Sedimentary Geology, 85 (1993) 557–577
Elsevier Science Publishers B.V., Amsterdam

Longitudinal fluvial drainage patterns within a foreland basin-fill: Permo–Triassic Sydney Basin, Australia

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Received June 10, 1992; revised version accepted December 11, 1992

ABSTRACT

Cowan, E.J., 1993. Longitudinal fluvial drainage patterns within a foreland basin-fill: Permo–Triassic Sydney Basin, Australia. In: C.R. Fielding (Editor), Current Research in Fluvial Sedimentology. Sediment. Geol., 85: 557–577.

The north–south trending Permo–Triassic Sydney Basin (southern sector of the Sydney–Bowen Basin) is unique compared to many documented retro-arc foreland basins, in that considerable basin-fill was derived from a cratonic source as well as a coeval fold belt source. Quantitative analysis of up-sequence changes in sandstone petrography and palaeoflow directions, together with time–rock stratigraphy of the fluvial basin-fill, indicate two spatially and temporally separated depositional episodes of longitudinal fluvial dispersal systems. A longitudinal drainage-net similar in geometry to the modern Ganga River system (reduced to 60% original size) explains many of the palaeoflow patterns and cross-basinal petrofacies variation recorded in the basin-fill. The Late Permian to Early Triassic rocks reveal a basin-wide southerly directed fluvial drainage system, contemporaneous with east–west shortening recorded in the New England Fold Belt. In contrast, the Middle Triassic strata reveal a change to an easterly directed fluvial system, correlated to a shift in orogenic load to a NW–SE orientation in the fold belt northeast of the basin. The detailed petrofacies variation in the deposits of the second longitudinal fluvial dispersal system reveals vertical jumps in petrofacies compositions, with uniform compositions between jumps. The petrological jumps are interpreted as the result of minor fault adjustments in the fold belt, resulting in changing rates of sediment supply to the foreland basin. Uninterrupted erosion of the same terrain most likely caused the compositional uniformity between jumps. The identification of similar longitudinal fluvial systems, with transverse variation in detrital composition, is likely to help resolve the tectonic history of foreland fold belts elsewhere.

Introduction

The major detrital source of foreland basins is the active fold-thrust belt or magmatic arc (Dickinson, 1986). Some studies, however, point out that foreland basins partly derive material from the cratonic side of the basin as well as the tectonically active orogenic margin (Meckel, 1967; Jones, 1972; Graham et al., 1976; Heller et al., 1988; López Gamundi et al., 1990). Modern alluvial systems reveal such intermixing of bivariant detrital provenance, and the style of sediment dispersal responsible for its deposition can be characterised broadly into two categories: longitudinal and transverse dispersal systems.

On a basin-wide scale, the orientations of longitudinal systems are parallel, and transverse systems are orthogonal, to the coeval orogen (Miall, 1981; Dickinson, 1988; Burbank and Beck, 1991). The orientation of the Ganga River system, a modern longitudinal drainage system, follows the present axis of maximum subsidence that parallels the thrust-load expressed by the strike of the Himalayan fold-thrust belt (Fig. 1). The northern tributaries of this large river system receive sediment from the fold-thrust belt, whereas the southern tributaries tap the rocks of the Indian shield (cf. Miall, 1981, fig. 1). The resulting detrital composition of the Ganga River is a mixture of two distinct sedimentary provenances; a major

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contribution of sediment from a recycled orogenic source, and a minor contribution from a cratonic interior source. In contrast, the modern Amazon River system represents a transverse drainage system, characterised by downstream compositional maturity away from the orogen (Franzinelli and Potter, 1983).

The longitudinal drainage systems, being confined within the depositional margins of the foreland basin, not only preserve orogenic and cratonic detritus within the basin stratigraphy, but petrographic variations may be expected orthogonal to the palaeoflow direction at any given time. Orogen-sourced transverse drainage systems, on the other hand, record down-stream variation in detrital composition, and the intermixing of cratonic material does not occur within the confines of the foreland basin, hence the resulting composition of detritus deposited by transverse dispersal systems is wholly orogenic in origin.

In the Sydney–Bowen Basin, a Permo–Triassic retro-arc foreland basin, a significant component of the basin-fill was derived from the cratonic side, as well as the orogenic side of the basin (Conaghan et al., 1982; Fielding et al., 1992). The cross-basinal petrofacies and palaeoflow data from the dominantly fluvial Late Permian to Middle Triassic strata of the Sydney Basin (southern sector of the Sydney–Bowen Basin) suggest that the sediment dispersal responsible for the basin-fill was that of two temporally separate longitudinal fluvial systems. This paper examines in detail the waning stage of the first longitudinal system and the development of the second system in the Sydney Basin. The orientation of the two dispersal systems yields information on the temporal change of thrust-load orientation in the coeval fold belt, enabling structural data from the fold belt to be examined in light of this information for possible correlations.

Geological overview

As the southern sector of the meridionally orientated Sydney–Bowen Basin, the Permo–Triassic Sydney Basin is bound presently to the northeast by the northeasterly dipping thrust-system of the New England Fold Belt (Glen and Beckett, 1989). The basin thins to the southwest to an erosional margin overlying the early–middle Palaeozoic basement of the Lachlan Fold Belt (Fig. 2). Contemporaneous with deformation in the New England Fold Belt, the Sydney Basin was its retro-arc foreland basin, while the Lachlan Fold Belt constituted a craton during the Late Permian to Middle Triassic sedimentation (Jones et al., 1984).

Although generally considered a foreland basin, the Sydney Basin during the Early Permian evolved initially in a back-arc extensional setting (Scheibner, 1973; Collins, 1991). The mechanism of basin subsidence during the Early Permian was likely the result of crustal attenuation followed by thermal subsidence of the lithosphere (Brownlow, 1981), during which marine depositional environments predominated (Herbert, 1980). Foreland

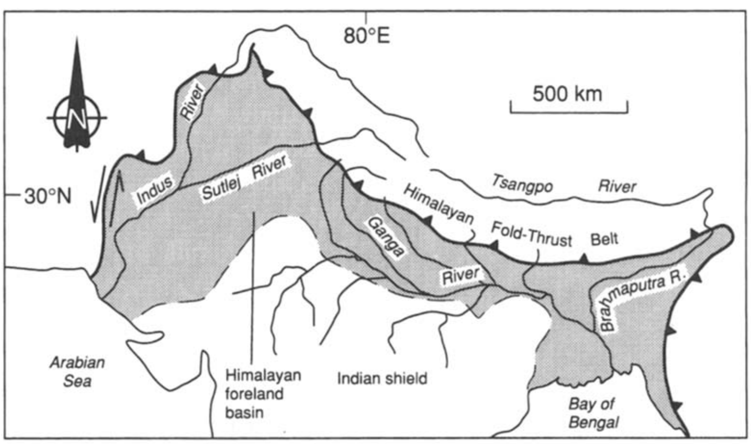


Fig. 1. Tectonic setting of the Ganga River system.

basin characteristics of the Sydney Basin first developed during the Late Permian at the time of the Hunter–Bowen Orogeny (Collins, 1991; Veevers et al., 1993), at which time coarse clastics were introduced into a paralic environment from the New England Fold Belt. Further denudation of the orogen, accompanied by reduction in the basin subsidence rate, resulted in a regressive succession, culminating in alluvial sedimentation by bedload streams carrying orogenically derived detritus towards the south (Herbert, 1980; Conaghan et al., 1982; Jones et al., 1987).

Dominantly fluvial sedimentation continued uninterrupted during the Late Permian to Middle Triassic, but contribution of orogenic detritus from the New England Fold Belt waned at the expense of cratonically derived sediments in the

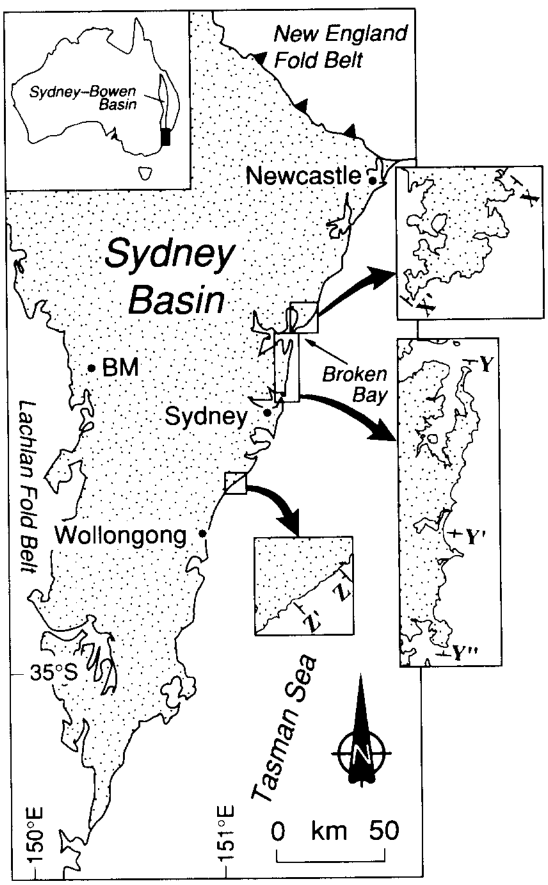


Fig. 2. General setting of the Permo–Triassic Sydney Basin and the study areas. *BM* = Blue Mountains. $X-X'$, $Y-Y'-Y''$ and $Z-Z'$ indicate locations of the coastal profiles of the stratigraphy shown in Fig. 4.

latest Early Triassic to Middle Triassic (Conaghan et al., 1982; Jones et al., 1984). It is the purpose of this paper to evaluate the petrology of these fluviatile sandstones to illuminate the tectonic influences experienced by the basin during this waning period of detrital contribution from the orogen. The fluvial rocks in question are the uppermost Narrabeen Group and the Hawkesbury Sandstone, exposed along the central coast region of New South Wales near Sydney (Figs. 2–4).

Stratigraphy and depositional environments

The coastal stratigraphy of the Lower to Middle Triassic succession in the study area has been divided into six compositionally uniform stratasets, referred to as *intervals* hereafter (A to F in Fig. 3). Boundaries between each of these stratigraphic intervals are sharply defined by laterally extensive discontinuities (> 50 km; Fig. 4) in sandstone composition. In terms of the conventional stratigraphic nomenclature applied to this succession south of Broken Bay (Fig. 2), these intervals extend upward from the topmost part of the Bulgo Sandstone through the Bald Hill Claystone/Garie Formation, the Newport Formation to the Hawkesbury Sandstone (Fig. 3). North of Broken Bay, all rocks except the Hawkesbury Sandstone belong to the Terrigal Formation (formerly Gosford Formation) of the Narrabeen Group (Fig. 3). Initially defined south of Broken Bay, the stratigraphic intervals A to F were traced laterally to the north beyond Broken Bay (Figs. 2, 4) using the petrographic data of McDonnell (1983). The interpreted depositional environments of these intervals are summarised in Table 1.

Sandstone petrology of the stratigraphic intervals

Petrofacies

The subdivision of the coastal succession into six compositionally uniform intervals is based on the up-sequence change in sandstone mineralogy, hence traditional stratigraphic boundaries were ignored in this analysis. Stratigraphic sections measured at twenty localities along the coastal exposures south of Broken Bay, and the collection of sandstone samples, enabled detailed examination of the stratigraphy and variation in detrital composition (Fig. 4). Ninety-five sandstone samples were selected for microscopic point-count analysis, with at least 500 points counted per slide applying the Gazzi-Dickinson method (Ingersoll et al., 1984). See Table 2 for a summary of detrital grain types.

Although the whole-rock quartz compositions of the sandstones (i.e., quartz percentage calculated from total of all rock-forming material, including matrix) are not widely dissimilar from one stratigraphic level to another, there is a general increase in quartz content moving up the stratigraphic section, accompanied by an anticlockwise rotation of palaeocurrent directions (Fig. 5b; see also Conaghan et al., 1982). What is of interest, however, is the fluctuation in vertical sandstone composition when the petrographic data are reduced in terms of total quartz (Q), total volcanolithic (Lv) and total sedimentary fragments (Ls) (Figs. 5, 6, 7d).

With the exception of interval B (Fig. 5), virtually devoid of extraclastic grains, each of the stratigraphic intervals are uniform in detrital sandstone composition. Abrupt compositional boundaries (expressed as Q% from a total of Q + Lv + Ls) are commonly located along laterally extensive erosional bases of amalgamated fluvial sheet sandstones. It is, therefore, appropriate to describe the preserved vertical sandstone compositional changes between each successive interval as true "jumps" in sandstone composition. The recognition of these intervals allowed the subdivision of the Newport Formation into three previously unrecognized lower, middle, and upper members (Fig. 5), as well as allowing a stratigraphic correlation of the upper Narrabeen Group between headlands and across Broken Bay.

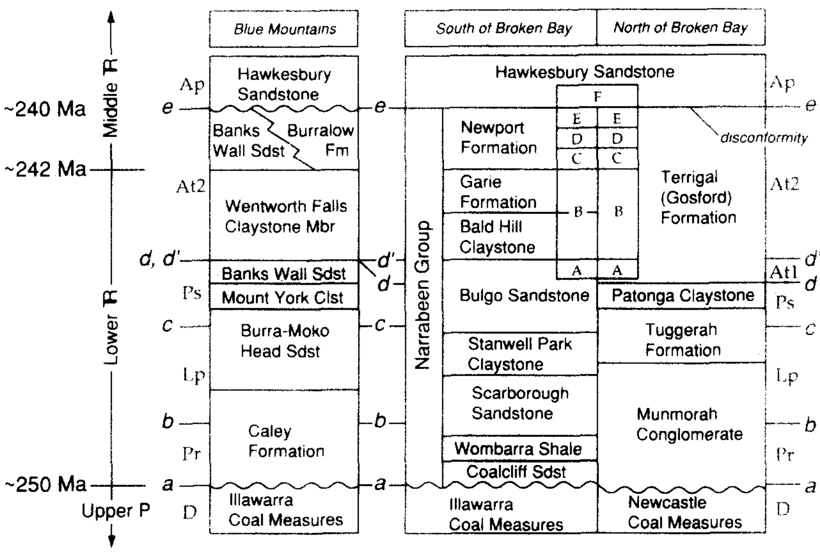


Fig. 3. Stratigraphy of the Upper Permian–Middle Triassic rocks, coastal and Blue Mountains area, Sydney Basin (see Fig. 2 for locations). Petrographically defined intervals designated for the upper Narrabeen Group, and the Hawkesbury Sandstone in capitalized letters (*A–F*, inset box). Spore–pollen zone boundaries based on Helby (1970, 1973) and Morgan (1976). The Banks Wall Sandstone above the Wentworth Falls Claystone Member is equivalent to the "Western Burralow Facies" of Bembrick (1980, p. 158). Spore–pollen zones as follows: *D = Dulhuntyispora*; *Pr = Protohaploxypinus reticulatus*; *Lp = Lunatisporites pellucidus*; *Ps = Protohaploxypinus samoilovichii*; *At1 = Aratrisporites tenuispinosus*, lower zonule; *At2 = Aratrisporites tenuispinosus*, upper zonule; *Ap = Aratrisporites parvispinosus*. Letters *a–e* = time-planes representing the boundaries of spore–pollen zones used in Fig. 9 to reconstruct sequential palaeogeography. The position and age of Permian–Triassic boundary after Veevers et al. (1993), but the boundary could be as old as 255 Ma (Gulson et al., 1990). Early Triassic–Middle Triassic boundary age after Forster and Warrington (1985). 240 Ma for the spore–pollen zone boundary *e* is poorly constrained, but lies within the Anisian Stage (Helby et al., 1987), between 242 Ma and 235 Ma (Forster and Warrington, 1985).

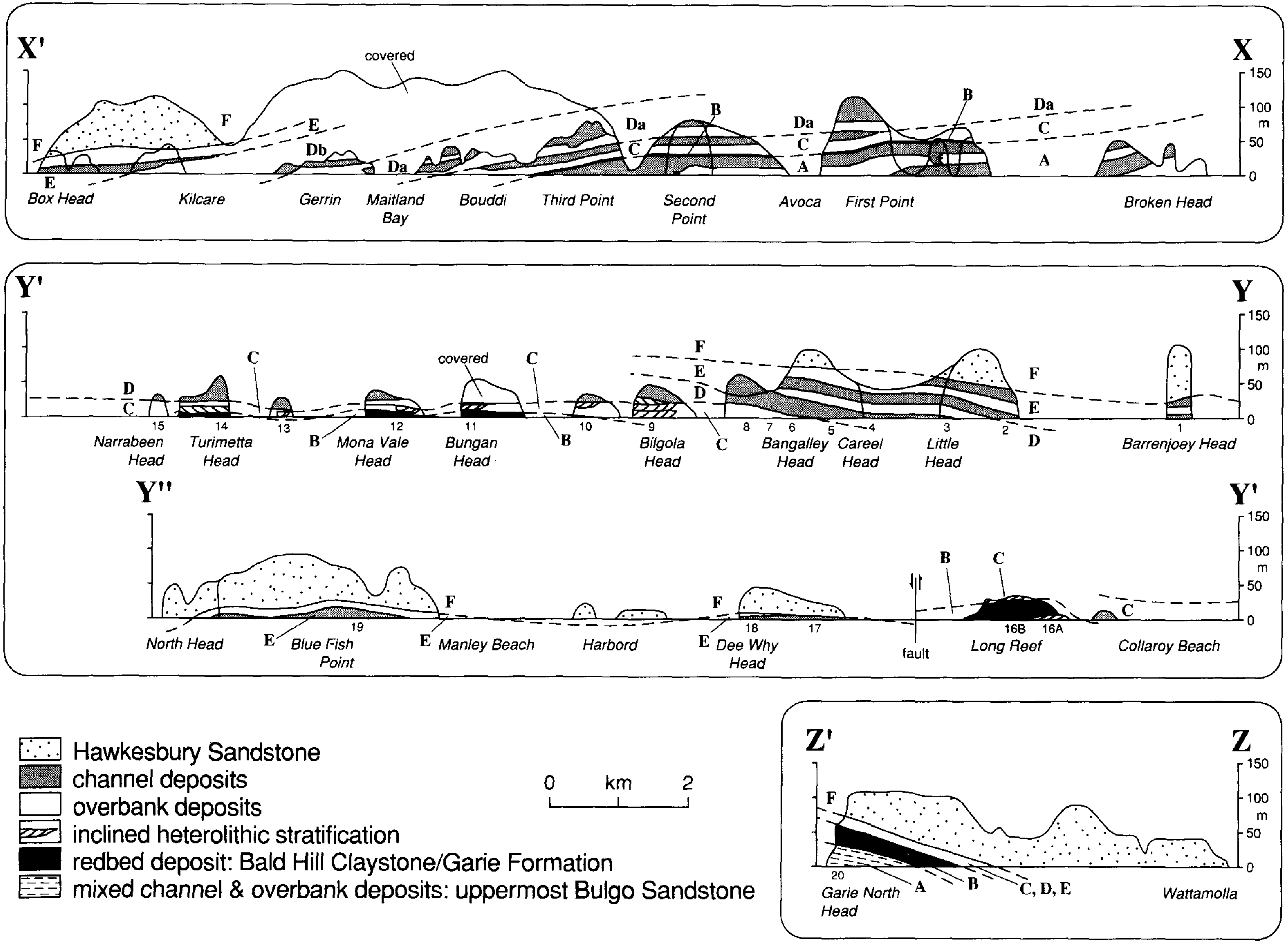


Fig. 4. Vertically exaggerated coastal profiles of study area (locations in Fig. 2). Note laterally continuous channel sandstone and thick overbank deposits within intervals. 2–10 m thick inclined heterolithic stratifications (Thomas et al., 1987) are abundant in interval C and base of D. Cross-section north of Broken Bay ($X-X'$) modified from McDonnell (1974). Numbers *1–20* are locations of measured sections appended in Cowan (1985).

TABLE 1

Depositional environments and sandstone provenance of the stratigraphic intervals

	Sedimentological character	Depositional interpretation
Interval A, uppermost Bulgo Fm.	Vertically repeated ~2 m thick sandstone sheets and intervening mudrock; LA not laterally continuous (< 5 m).	Extensive braidplain with episodic growth of bank-attached bars (Reynolds and Glasford, 1989).
Interval B, Bald Hill Claystone and Garie Fm.	~5 m thick laterally continuous LA; abundant haematitic mudrock; no extraclasts—except one quartzarenitic IHS deposit in section 16A (Long Reef, Fig. 4); abundant trace fossils in fine-grained deposits.	Westerly flowing highly meandering channels; recycled regolith from a volcanic terrain to the east (Ward, 1972; Goldbery and Holland, 1973; Retallack, 1977; Hamilton and Galloway, 1989); brackish water influence indicated by trace fossils (Naing, 1991).
Interval C, lower Newport Fm.	~8 m thick IHS; abundant trace fossils in silt/mudrocks; floodbasin fines contain abundant trace fossils.	Tidally influenced meandering channels (IHS); brackish water influence in fines (Naing, 1991).
Interval D, middle Newport Fm.	Lower portion (Da) is same as interval C; upper portion (Db) contains no IHS but cross-bedded laterally extensive sheet sandstones present; floodbasin fines contain abundant trace fossils.	Highly meandering tidally influenced streams (Da) replaced by broad less sinuous streams (Db); brackish water influence in fines (Naing, 1991).
Interval E, upper Newport Fm.	Cross-bedded sandstone sheets; no obvious LA; thick silt/mudrock between multistoried sandstones.	Braidplain deposition; intervening fines record temporary removal of channel activity.
Interval F, Hawkesbury Sandstone.	Multistoried cross-bedded sandstone sheets.	Large low-sinuosity river (Conaghan and Jones, 1975; Conaghan, 1980; Rust and Jones, 1987).

LA = lateral accretion; IHS = inclined heterolithic stratification (Thomas et al., 1987).

Twenty-eight modal point-count analyses of McDonnell (1983) from north of Broken Bay were processed and plotted along with modal point-count data for the 95 samples obtained from south of Broken Bay (Figs. 5, 7). In terms of a Q–F–L sandstone classification (Folk, 1980; chert is included in L), interval A is a litharenite with compositional mean plotting in the upper portion of the litharenite field (Fig. 7a). Interval C, a quartzarenite, contrasts sharply with the

TABLE 2

Grain parameters

Q = Qm + Qp	where	Q = total quartzose grains excluding sedimentary chert; Qm = monocrystalline quartz (plutonic, vein, and minor volcanic); Qp = polycrystalline aphanitic quartz excluding chert.
F = P + K	where	F = total feldspar; P = plagioclase; K = K-feldspar.
L = Lm + Lv + Ls	where	L = total unstable lithics including chert; Lm = metamorphic aphanitic lithics; Lv = volcanic aphanitic lithics; Ls = sedimentary aphanitic lithics and chert.
Lt = L + Qp		

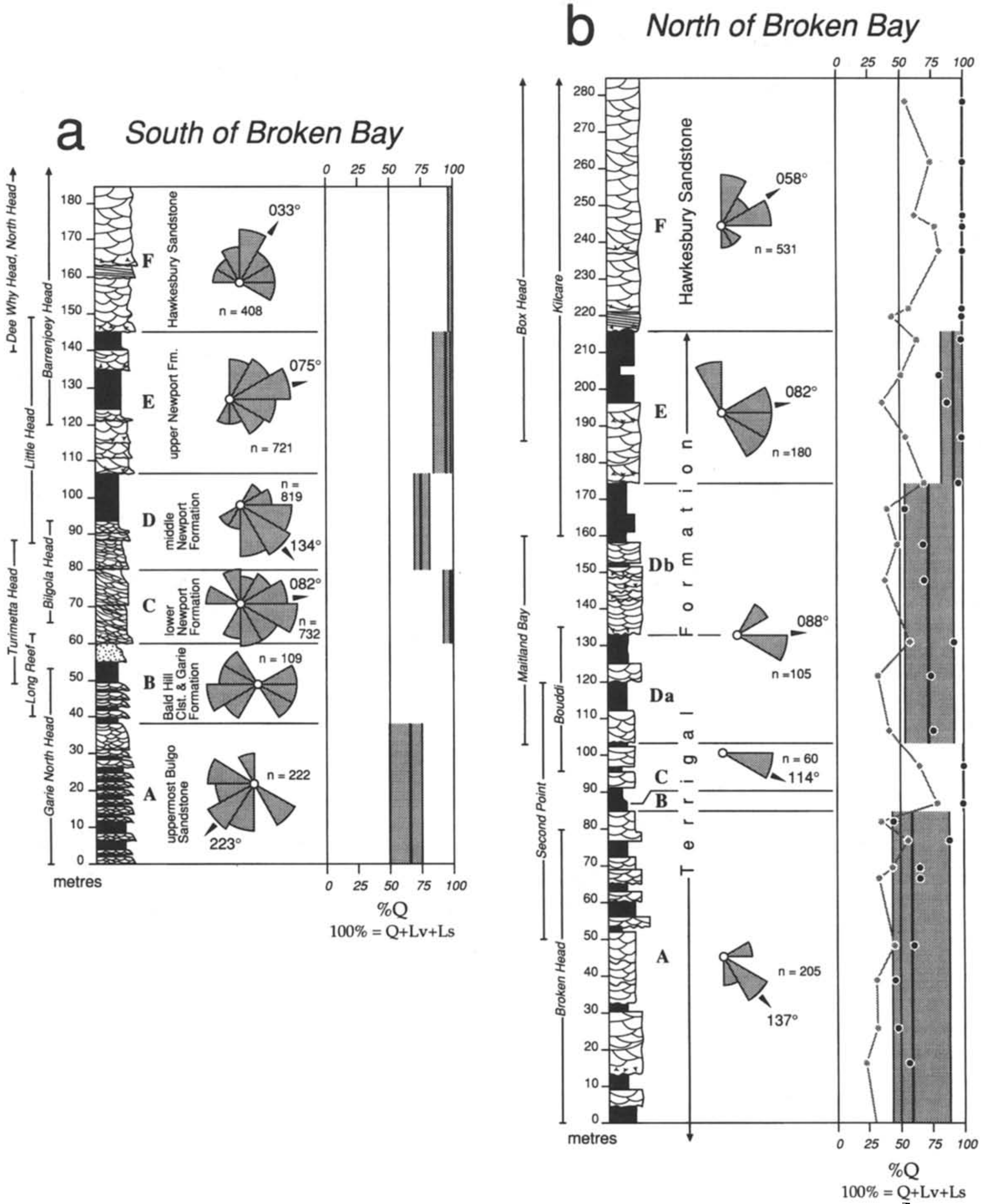


Fig. 5. (a) Composite stratigraphic section of the coastal exposures south of Broken Bay. Section produced by data amalgamated from twenty stratigraphic sections (locations: Figs. 2 and 4). Palaeocurrent data from trough cross-stratification axes (n = number of readings). Fields of sandstone compositions shaded in %Q column; mean value indicated by thick line for each interval. Individual %Q values are not plotted due to overcrowding of data, but stratigraphic locations and compositions of 95 samples represented in this composite section appended in Cowan (1985). (b) Composite stratigraphic section of the coastal exposures north of Broken Bay. Stratigraphic section and palaeocurrents modified from McDonnell (1974, 1983). Petrographic data modified from McDonnell (1983); grey dots = whole-rock percent quartz as originally analysed by Conaghan et al. (1982) and McDonnell (1983); black dots = %Q as a total of Q + Lv + Ls (see text). The shaded area represents the field in which the %Q compositions occur. Intervals discussed in text shown as capital letters (A–F). See text and Table 1 for the subdivision of interval D into Da and Db.

composition of A. Interval D returns to a more lithic composition much like interval A, and plots in the litharenite field. Interval E plots in the uppermost portion of the quartzose litharenite field succeeded by the most mature interval, the quartzarenitic interval F, the Hawkesbury Sandstone.

The detrital compositions are largely deficient in feldspars (Fig. 7), and this is interpreted to record the original detrital compositions. The paucity of feldspars in the upper Narrabeen Group was also noted by Dutta and Wheat (1988), who attributed the up-sequence decrease in volcanic rock-fragments and feldspars and corresponding increase in chert fragments in the Narrabeen Group to be the result of chemical weathering. However, the abundance of radiolarian ghosts observed in chert fragments point to an original detrital origin for the chert fragments, rather than chemical weathering of labile rock-fragments and feldspars. Feldspars are readily identifiable in thin-section with evidence of only slight alteration.

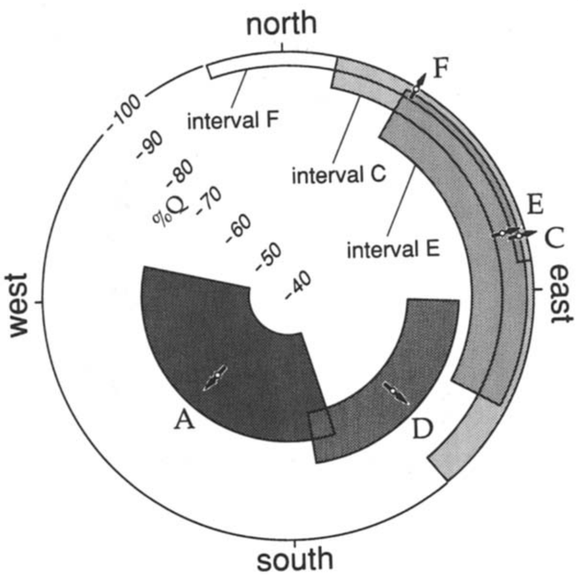


Fig. 6. Palaeocurrent and sandstone compositions from south of Broken Bay. Radial directions indicate palaeoflow, and distance from centre indicate %Q of the sandstones (as a % of Q + Lv + Ls). Arrows plotted in the position of mean palaeoflow and %Q. Boundaries for palaeocurrent data ± one circular standard deviation from mean. The boundaries for %Q correspond with lowest and highest values found in each interval.

Provenance indicators

In detail, the main provenance-indicator detrital grain-types present in these rocks are plutonic quartz, sedimentary chert/argillite with or without radiolaria, and felsic volcanic fragments. Figures 5 and 6 clearly show that the most lithic detritus is derived from the north or northeast. Data obtained from south of Broken Bay reflect this, where petrographically immature litharenites have a provenance to the northeast (interval A), in contrast to the quartzarenites (intervals C and F) which were derived from the southwest and west (Fig. 6). Quartzose litharenitic intervals with intermediate compositions show a palaeoflow direction between the two end-member compositions, that is, to the east or southeast (intervals D and E).

The source of the quartz-rich sandstones, mostly composed of plutonic quartz, is consistent with the rocks of the Lachlan Fold Belt to the south and west of the currently preserved basin (Fig. 2). Carboniferous felsic calc-alkaline plutons are the likely source rocks for these sediments.

Carboniferous ignimbrites exposed along the southwestern perimeter of the New England Fold Belt (McPhie, 1983) likely provided abundant felsic volcanic grains characteristic of the lithic end-member of the sandstones. Alternatively, some of the felsic volcanic clasts may have been derived from the coeval Late Permian to Triassic high-level intrusives and extrusives of the New England Fold Belt (Shaw and Flood, 1981) as suggested by Jones et al. (1987) and Shaw et al. (1991).

The chert/argillite component of the lithic detritus was likely derived from the lithological equivalent of radiolarian-bearing deformed Late Silurian to Carboniferous radiolarites and metaturbidites, now preserved in the New England Fold Belt (Ishiga et al., 1988). The sporadic occurrence of radiolarian ghosts in these rock-fragments attests to a deepwater origin for their source rock.

Because feldspar is a minor component throughout the studied sequence, as seen in the Q–F–L and Qm–Lt–F plots (Figs. 7b, 7c), the proportion of lithic fragments to quartz essen-

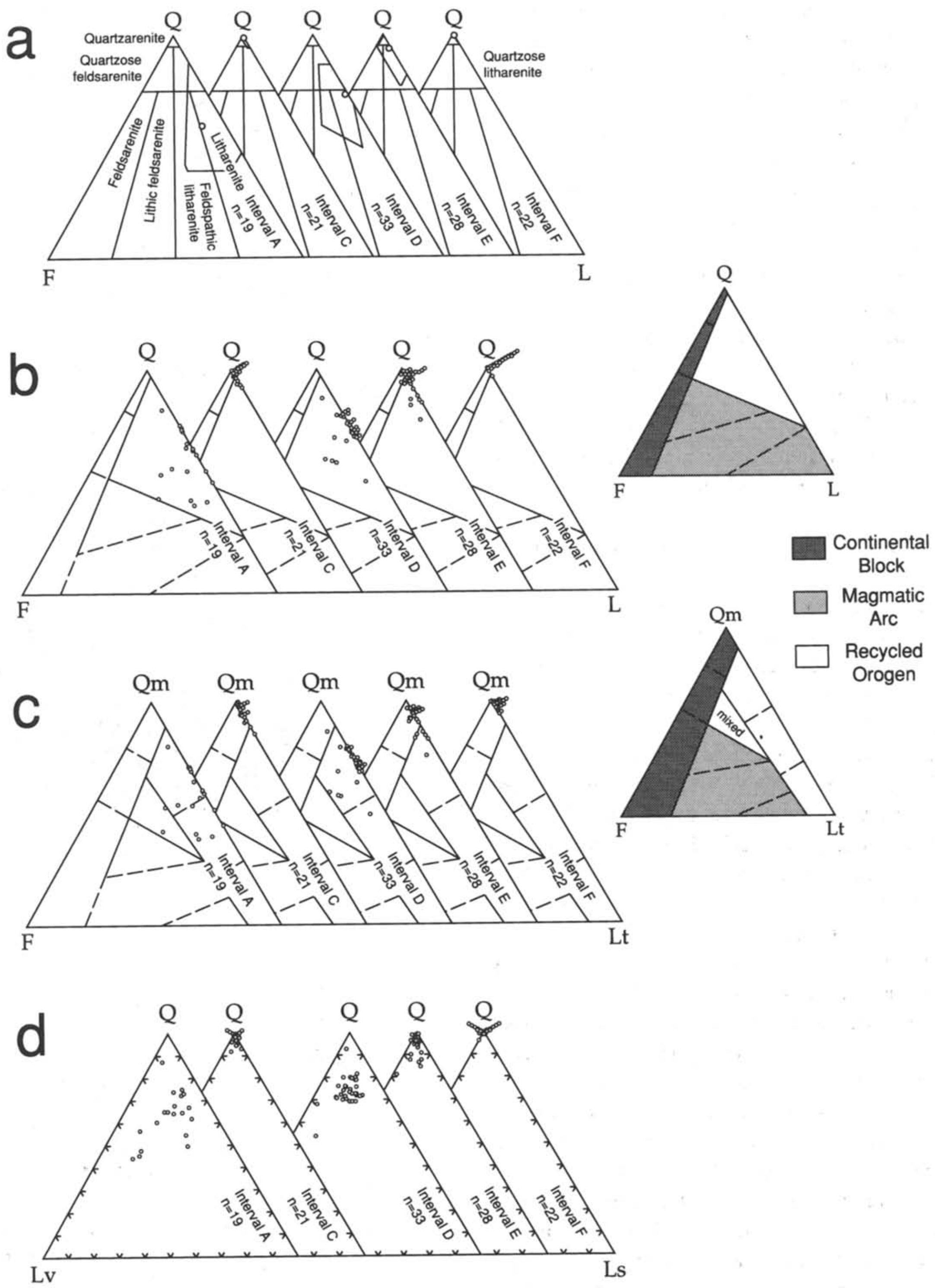


Fig. 7. (a) Q–F–L ternary plots of point-count data (Folk, 1980). Dots indicate mean composition; envelopes mark outer limits in which compositions lie. Chert fragments included in L. (b–d) Q–F–L, Qm–F–Lt and Q–Lv–Ls ternary diagrams. Provenance discriminating fields after Dickinson et al. (1983).

tially distinguishes one stratigraphic interval from another. As such, the Q–F–L and Q–Lv–Ls diagrams are best in characterising the composition of the stratigraphic intervals (Figs. 7a, 7b, 7d). A wider spread in the data is evident in the Qm–Lt–F plot (Fig. 7c), since the allocation of polycrystalline quartz Qp is to the Lt pole.

Provenance discrimination fields of Dickinson et al. (1983) yield predictable results (Figs. 7b, 7c). The Q–F–L and Qm–Lt–F plots indicate switching between recycled orogen and cratonically derived continental block provenances from one interval to another. Intervals A and D are wholly within the recycled orogen field, with interval A being characteristic of typical foreland basin compositions (cf. Dickinson, 1988). Intervals C and E have mixed affinities, with interval C being more cratonic in origin. Interval F, in contrast, is wholly cratonic derived.

Significance of the vertical compositional jumps

Within the Sydney Basin discrete compositional jumps between the stratigraphic intervals, that are otherwise relatively uniform in petrographic composition, were identified previously within the lower Narrabeen Group (Ward, 1971). Compositional jumps, and compositional uniformity between jumps have not been documented in much detail from other alluvial basins; stacking of compositionally distinct fluvial bodies has been identified elsewhere, however (Behrensmeyer and Tauxe, 1982; Putnam, 1982; Burbank and Raynolds, 1988).

While the first appearance of distinct lithology is indicative of thrust-loading at the basin margin, continued pulses of the same lithology cannot provide significant tectonic information unless they can be confidently time-correlated to increases in basin subsidence caused by orogenic thrust-loading (Jordan et al., 1988). Nevertheless, as pointed out by Jordan et al. (1988, p. 319), the later detrital pulses can be interpreted in one of three ways in which the same lithologies represent: (1) continued erosion of the same fault block(s); (2) renewed uplift of the source area by a younger fault; or (3) reworking of previously deposited foreland basin strata.

It is proposed that the vertical compositional jumps observed in the Sydney Basin were produced by renewed uplift of the source area by a younger fault, and that the compositional uniformity between jumps was caused by continued erosion of the same source area. Interval B is unique in that it shows evidence of a source area dominated by reworked regolith. These mechanisms are assumed to operate within a dual provenance physiographic framework, and a basin drainage-net comprising a central trunk system and tributaries tapping the two detrital sources. Because of this dual provenance, changes in trunk stream detrital compositions cannot be linked simply to composition differences in thrust plates in the fold belt, but the contribution of the cratonic source must also be considered.

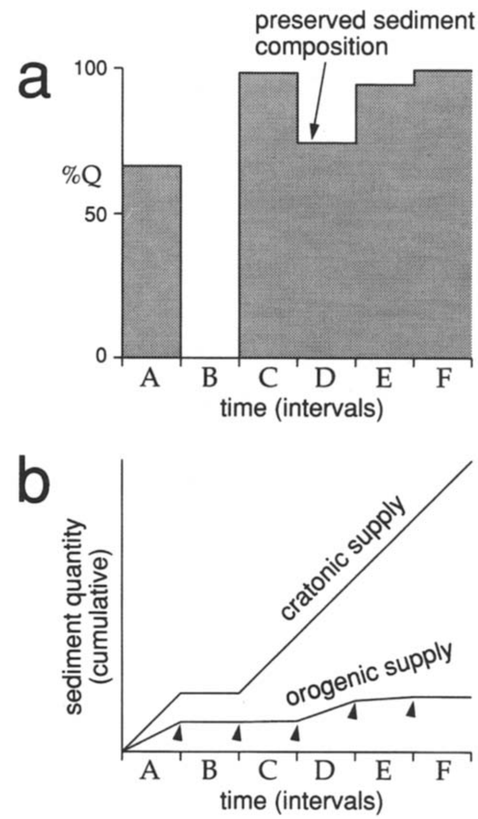


Fig. 8. (a) Mean %Q values (as a % of Q+Lv+Ls) of stratigraphic intervals against time represented by equal interval time units. (b) The pattern seen in (a) can be the result of mixing detritus of the ratios as shown (slope ratios). To produce compositional jumps, rate of sediment supply from the orogen must be changed (arrowed) if a constant rate of sediment is shed from the craton.

One possible mechanism of obtaining the compositional jumps is by periodically altering the rate of sediment supply from the orogenic source (Fig. 8). If we consider a constant supply of 100% Q from the tectonically inactive craton at a fixed rate (assuming orogenically derived sediments are 0% Q), one can produce a compositionally constant supply of detritus in the trunk stream by keeping the rate of sediment supply from the orogen constant (Fig. 8b). If the rate of sediment supply from the orogen changes at any time (shown by the arrowed kinks in the "orogenic supply" plot, Fig. 8b), the composition of the trunk stream will also dramatically change (as seen in the mean percentage Q values from the data south of Broken Bay, Fig. 8a), resulting in vertical jumps of sandstone compositions in the stratigraphy. In this scenario, changes in the rate of detrital supply from the New England Fold Belt could be the result of episodic movements on thrust faults, thereby changing the local gradient of the orogenic source area. Similar results are obtained by changing the supply rate of sediment from the craton, although in this case the mechanism of episodic change in the rate of sediment supply cannot be simply tied to tectonic activity in the orogen. In each scenario, however, if the rate of sediment supply is assumed to be constant during a given interval of time (Fig. 8), this results in uniform detrital composition for each interval.

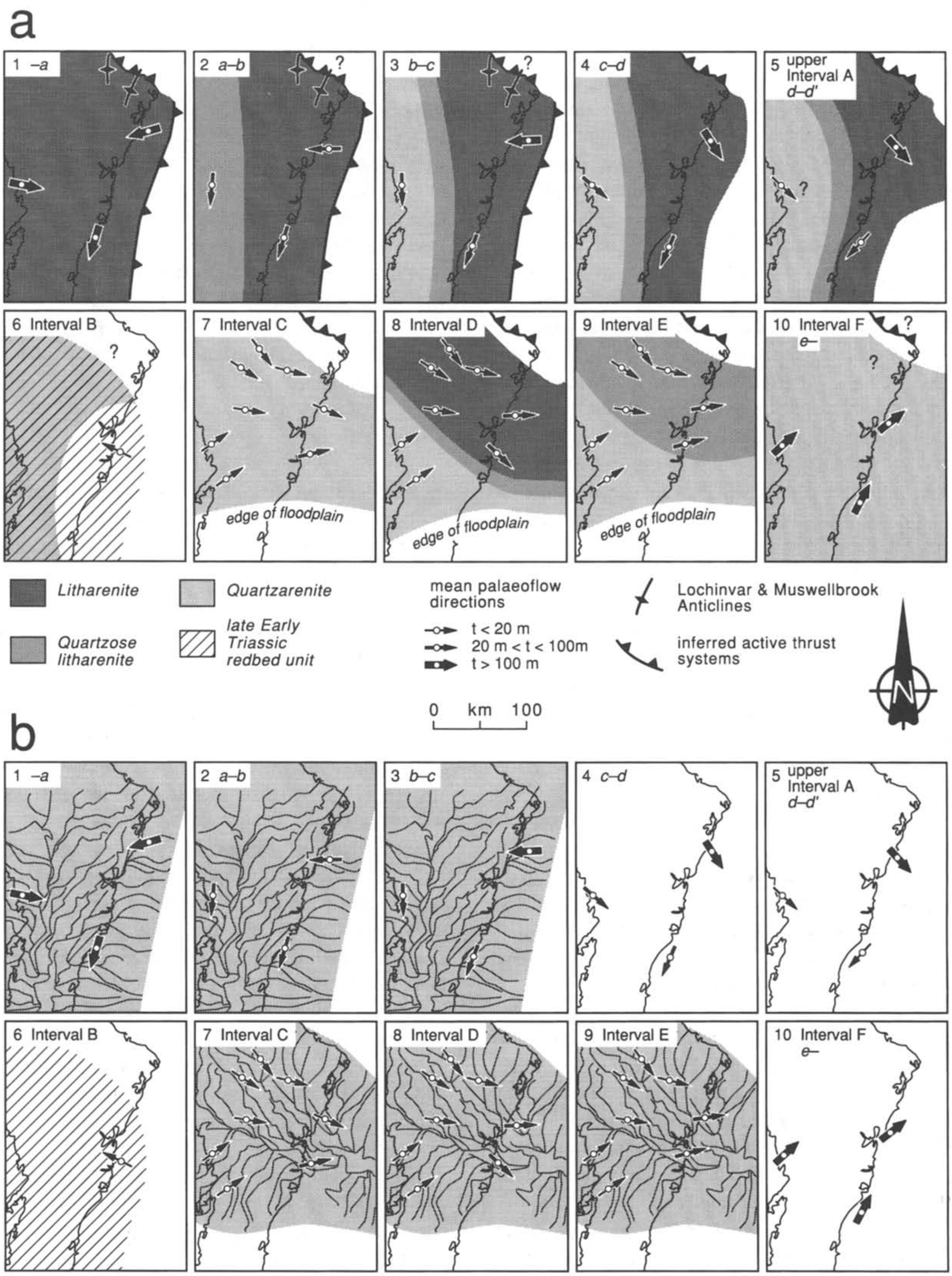
Another possible mechanism for producing vertical jumps in detrital sandstone compositions is by partial preservation of the foreland stratigraphy. This is expected when the net sediment accumulation is greater than the rate of subsidence, when some of the sediment is transported away from the depositional axis of the basin (as in the *progradational model* of Burbank and Beck, 1991). Such cases are typically characterised by transverse fluvial systems rather than longitudinal ones; however, longitudinal fluvial systems can be associated with a prograding depositional surface if there is significant detrital contribution from the cratonic side of the basin as is the case with the Sydney Basin (Burbank and Beck, 1991, fig. 1D). Partial preservation of gradually changing composition of detrital material into the foreland in such a progradational scenario will result in vertically discontinuous sediment compositions. Nonetheless, this progradational scenario may not hold for the Narrabeen Group, since some of these fluvial deposits record deposition close to sea level (intervals B, C and D, Table 1)—this is typical of aggrading foreland strata where deposition occurs close to the local base-level (Burbank and Beck, 1991). Hence, it is more reasonable to interpret the vertical compositional jumps as the result of episodic changes in the rate of sediment supply into the basin rather than partial preservation of foreland strata.

Late Permian–early Middle Triassic fluvial history of the Sydney Basin

Time–stratigraphy

The Permian–Triassic time–stratigraphy of the Sydney Basin strata is poorly constrained (Fig. 3). In the absence of geochronological data, Conaghan et al. (1982) used spore–pollen palynological zonation boundaries (Helby, 1970, 1973) as approximate time planes. For example, the redbed unit of interval B recording a period of basin-wide starvation of sediment input approximates a time plane. The coincidence of the base of interval B to the palynological zonation boundary d' (Fig. 3), is consistent with the interpretation that the spore–pollen zonation boundaries likely represent approximate time planes (Conaghan et al., 1982). A similar approach is adopted here (Fig. 3), although in detail some zonation boundaries are positioned differently to those proposed by Conaghan et al. (1982, their fig. 3) to be more consistent with the spore–pollen zonation boundaries proposed by Helby (1970, 1973). In particular, palynological data do not support time-equivalence of the upper Narrabeen Group and the Hawkesbury Sandstone, for the two formations show marked differences in spore–pollen assemblages, suggesting instead a disconformable relationship (Helby, 1973, p. 151).

Time–stratigraphy based on palynological zonation of the Sydney Basin (Helby, 1970, 1973), together with available petrography and palaeocurrent data (Goldbery and Holland, 1973;


a
1 –a
2 a–b
3 b–c
4 c–d
5 upper Interval A d–d'
6 Interval B
7 Interval C
8 Interval D
9 Interval E
10 Interval F e–
?
edge of floodplain
Litharenite
Quartzarenite
Quartzose litharenite
late Early Triassic redbed unit
mean palaeoflow directions
t < 20 m
20 m < t < 100m
t > 100 m
Lochinvar & Muswellbrook Anticlines
inferred active thrust systems
0 km 100
N
b

Conaghan et al., 1982; P.J. Conaghan, unpubl. data; Fig. 5 herein), allows sequential reconstruction of fluvial sedimentation in the Sydney Basin (Figs. 3, 9). Figure 9a shows time frames 1–10 that depict the evolution of the detrital compositions and associated palaeoflow directions of fluvial sandstones across the basin. Size of the palaeoflow arrows indicates the thicknesses of sediment accumulated at each of the locations (see Fig. 9 for data source). Superposition of the modern drainage-net of the Ganga River system (60% original scale) on the Sydney Basin illustrates the sediment dispersal patterns in terms of a longitudinal drainage pattern (Fig. 9b). Almost all palaeocurrent patterns and detrital compositional variations can be adequately explained by this analogy. The fitted palaeodrainage pattern indicates a wholesale reorganization of the longitudinal drainage pattern from a formerly north–south orientation to an east–west orientation. In detail the salient characteristics of the fluvial history are as follows.

Late Permian–early Early Triassic southerly directed fluvial drainage (frames 1–3 in Fig. 9)

The main direction of sediment dispersal was toward the south or south-southwest during the first phase of the fluvial and fluvial–lacustrine sedimentation (frames 1–3 in Fig. 9). The westerly directed palaeocurrents in the northern coastal exposures are interpreted as tributaries to a southerly flowing longitudinal fluvial system that persisted until about time *d* in the late Early Triassic (Jones et al., 1987; Veevers et al., 1993). The sandstone composition varies across the longitudinal system, being more quartzose on the western cratonic margin of the basin, and these domains migrated through time toward the east (frames 1–3 in Fig. 9a). Although detailed petrofacies data are lacking from modern longitudinal rivers for comparison, transverse petrofacies variation is likely characteristic of longitudinal fluvial systems that flow parallel to the orogen. Progradation of cratonically sourced sediments and temporal increase in the asymmetry of sediment thickness to the east suggest that differential subsidence occurred across the basin, with high subsidence rates close to the fold belt in the east.

The orientation of the southerly directed fluvial dispersion, together with its transverse detrital compositional variation is interpreted to record the presence of the southern extension of the New England Fold Belt orientated approximately parallel to the present coastline (frames 1–3 in Fig. 9). The idea that the onshore segment of the New England Fold Belt passed laterally into a southerly trending offshore segment was first suggested by David (1907), and supported by more recent studies by Ward (1972, 1980) and Jones et al. (1984, 1987). Isopach maps of the sediments deposited during this phase show contour maxima that are orientated approximately meridionally near the present coast-line (Mayne et al., 1974, pp. 52–68), consistent with north–south thrust-loading in this offshore segment of the New England Fold Belt.

Late Early Triassic cessation of the southerly directed drainage (frames 4–6 in Fig. 9)

During the deposition of interval A, the sediment dispersal pattern north of Broken Bay changed from one of southwesterly to dominantly southeasterly palaeoflow. Southwesterly directed palaeoflow persisted in the south coast region

Fig. 9. Late Permian–Middle Triassic sedimentation in the Sydney Basin. Size of palaeoflow arrows indicates sediment thickness deposited during each time frame. Data for time frames 1–4 and 10 from Conaghan et al. (1982, their table 1). Coastal data for frames 5–9 from Fig. 5. Aerial extent and palaeocurrents of redbed unit in frame 6, and data for palaeocurrents for inland exposures for frames 7–9 from Goldbery and Holland (1973, fig. 9, table 3). Stratigraphic positions of inland palaeoflow data from Goldbery and Holland (1973) are uncertain but within the stratigraphic levels of intervals C, D and E, so these palaeoflows are repeatedly shown in frames 7–9. Italicised letters for frames 1–3 correspond to time planes (spore–pollen zone boundaries) defined by Conaghan et al. (1982, figs. 5A–5C). Time planes *d*, *d′* and *e* depicted in frames 4, 5 and 10 are defined in Fig. 3. (a) Petrofacies distribution across the basin as defined by Q–F–L compositions. (b) Ganga River system (60% original scale) superimposed on some of the palaeoflow patterns of the basin.

(frames 4, 5 in Fig. 9a), but four-fold greater thickness of sediment accumulated in the north compared to the rest of the basin. The record of shallow, frequently avulsed, fluvial deposits in upper interval A south of Broken Bay, contrasts with the thick amalgamated sandstone sheet deposits that are present north of Broken Bay (Fig. 5); differential subsidence is indicated with fluvial channels tending to favour the site of maximum subsidence (cf. Alexander and Leeder, 1987). This interval marks a change in the sedimentation axis of the basin as well as the demise of the offshore segment of the New England Fold Belt as a sediment source for the basin. However, the influence of the offshore New England Fold Belt remained until the end of interval A, suggested by the orogen-parallel palaeocurrents in the south (Ward, 1972, 1980). The unusual pattern of palaeocurrents across the basin may reflect basin partitioning into a southern and a northern segment, and this is supported by a similar north and south division of the distribution of sandstones in the upper Bulgo Sandstone (Hamilton and Galloway, 1989, p. 244). The basin partitioning may reflect a presence of a peripheral bulge south of Sydney that developed coeval with crustal loading in the onshore New England Fold Belt. The upper Narrabeen Group (intervals B–E) overlying interval A thins markedly south of Sydney in support of such an hypothesis (Fig. 4).

Following the rotation of the sedimentation axis, the extraclastic sedimentary influx into the basin immediately adjacent to the offshore New England Fold Belt essentially ceased during the accumulation of interval B (frame 6 in Fig. 9). It is unknown whether sedimentation took place along the southern flank of the onshore New England Fold Belt at this time since there is no preserved record, but negligible deposition is suggested by the decreasing thickness of interval B towards the north (Figs. 4, 5). Quartzarenitic channel sandstones are present in correlative redbeds in the west of the basin, away from the coastal exposures (Goldbery and Holland, 1973; Hamilton and Galloway, 1989), indicating a contribution of detritus from the craton. Thickest accumulation of redbed deposit, devoid of extraclasts, parallels the present coast (Hamilton and Galloway, 1989, fig. 12), indicating a depositional pattern still influenced by the offshore New England Fold Belt. The redbed deposit of interval B, composed almost entirely of reworked intraclastic (regolith) material derived mainly from the east (Goldbery and Holland, 1973), is analogous to the postorogenic deposits produced when erosion predominates in the thrust belt during its inactivity (cf. Heller et al., 1988). The deposition of interval B just prior to the complete reorientation of the longitudinal dispersal system is consistent with the offshore segment of the New England Fold Belt being tectonically inactive at this time.

Early Middle Triassic southeasterly directed fluvial drainage (frames 7–9 in Fig. 9)

The southeasterly directed fluvial drainage that developed during the deposition of interval A developed into a basin-wide southeasterly to easterly directed system during the deposition of intervals C, D and E. The resumption of fluvial sedimentation occurred with high-sinuosity quartzose streams of interval C, where streams fed detritus from the cratonic source. Renewed crustal loading within the onshore segment of the New England Fold Belt may have caused flexural tilting of the basin resulting in this minor clastic pulse from the craton (cf. Heller et al., 1988). It is unknown whether orogenic detritus was deposited immediately adjacent to the onshore New England Fold Belt during interval C deposition, but the overlying quartzlitharenitic interval D may represent a basin-ward migration of such a deposit (frame 8 in Fig. 9a). The high-sinuosity fluvial style that had characterised interval C was eventually replaced by low-sinuosity bedload streams during interval D, marked by the lack of laterally continuous point bar deposits (Db), and this fluvial style continued until the end of interval E. During the accumulation of the succession that comprises intervals C, D and E, the south coast area was devoid of any fluvial channel activity (Figs. 2 and 4, cross-section Z–Z'). Only 12 m of overbank material were deposited here, compared to thicker accumulations of fluvial deposits in the areas immediately south and north of Broken Bay (80 m and 125 m, respectively), reflecting the highly asymmetric, and restricted, basin-fill pattern as a result of differential subsidence ongoing during the deposition of interval A.

The easterly directed palaeodrainage parallel to the presently preserved onshore segment of the New England Fold Belt, the pulses of quartzose litharenitic detritus of intervals D and E, together with the northwest–southeast trend of the isopach maxima for the Narrabeen Group (Mayne et al., 1974, p. 73) all suggest that a northwest–southeast orientated crustal load was responsible for the sedimentary pattern of this phase of deposition.

Early Middle Triassic northeasterly directed fluvial drainage (frame 10 in Fig. 9)

The advance of quartzose fluvial sediment from the craton, with no marked asymmetry to its pattern of accumulated thickness, marks the last phase of predominantly fluvial sedimentation in the Middle Triassic Sydney Basin (frame 10 in Fig. 9). In contrast to interpretations of previous workers (Bunny and Herbert, 1971; Conaghan et al., 1982), it is argued here that the Hawkesbury Sandstone is not laterally equivalent to any of the underlying fluvial deposits, and that there is a distinct possibility of a hiatus between this unit and the underlying strata (Fig. 3). The fluvial drainage pattern of the Hawkesbury Sandstone cannot be adequately explained in terms of a foreland basin longitudinal drainage pattern, because of the lack of preserved evidence for either a related trunk stream or cross-basinal variation in detrital composition. Moreover, although the sedimentary facies exhibited in the craton-sourced Hawkesbury Sandstone may resemble those inferred from the Brahmaputra River (Conaghan and Jones, 1975; Conaghan, 1980; Rust and Jones, 1987), its orogen-directed palaeoflow is unlike that of the thrust-belt sourced Brahmaputra River (Fig. 1). The sedimentology of the Hawkesbury Sandstone suggests unusually high discharges from the cratonic side of the foreland basin (cf. Conaghan, 1980), likely derived from melt waters from alpine glaciers present at this high-latitudinal position of the Sydney Basin (85° South; Embleton, 1984). Altitude of the Lachlan Fold Belt during the Permian and Triassic was estimated by Lambeck and Stephenson (1986) to be, in places, 2500 m above sea level—nearly three times the present height of the eastern highlands. As com-

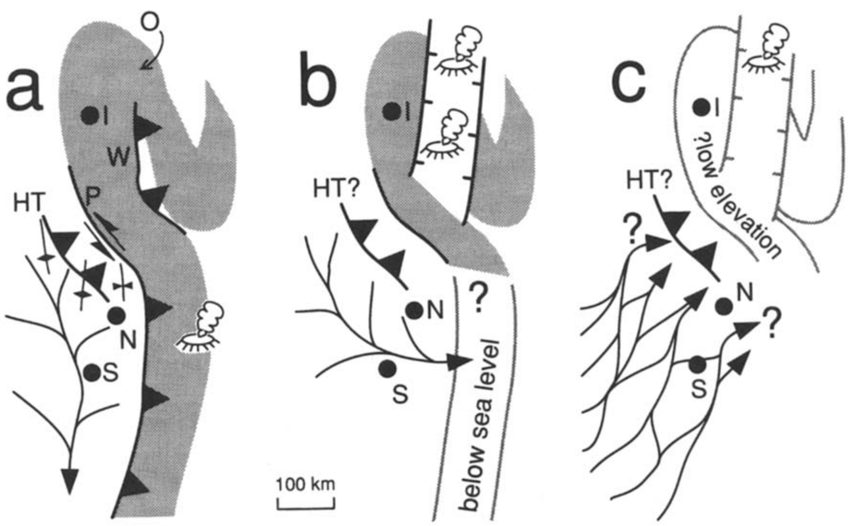


Fig. 10. Fluvial drainage of the Sydney Basin and related Permian–Triassic tectonic deformation in the New England Fold Belt (Collins, 1991, 1992; Shaw et al., 1991). Shaded areas represent the crustally thickened New England Fold Belt; (a) latest Permian to Early Triassic (upper Newcastle Coal Measures, lower Narrabeen Group), structural features after the D1–D4 deformational events of Collins (1991); (b) early Middle Triassic (Newport Formation); (c) Middle Triassic (Hawkesbury Sandstone). *I* = Inverell; *N* = Newcastle; *S* = Sydney; *W* = Wongwibinda Fault; *P* = Peel–Manning Fault System; *O* = Texas–Coffs Harbour double orocline; *HT* = Hunter Thrust System.

mented by Lambeck and Stephenson (1986, p. 256), the palaeoaltitude of the Lachlan Fold Belt likely played a large role in providing the Sydney Basin with voluminous detritus; thus, the facies characteristics of the Hawkesbury Sandstone are entirely consistent with such a high-altitude cratonic source during the Middle Triassic.

Correlation with the deformational history of the New England Fold Belt

Precise correlation of the loading events, as predicted from the changing fluvial drainage patterns, with deformational events in the New England Fold Belt is hindered by the lack of chronological data in the Triassic strata (Fig. 3). The disparity that currently exists in interpretations of the deformational events in the New England Fold Belt further adds to this difficulty (e.g., Roberts and Engel, 1987; Collins, 1991). For this reason only a first-order correlation can be made.

Various workers have documented Late Permian east–west compressional deformation in the New England Fold Belt (see references in Collins, 1991). The growth of the meridionally trending Lochinvar Anticline (frames 1–3 in Fig. 9a) was initiated during the latest Early Permian, and continued to deform during the Late Permian (Mayne et al., 1974; Diessel, 1980). Analogous to syndepositional folds that are developed in front of thrust zones (e.g., Burbank et al., 1986; Burbank and Raynolds, 1988) the Lochinvar Anticline was a geomorphic entity during the Late Permian, influencing the depositional patterns of the Newcastle Coal Measures (Diessel, 1980; Jones et al., 1987). The history of the Lochinvar Anticline, as well as other meridionally trending folds, suggests that they were developed parallel to, and in front of, a thrust-load located east of the present coast (frames 1–3 in Fig. 9a). The southerly directed drainage at this time, together with its petrofacies variation orthogonal to palaeoflow, represents a longitudinal fluvial system largely controlled by this offshore extension of the New England Fold Belt (Fig. 10a).

The subsequent reorientation of the longitudinal drainage system, coincides with the deposition of the Bulgo Sandstone (frames 4 and 5 in Fig. 9). The easterly to southeasterly directed longitudinal fluvial system was well established by the time intervals C–E were deposited. Thrusting along the northwest–southeast trending Hunter Thrust System may have controlled the depositional pattern of this longitudinal fluvial system (Fig. 10b). The Hunter Thrust System and associated thrust-parallel low-amplitude folds are documented to have refolded earlier formed meridionally trending folds (Korsch and Harrington, 1981; Glen and Beckett, 1989; Collins, 1991). The timing of this protracted deformation is not clearly known, however, due to the absence of rocks younger than Late Permian seen disrupted by the Hunter Thrust System. Roberts and Engel (1987) suggest that northeast–southwest compression related to the Hunter Thrust System occurred during the Triassic, which is consistent with the reorientation of the longitudinal drainage system recorded in the Triassic strata.

Collins (1991, 1992), in contrast, regards the major movement on the Hunter Thrust System to have occurred in the latest Permian, followed by a more significant large-scale longitudinal shortening of the New England Fold Belt by oroclinal bending (Fig. 10a, Texas–Coffs Harbour orocline). Large displacements on the Peel–Manning Fault System and associated faults within the New England Fold Belt resulted in topographic uplift, providing voluminous orogenic detritus into the Sydney Basin during the latest Permian (Collins, 1992). According to this scenario, the crustal load responsible for the southerly directed fluvial drainage resulted from the southerly extension of the New England Fold Belt, possibly bounded on the west by an extension of the Peel–Manning Fault System (Fig. 10a). The Hunter Thrust System does not extend to the present coast (Collins, 1992), and therefore, may not have provided much in terms of a detrital source or significant crustal load during the southerly directed drainage.

The Texas–Coffs Harbour orocline of the New England Fold Belt started to develop as early as the Late Carboniferous and continued to deform during the Middle Triassic (Korsch et al., 1990; Veevers et al., 1993). Crustal thickening resulting from this protracted deformation in the onshore New England Fold Belt, together with the Early

Triassic denudation of the offshore New England Fold Belt, marks a counter-clockwise shift in crustal-load orientation. This shift in crustal load, and renewed thrusting in the fold belt, likely produced the easterly directed fluvial system of the Middle Triassic (Fig. 10b). Accompanying the large-scale shift of the orogenic load, quartzose litharenitic sandstones of intervals D and E suggest smaller-scale Middle Triassic fault movements in the onshore segment of the New England Fold Belt. It is unknown whether these adjustments represent Middle Triassic movements along the Hunter Thrust System or movements on some other faults further north. The presence of radiolarian chert in the sandstones, the source of which presently lies north of the Peel–Manning Fault System (Fig. 10a), favours the second interpretation. But the continuation of orogenic shortening after the Middle Triassic is supported by the presence of northeast-dipping thrust faults in the Hawkesbury Sandstone near Sydney (Mills et al., 1989). It is highly probable, therefore, that the Hunter Thrust System and associated splay faults (cf. Glen and Beckett, 1989) exerted a greater influence on the drainage pattern of the Middle Triassic fluvial deposits than in the Late Permian or Early Triassic with continued craton-ward propagation of thrusts from the north and northeast.

Although the orogen-directed palaeoflow of the Hawkesbury Sandstone is difficult to interpret, the basin-wide disconformity/unconformity between the Hawkesbury Sandstone and the underlying strata points to change in tectonic regime (Fig. 3). Renewed crustal loading in the New England Fold Belt may explain the orogen-directed palaeoflow, with the southwestward increase in discordance of the basal angular unconformity (Herbert, 1980) resulting from peripheral bulge uplift of the distal edge of the basin (cf. Armin, 1987). Furthermore, the Hawkesbury Sandstone was deposited after the emplacement of voluminous plutons in the New England Fold Belt (Shaw et al., 1991). The preservation of coeval volcanic epiclastics with these shallow-level intrusives (Shaw and Flood, 1981; Shaw et al., 1991) suggests, but does not prove, that the New England Fold Belt was a lowland during eruption, possibly aiding the development of an orogen-dipping palaeoslope (Fig. 10c; W.J. Collins, pers. commun., 1992).

While the pattern of palaeocurrents and cross-basinal variation in petrofacies recorded in the Sydney Basin is consistent with a longitudinal foreland drainage (cf. Fig. 1), two features are strikingly different to that found in other foreland basins. These are: (1) the relatively narrow width of the basin compared to other foreland basins (e.g., Alberta, Appalachian, Himalayan); and (2) the inferred presence of an elevated craton, supplying abundant cratonic sediment. These two features were likely inherited from the Early Permian extensional phase of the basin, and are unlikely to be shared with foreland basins formed entirely from crustal flexure. The narrow width of the foreland basin in the Late Permian and Triassic may have resulted from crustal loading on an extended thermally young lithosphere with low flexural rigidity (cf. Beaumont, 1981; Hagen et al., 1985). Evidence for continued thermal activity is manifested by Middle Triassic teschenitic intrusions of the northern Sydney Basin (Gamble et al., 1988). Alternatively, the basin width may have been restricted by the presence of the cratonic highland to the west that initially formed the margin of the Early Permian extensional basin. Perhaps the unusual volume of cratonic sediment as recorded in interval C and the Hawkesbury Sandstone reflects in part an already elevated cratonic source, but also in part the behaviour of a thermally young crust that produced an amplified peripheral bulge during crustal loading. However, this interpretation remains speculative until better correlations can be made with the deposition of these quartzose sandstones and deformational events in the New England Fold Belt.

Conclusions

The study of basin-wide changes in sediment dispersal patterns and petrofacies in the Sydney Basin has led to the following conclusions that are likely to be of general relevance for the study of ancient alluvial foreland basin-fills.

(1) Longitudinal fluvial dispersal systems develop parallel to the strike of the crustal load,

and can be distinguished from transverse dispersal systems by their variation in petrofacies orthogonal to the flow direction. Provided that good time–stratigraphic data are available, these systems can be recognized in the ancient record.

(2) Changing orientations of crustal loads in the New England Fold Belt are inferred to have resulted in two temporally separate basin-wide longitudinal fluvial systems in the adjacent Permo–Triassic Sydney Basin. The inferred timing of the development of these dispersal systems is consistent with presently known structural chronology from the fold belt. The identification of cross-palaeoflow variation in petrofacies, and the temporal variation in the orientation of longitudinal fluvial systems is important in reconstructing the orientation of the crustal load in the coeval fold belt.

(3) Cratonic detritus is expected in other flexural foreland basins, although its volume is likely to be minimal. The unusual abundance of cratonic material in the Sydney Basin is consistent with an elevated craton inherited from earlier crustal extension. Abundance of cratonic detritus in other foreland basins may point to a similar tectonic inheritance of cratonic highland.

(4) Inferred to record the episodically changing rate of sediment supply from the fold belt, petrographically distinct intervals characterise the stratigraphy of the second longitudinal fluvial system identified in the Sydney Basin. Minor fault adjustments made in the fold belt, resulting in episodic pulses of compositionally uniform detritus, likely produced these petrographic intervals. Similar episodic pulses of detrital contributions from coeval fold belts are likely to be represented in other foreland basins.

(5) Although the orogen-sourced Brahmaputra River may be used as a depositional facies analogue for the Hawkesbury Sandstone, it is an inappropriate tectonogeomorphic analogue for the craton-sourced low-sinuosity fluvial deposit. The facies character of the Hawkesbury Sandstone suggests unusually high discharges from the cratonic side of the foreland basin, consistent with a fluvial derivation from a possibly glaciated, high-latitude and upland terrain. Although speculative, the orogen-directed flow of the Hawkesbury Sandstone may have resulted from tilting caused by renewed thrust-loading in the New England Fold Belt to the north. Clearly, it is important to investigate the tectonic setting of fluvial deposits when considering their modern analogues, and to consider the implication of the depositional facies analogue at a basin scale.

Acknowledgements

This study stems from research funded by and conducted at Macquarie University (1984–1985). Dr. Patrick J. Conaghan suggested and supervised this project, and I thank him for his invaluable support, ongoing discussion of the ideas embodied in this paper and constructive criticism of the manuscript. The construction of Figure 9 would not have been possible without the use of data appended in Conaghan et al. (1982) and unpublished petrographic data of P.J. Conaghan. R. Helby gave helpful advice on interpreting his published palynological data. K.L. McDonnell is thanked for the use of his unpublished material. J.G. Jones and J. Roberts are thanked for their valuable criticism of an earlier manuscript. P.D. Godin, L. De Verteuil, C.R. Fielding, two official reviewers, and in particular W.J. Collins, are thanked for their critical reviews of the manuscript. The manuscript was prepared at the Department of Geology, University of Toronto.

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