derived sediment (Gray 1990). Hence the substrate is more likely a complete Cambrian arc-marginal sea system with substantial volcanic and sedimentary sequences, fragments of which are revealed by thrust faulting in the greenstone belts.

Following the Delamerian Orogeny, reactivation of subduction eastward of the Australian continent may have occurred, and Ordovician volcanics of central New South Wales are interpreted in this light (e.g. Powell 1983). Thus the new tectonic setting might have been (west to east): continent-marginal sea (Ordovician turbidite deposition)-volcanic arc. However, the difficulty for this interpretation is the lack of a major unradiogenic island arc-derived component in the Sr isotopic signature of the turbidites. At the very least the island arc was not a significant sediment contributor to the turbidites, and this may be explained by a variety of factors, such as the arc not extending as far southward as previously thought, northward currents preventing the southward migration of volcanogenic sediment, or the swamping of arc-derived detritus by sediment from the mountain belt to the west. An alternative view of the Ordovician volcanics reduces their significance in relation to the turbidites: namely, that they are dominantly shoshonites and not indicative of an active subduction-related volcanic arc, and that their sedimentary influence is marginal to the volcanoes (Wyborn 1992). In conclusion, the isotopic data argue for the pure passive continental margin interpretation, rather than the back arc.

In Silurian to Early Devonian time the depositional environments and tectonic setting changed dramatically across large areas of the Lachlan Orogenic Belt, particularly in the east. For example, there was abundant rhyolitic volcanism in eastern Victoria and central-southern New South Wales. However, the eroding Delamerian mountain chain continued to supply sediment to an extensive sedimentary basin in central Victoria and northeastern Tasmania until the final stages of marine deposition in the Lachlan Orogenic Belt in the mid-Devonian.

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