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Palaeozoic synorogenic sedimentation in central and northern Australia: a review of distribution and timing with implications for the evolution of intracontinental orogens

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The Palaeozoic Alice Springs Orogeny was a major intraplate tectonic event in central and northern Australia. The sedimentological, structural and isotopic effects of the Alice Springs Orogeny have been well documented in the northern Amadeus Basin and adjacent exhumed Arunta Inlier, although the full regional extent of the event, as well as lateral variations in timing and intensity are less well known. Because of the lack of regional isotopic data, we take a sedimentological approach towards constraining these parameters, compiling the location and age constraints of inferred synorogenic sedimentation across a number of central and northern Australian basins. Such deposits are recorded from the Amadeus, Ngalia, Georgina, Wiso, eastern Officer and, possibly, Warburton Basins. Deposits are commonly located adjacent to areas of significant basement uplift related to north–south shortening. In addition, similar aged orogenic deposits occur in association with strike-slip tectonism in the Ord and southern Bonaparte Basins of northwest Australia. From a combination of sedimentological and isotopic evidence it appears that localised convergent deformation started in the Late Ordovician in the eastern Arunta Inlier and adjacent Amadeus Basin. Synorogenic style sedimentation becomes synchronously widespread in the late Early Devonian and in most areas the record terminates abruptly close to the end of the Devonian. A notable exception is the Ngalia Basin in which such sedimentation continued until the mid-Carboniferous. In the Ord and Bonaparte Basins there is evidence of two discrete pulses of transcurrent activity in the Late Devonian and Carboniferous. The sedimentological story contrasts with the isotopic record from the southern Arunta Inlier, which has generally been interpreted in terms of continuous convergent orogenic activity spanning most of the Devonian and Carboniferous, with a suggestion that rates of deformation increased in the mid-Carboniferous. Either Carboniferous sediments have been stripped off by subsequent erosion, or sedimentation outpaced accommodation space and detritus was transported elsewhere.

KEY WORDS: Alice Springs Orogeny, Amadeus Basin, Arunta Inlier, biostratigraphy, central Australia, geochronology, Palaeozoic, sedimentation, tectonics.

INTRODUCTION

A well-preserved record of intraplate sedimentation and tectonics spanning much of the Neoproterozoic and Palaeozoic is found in the sedimentary basins of central and northern Australia. This depositional system was initiated during the Early Neoproterozoic, but was later deformed and segmented by zones of basement uplift during two major intraplate orogenic events, the Late Neoproterozoic – earliest Palaeozoic Petermann Ranges Orogeny and the mid- to Late Palaeozoic Alice Springs Orogeny. Intraplate orogenies, of which these are classic examples, are enigmatic events that are not yet fully understood (Lambeck 1984; Hand & Sandiford 1999). Factors such as the duration and rate of orogenesis, as well as the dimensions and shape of the orogen and its orientation with respect to contemporaneous plate-margin activity, are fundamental parameters that need to be defined in order to fully understand such events (Sandiford *et al.* 2001). In this review we will focus specifically on the Alice Springs Orogeny.

A number of studies (Shaw 1991; Shaw *et al.* 1991; Dunlap & Teyssier 1995; Dunlap *et al.* 1995) have discussed the local effects and timing of the Alice Springs Orogeny in the southern and eastern Arunta Inlier and in the adjacent Amadeus Basin, areas in which the effects of orogenesis are perhaps best developed. However, it is clear that the event was much more widespread, although details remain sketchy. There are reports of similar aged deformation, or of syntectonic-style sedimentation from the Georgina, Wiso, Ngalia, eastern Officer, Warburton, Ord and Bonaparte Basins. Similarly, apatite fission track data point to widespread denudation of the Australian continent during Alice Springs Orogeny times (Hill & Kohn 1998; Kohn *et al.* 1998).

It is clear that deformation was not spatially continuous throughout the Alice Springs Orogen, but was focused

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at a number of discrete loci, generally situated along the current structural margins of the preserved basins and in areas of now-exhumed basement. The controls on the localisation of such deformation form the subject of several recent papers by the authors (Sandiford & Hand 1998; Hand & Sandiford 1999; Sandiford *et al.* 2001). In this review, we focus on the regional extent of deformation and more specifically on the associated syntectonic sedimentation related to the Alice Springs Orogeny and the evidence for the timing of activity in each area. As isotopic studies have been largely restricted to the southern and eastern Arunta Inlier, the identification of Alice Springs-aged orogenic activity in other areas must be based largely on the association of deformation with biostratigraphically dated synorogenic-style sedimentary deposits. In some cases, it must be inferred on the presence of such deposits alone. We also make comparisons between the regional stratigraphic and localised isotopic records. Throughout this paper we use the 1996 Australian Phanerozoic time-scale (Young & Laurie 1996).

CENTRAL AND NORTHERN AUSTRALIAN BASINS

During the Neoproterozoic a large (~2×10^6 km^2), more or less continuous, depositional system, referred to as the Centralian Superbasin, occupied part of what is now inland Australia (Walter *et al.* 1995) (Figure 1). During this time, extension in the east led eventually to rifting and the development of a new continental margin east of the currently exposed Adelaide 'Geosyncline' of South Australia (Powell *et al.* 1994; Walter & Veevers 1997). The first major structural disruption of the Centralian Superbasin occurred during the latest Neoproterozoic to Early Cambrian Petermann Ranges Orogeny. This event led to the uplift and exposure of Palaeoproterozoic–Mesoproterozoic basement of the Musgrave Inlier, separating what is now the Amadeus Basin from the Officer Basin to the south. Deformation and uplift may have been focused in an area of comparatively thick Neoproterozoic sedimentation (Sandiford & Hand 1998). In many respects the Petermann Ranges Orogeny was very similar to the later Alice Springs Orogeny, which had its main loci

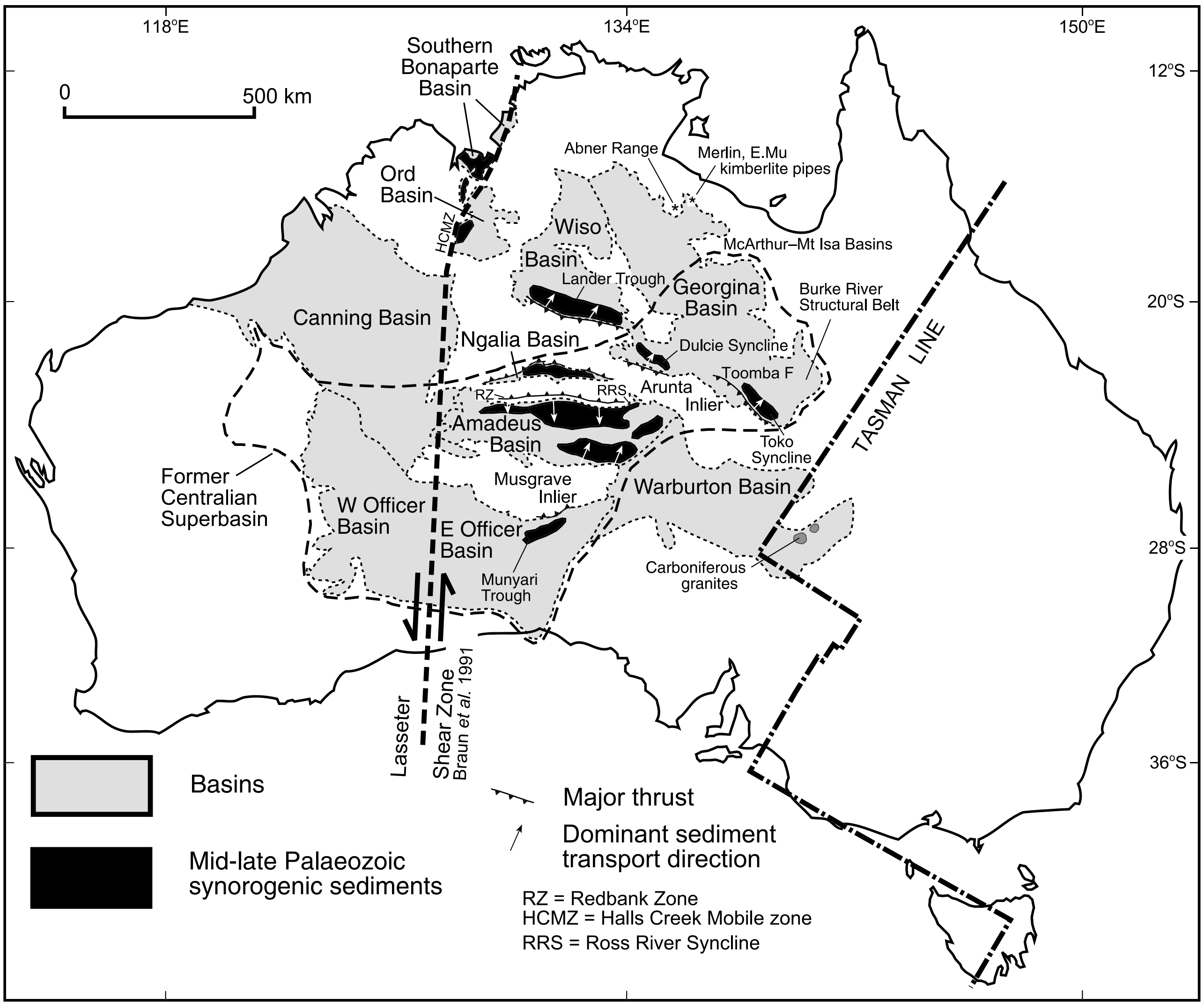

Figure 1 Locality map showing basins and basement inliers mentioned in the text and the distribution of the former Centralian Superbasin. The distribution of synorogenic or synorogenic-style sedimentation inferred to be related to the Alice Springs Orogeny is indicated.

further north, also in areas bearing a thick sedimentary cover much of which accumulated subsequent to the Petermann Ranges Orogeny. During the Early Palaeozoic the depositional area expanded with the development of northern extensions of what are now the Georgina and Wiso Basins, and southern extensions of the Officer Basin. Particularly thick sediments accumulated in what is now the northern Amadeus Basin and probably over the area now occupied by the southern Arunta Inlier (Sandiford & Hand 1998; Hand & Sandiford 1999). This belt of sedimentation apparently extended west and east into the Canning and Warburton Basins, respectively. While this is often considered to represent a thermal sag phase of sedimentation in central Australia (Korsch & Lindsay 1989), there is now evidence of high-grade metamorphism and deformation in the Arunta Inlier during the Early Ordovician (Mawby *et al.* 1998, 1999; Miller *et al.* 1998; Hand *et al.* 1999b). This event was most likely extensional in nature (Mawby *et al.* 1998, 1999; Hand *et al.* 1999b) and its timing seems to correlate well with the deposition of thick marine sequences in the northern Amadeus Basin (Larapinta Group) as well as equivalents in other basins. The timing also corresponds with the development of extensional troughs in the Canning Basin in Western Australia (Romine *et al.* 1994). Extension was much longer lived in the west, and it has long been observed that the essentially north–south shortening during the Alice Springs Orogeny in central Australia was approximately coeval with continuing north–south- to northeast–southwest-directed extension in the Canning Basin and elsewhere in Western Australia. Braun *et al.* (1991) have proposed that these areas are separated by a crustal-scale transcurrent feature, the Lasseter Shear Zone, running through the Halls Creek Province between the Amadeus and Canning Basins and continuing south to the southern edge of the continent (Figure 1). During the Devonian–Carboniferous the Lasseter Shear Zone has been interpreted as separating crustal blocks, which were undergoing compression to the east, from those undergoing extension to the west.

Basement uplift during the Alice Springs Orogeny segmented the northern portion of the original Centralian Superbasin, and its Palaeozoic extensions, creating the structural or partially structural inliers now comprising the Amadeus, Ngalia, Wiso and Georgina Basins. Locally, these new basins continued to fill with synorogenic sediments after segmentation of the superbasin. Palaeozoic sedimentation, including synorogenic-style sediments corresponding in age to the Alice Springs Orogeny, are also present in the Ord and Bonaparte Basins distributed along the Halls Creek Mobile Zone in northeast Western Australia. These sequences will also be reviewed here, although it seems likely that they were deposited in response to strike-slip tectonics along the northern Lasseter Shear Zone rather than being purely related to compressional tectonics.

ALICE SPRINGS OROGENY: A REVIEW OF DEFINITIONS

The term Alice Springs Orogeny has been used in various restricted or extended senses by many different authors. Only a brief historical review will be given here. The term was first introduced by Forman (1966) for the last major episode of deformation expressed in the Amadeus Basin and best developed along its northern margin. At the time this event was considered to be restricted essentially to the Devonian, resulting in the deposition and subsequent deformation of the Pertnjara Group in the Amadeus Basin. Forman *et al.* (1967) extended the concept of the Alice Springs Orogeny to encompass a 'pre-orogenic phase' from the Late Ordovician to Middle Devonian, followed by a Middle to Late Devonian 'orogenic phase'. In contrast, Wells *et al.* (1970) restricted the Alice Springs Orogeny to the tectonic episode responsible for folding the Pertnjara Group late in the Devonian or in the Carboniferous. A new term, Pertnjara Movement, was established for the event deemed responsible for an unconformity at the base of the Pertnjara Group.

Early work on Palaeozoic deformation in central Australia focused mainly on the dècollement-style deformation in the Amadeus Basin, although the involvement of basement to the north had long been recognised. Stewart (1971) was the first to investigate the timing of Palaeozoic deformation in the basement using isotopic techniques, leading to an escalation of such studies in subsequent years (see review by Dunlap & Teyssier 1995).

Bradshaw and Evans (1988) provided a detailed review of the varying definitions of the Alice Springs Orogeny used up until that time, and discussed the timing and significance that should be placed on various stratigraphically recognised events. They essentially followed Forman *et al.* (1967) in adopting a broad definition of the Alice Springs Orogeny encompassing all convergent deformation in central Australia from *ca* 450 Ma to the late Palaeozoic. Bradshaw and Evans (1988) recognised six discrete 'movements' within the Alice Springs Orogeny, mainly identified on the basis of local unconformities or structural features in the Amadeus and Ngalia Basins, which they considered to range in age from latest Ordovician (Rodinga Movement) through to the Early Permian (Waite Creek Movement). However, the majority of more recent workers (such as Shaw 1991) have preferred to restrict the Alice Springs Orogeny to the time interval between *ca* 400 Ma and 300 Ma, starting with the Pertnjara Movement, when there is copious evidence for basement involvement and isotopic resetting.

The notion of an earlier start to the Alice Springs Orogeny has recently been supported by new isotopic studies that identify two distinct basement events during the Ordovician in the southeast Arunta Inlier. The first, a high-grade metamorphic and deformational episode in the Early Ordovician, is probably extensional in nature (Mawby *et al.* 1998, 1999; Hand *et al.* 1999b) and, thus, would appear to be distinct from the characteristically convergent Alice Springs Orogeny. However, this was followed by an episode of convergent movement on the Bruna Detachment Zone at *ca* 450 Ma in the Late Ordovician (Mawby *et al.* 1999).

RECORD OF SYNOROGENIC SEDIMENTATION

Style of sedimentation

Until the Late Ordovician, sedimentation throughout the Centralian Superbasin was largely of shallow-marine origin, with the exception of proximal deposits associated with the Petermann Ranges Orogeny and some other local deposits. After this time, preserved sediments in the region are largely non-marine and record a variety of alluvial environments, including conglomeratic fans adjacent to regions of elevated terrain, and minor lacustrine and aeolian deposition. Sediments tend to be thickest in asymmetrical synclines near basin margins, often adjacent to major basinward-directed thrust faults. Facies trends and palaeocurrent evidence, where available, suggest derivation of sediments from the upthrown fault block. In later deposits (mid-Devonian to Carboniferous) thick conglomeratic wedges are locally preserved, implying substantial relief and exhumation in the source area. In some cases, such as the Brewer Conglomerate, the successive unroofing of the orogen may be documented by the ageing of the clast population up through the synorogenic sequence (Jones 1972, 1991). The distribution of synorogenic deposits discussed below is indicated in Figure 1. Stratigraphic sequences are summarised in Figures 2 and 3.

Northern Amadeus Basin

Fully marine sedimentation dominates the Amadeus Basin Ordovician section (Larapinta Group) up until the conclusion of deposition of the Stokes Siltstone, a unit straddling the Early/Late Ordovician boundary (Shergold *et al.* 1991). A well-developed connection with the Canning Basin also existed up until this time (Walley *et al.* 1991). An extensional setting is supported by the style of sedimentation, but also by a synchronous Early Ordovician basement metamorphic event that has been interpreted as being related to an extensional episode (Mawby *et al.* 1998, 1999; Hand *et al.* 1999b). A permanent change in the style of sedimentation occurred suddenly with the incoming of coarse clastic sediments at the base of the overlying Carmichael Sandstone. This contact is at least locally disconformable. The Carmichael Sandstone, which is up to 150 m thick (Wells *et al.* 1970), is mainly of deltaic origin and shows evidence that sediment was derived from both the northwest and southeast (Walley *et al.* 1991). Various workers (Lindsay & Korsch 1991) considered this formation to reflect a shift to a compressional phase of tectonism. Although defined as the top unit of the Larapinta Group, Lindsay and Korsch (1991) suggested that the Carmichael Sandstone would be stratigraphically better placed as a basal member of the overlying Mereenie Sandstone. The suggestion of a change in tectonic style has recently been supported by isotopic evidence of convergent activity in the basement at *ca* 450 Ma (Mawby *et al.* 1999). Based on rare fossils, the Carmichael Sandstone is Late Ordovician (Caradoc) in age (Shergold *et al.* 1991). Deposition of the Carmichael Sandstone probably

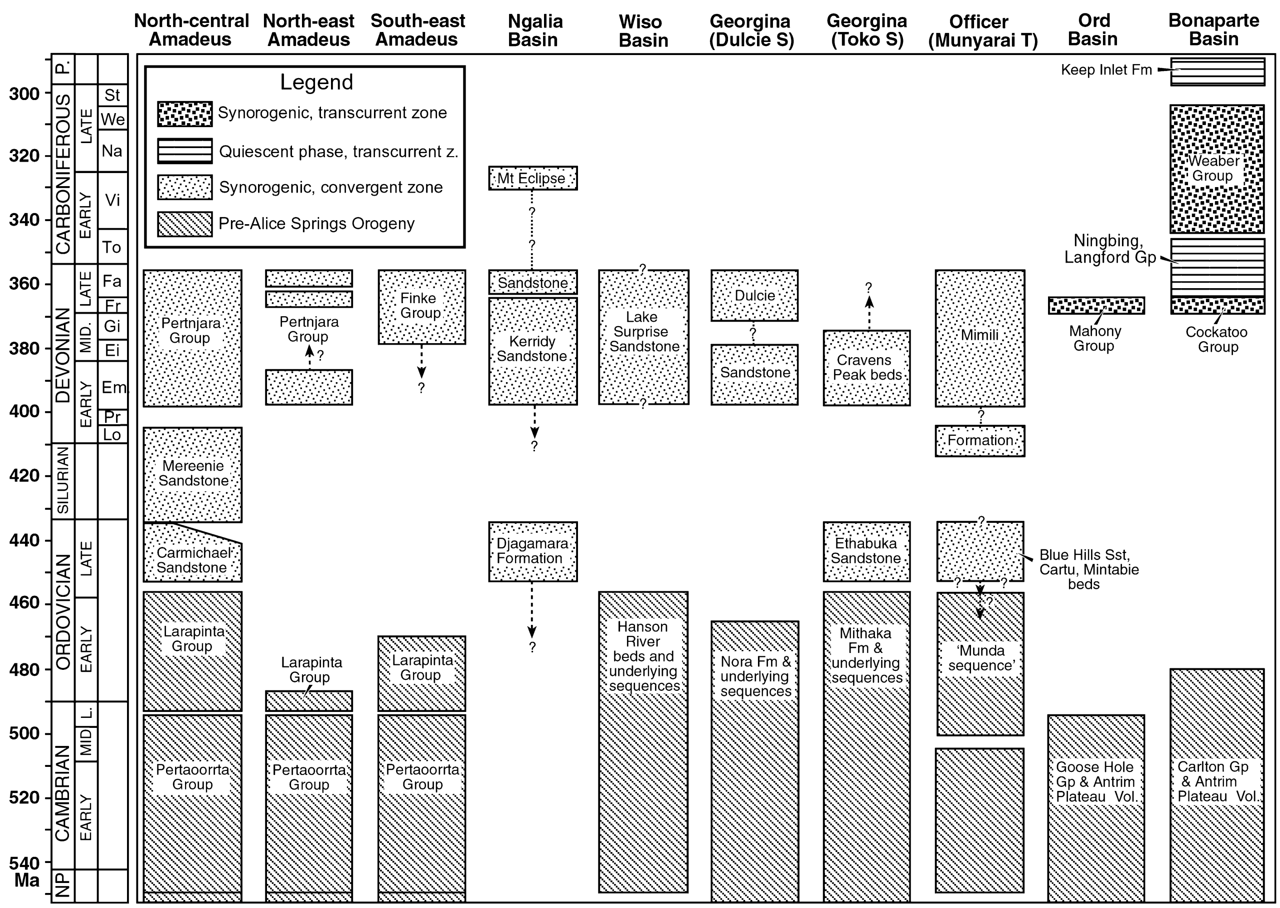

Figure 2 Stratigraphic overview of Palaeozoic sedimentation in the basins discussed in this review. This, and subsequent stratigraphic tables use the Australian Phanerozoic time-scale (Young & Laurie 1996). Fm, formation; Gp, group; S, syncline, Sst, sandstone; T, trough; Vol, volcanics.

corresponds to the time, or at least the beginning of the time, of uplift and erosion of up to 3000 m of sedimentary sequence in the northeast Amadeus Basin—the Rodingan Movement of Wells *et al.* (1970). The Carmichael Sandstone is absent from the eroded area. Warren (1983) has suggested that approximately 4000 m of uplift may have occurred in the Arunta Inlier at this time.

The Carmichael Sandstone is overlain by up to 1500 m (Wells *et al.* 1970) of Mereenie Sandstone, deposited mainly in aeolian and fluvial environments (Walley *et al.* 1991). Although possibly conformable with the Carmichael Sandstone in western areas, the Mereenie Sandstone extends much further east, unconformably onlapping at least part of the eroded area in the northeast Amadeus Basin. The age of the Mereenie Sandstone is not well constrained at the present time, and from its stratigraphic position it could range from Late Ordovician to Early Devonian. An enigmatic fossil fish occurrence with a maximum age of late Early Devonian is known from an allochthonous sandstone unit in the Gosses Bluff impact structure, but although this unit has been interpreted to be from the lower Mereenie Sandstone (Wells *et al.* 1970), Young (1985) argued that it may equally well belong to the lower Pertnjara Group. From palaeomagnetic data, Li *et al.* (1991) suggested that the Mereenie Sandstone is mostly of Silurian age. The same study suggests a mid-Devonian age for the lower part of the overlying Pertnjara Group, which is consistent with biostratigraphic data. Although the Mereenie Sandstone was originally mapped in the Ross River Syncline in the northeastern part of the basin (Wells *et al.* 1970), fossil evidence now indicates that this unit is part of the younger Pertnjara Group, which here lies unconformably over the Cambro-Ordovician Pacoota Sandstone (Young *et al.* 1987). The significance of this is that a large area of the eastern Amadeus Basin may have continued to be exhumed and eroded during deposition of the Mereenie Sandstone.

The Mereenie Sandstone and older units are overlain unconformably by the coarsening upward succession of the Pertnjara Group. This group comprises, in ascending order, the fluviolacustrine Parke Siltstone, the fluvial Hermannsburg Sandstone and alluvial-fan-deposited Brewer Conglomerate (Figure 3). The deposits accumulated in a southward-thinning wedge, which is thickest near the present homoclinal margin of the northern Amadeus Basin, and clearly derived from erosion of elevated topography to the north (Jones 1991). The formations generally interdigitate and have a number of recognised members, details of which can be found in Jones (1991).

The Pertnjara Group preserved locally near the northern margin of the eastern Amadeus Basin (Ross River Syncline) is somewhat different from other areas. The lowest unit is the 'N'Dahla Member', which was originally assigned to the Cambro-Ordovician Pacoota Sandstone prior to the discovery of Devonian fish fossils (Young

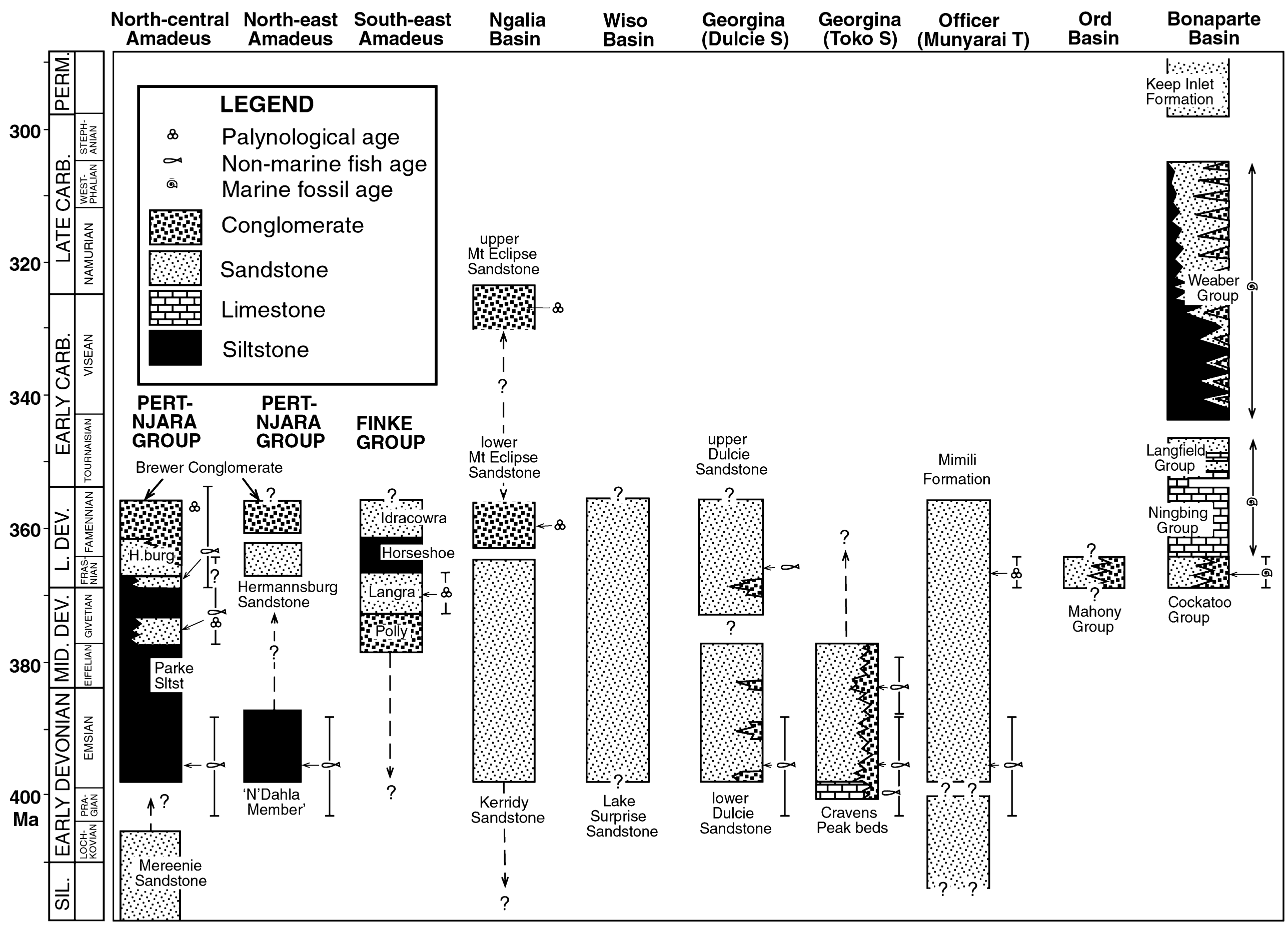

Figure 3 Detail of Devonian–Carboniferous stratigraphy of the Amadeus, Ngalia, Wiso, Georgina, eastern Officer, Ord and Bonaparte Basins. S, syncline; Sltst, siltstone, T, trough.

et al. 1987). The fish fauna suggests equivalence with the basal member of the Parke Siltstone. An overlying aeolian sandstone unit is considered by Jones (1991) as equivalent to the lower Hermannsburg Sandstone and this is overlain by fluvial sandstones of the upper Hermannsburg Sandstone. Here, the Brewer Conglomerate lies above an unconformity, as it does in other eastern exposures of this unit.

Although rarely fossiliferous, the Pertnjara Group has been dated using non-marine fish fossils and palynology. The lowermost strata of the Pertnjara Group contain elements of the widespread *Wuttagoonaspis* fish assemblage at several localities (Young 1988). Following a recent reassessment of the relationship between marine and non-marine Devonian fish faunas in Australia, the *Wuttagoonaspis* assemblage is now considered to range from Pragian to Emsian (Early Devonian) according to Young (1996). Higher levels in the Parke Siltstone have fish faunas and palynofloras of Givetian–?Frasnian (late Middle – early Late Devonian) and Frasnian–Famennian (Late Devonian) age, respectively (Shergold *et al.* 1991). Palynological samples recovered from the Undandita Member at the top of the Brewer Conglomerate have been identified as Late Devonian in age (Playford *et al.* 1976) and, recently, more specifically identified as late Famennian (Jones 1991).

Southern Amadeus Basin

The assumed correlatives of the Pertnjara Group in the southeast Amadeus Basin are referred to as the Finke Group. This succession, which locally exceeds 1000 m in thickness (Wells *et al.* 1970; Jones 1973), is poorly exposed and lies unconformably over Neoproterozoic strata and locally over basement of the Musgrave Inlier. The overall sequence shows a fining-upward trend from the Polly Conglomerate, through the mainly arenaceous Langra Formation to the Horseshoe Bend Shale, being finally capped by the Idracowra Sandstone (Figure 3). Jones (1973) identified a variety of alluvial fan, fluvial and playa lake palaeoenvironments, with the bulk of the detritus derived from the south and interdigitating with north-derived sediments of the Pertnjara Group. Aside from stratigraphic constraints, the only evidence for the age of the Finke Group comes from late Givetian – early Frasnian (late Middle – early Late Devonian) palynomorphs in drillcore of the Langra Formation and Horseshoe Bend Shale (Edgoose *et al.* 1993), suggesting a correlation of this unit with the upper Parke Siltstone. The Finke Group generally resembles the Pertnjara Group further north, but interestingly the succession is essentially reversed, with the coarsest sediments at the base, presumably indicating the peak period of uplift and denudation, with evidence of decreasing energy up-section.

Ngalia Basin

The ~300 m-thick marginal marine Djagamara Formation lies unconformably over Neoproterozoic or Cambrian strata and is considered by Wells and Moss (1983) to be the equivalent to the Cambro-Ordovician Larapinta Group of the Amadeus Basin. Young *et al.* (1995) suggested equivalence with the Cambro-Ordovician Pacoota Sandstone of the basal Larapinta Group. However, the unit is unfossiliferous except for local trace fossils, which are not age diagnostic. Cooper *et al.* (1971) reported a K–Ar glauconite date of *ca* 447 Ma, which is consistent with a Late Ordovician (Caradoc) age, although an older age is possible if Ar has been lost (Wells & Moss 1983). If the age is correct, equivalence with the Carmichael Sandstone would be implied (Figure 2).

The Djagamara Formation is overlain by up to 700 m of immature unfossiliferous Kerridy Sandstone, which was probably deposited in a fluvial setting (Wells & Moss 1983). The contact is at least locally an angular unconformity. The age of the Kerridy Sandstone is poorly constrained and could range, on the basis of external stratigraphic constraints, from Late Ordovician to Late Devonian. Wells and Moss (1983) have suggested equivalence with either the Carmichael or Mereenie Sandstone of the Amadeus Basin, while Shaw (1991) suggested equivalence with the Mereenie Sandstone. However, it could equally well correlate with the lower Pertnjara Group. The main phase of orogenic activity would appear to be associated with the locally thick (up to ~2400 m) and conglomeratic Mt Eclipse Sandstone, separated from the Kerridy Sandstone by an angular unconformity. Some folding of the Kerridy Sandstone occurred before deposition of the Mt Eclipse Sandstone (Young *et al.* 1995), with the angular unconformity at the base of the younger unit cutting right down to the level of the Proterozoic Vaughan Springs Quartzite at the base of the Ngalia Basin succession (Wells & Moss 1983). A fluvial environment is most likely, with clast lithologies, lateral facies, grainsize trends and palaeocurrent data suggesting derivation of material from uplifted basement areas to the north (Wells & Moss 1983; Young *et al.* 1995). The age of the formation ranges from Late Devonian at the base to Late Carboniferous at the top based on occurrences of plant macrofossils and palynomorphs, but it is possible that a significant time break exists within the unit (Wells & Moss 1983).

Georgina Basin

Significant deformation in the Georgina Basin is restricted to the thicker areas of sedimentation along the southern margin in the Dulcie Syncline and Toko Syncline areas, and the Burke River Structural Belt in the far southeast part of the basin in Queensland (Smith 1972). The Dulcie and Toko Synclines are large northwest–southeast-trending asymmetric structures with their steep limb adjacent to the basement of the Arunta Inlier on the southern side. The regions are considered to contain up to 3 km and 10 km of sediments, respectively (Pegum & Loeliger 1990). Marine strata as young as Late Ordovician are preserved in the Toko Syncline (Draper 1980) and Early Ordovician in the Dulcie Syncline (Freeman & Woyzbun 1986) (Figure 2). The youngest marine unit in the Toko Syncline is the ~1150 m thick Ethabuka Sandstone (Draper 1980). This unit has been equated in age with the Carmichael Sandstone of the Amadeus Basin (Shergold *et al.* 1991), and as such may belong to the synorogenic package of sediments and comprise detritus shed from uplifted areas between the two basins. In both the Toko and Dulcie Synclines the marine Ordovician sequence is separated by a low-angle unconformity from overlying non-marine sandstone units, the Cravens Peak beds and Dulcie Sandstone, respectively (Figure 3). These units closely resemble post-Ordovician non-marine units elsewhere, such as the Mereenie Sandstone and parts of the Pertnjara Group of the Amadeus Basin. Pebble, cobble and boulder conglomerates are reported from the Cravens Peak beds and sporadic pebble conglomerates occur in the Dulcie Sandstone (Smith 1972). On the basis of the non-marine fish faunas, Gilbert-Tomlinson (1968) considered that a regional hiatus can be identified within the Dulcie Sandstone. The lower parts of each formation contain *Wuttagoonaspis*, suggesting correlation with the basal Pertnjara Group (Long *et al.* 1988) and a Pragian–Emsian (Early Devonian) age (Young 1996). A younger fish fauna in the upper part of the Cravens Peak beds has tentatively been assigned an Eifelian (Middle Devonian) age (Young 1996). A different fish fauna from the upper Dulcie Sandstone is probably Frasnian (Late Devonian) in age (Young 1988). It would appear that these clastic units were deposited in response to uplift to the south, with only very gentle folding or warping of the underlying succession prior to deposition. By analogy with similar-aged asymmetric synclines in the Amadeus Basin, these structures were probably growing during deposition, but also record a final phase of post-depositional folding probably during the Carboniferous. The southwest margin of the Toko Syncline is marked by a major south-dipping reverse fault (Toomba Fault) with the Arunta Inlier thrust to the northeast over the Toko Syncline with as much as 6.5 km vertical movement (Harrison 1980). Similar evidence of thrusting is present south of the Dulcie Syncline. Flat-lying sediments of probable Permian age unconformably overlie the folded rocks at the southern end of the Toko Syncline (Smith 1972).

The Burke River Structural Belt is deformed by essentially north–south-trending folds and faults that affect rocks up to Early Ordovician in age (Smith 1972). No syntectonic deposits appear to have been preserved in the area, but the similarity of structural vergence to the Toko Syncline area suggests that deformation was related to the Alice Springs Orogeny.

Wiso Basin

The Wiso Basin is mostly thin and relatively undeformed, but from geophysical evidence up to 3000 m of sediment is inferred to lie within the 300×100 km Lander Trough along the southern edge of the basin (Pegum & Loeliger 1990). The trough lies in the same orientation and is essentially along strike from the Dulcie and Toko Synclines of the contiguous Georgina Basin and is marked by a major regional gravity low similar to those developed further south over the Ngalia, Amadeus and Officer Basins. There is very little outcrop over the trough itself and its southern margin is inferred to be in fault contact with the Arunta Inlier (Kennewell & Huleatt 1980). The youngest marine sediments are the Hanson River beds (Figure 2), which crop out sparsely along the northern margin of the Lander Trough and further north. From seismic interpretation the unit thickens considerably to the south within the trough (Kennewell & Huleatt 1980). On fossil evidence the Hanson River beds are equivalent to most of the Larapinta Group up to Stokes Siltstone and, thus, extend to early Late Ordovician in age (Kennewell & Huleatt 1980; Pegum & Loeliger 1990). The Hanson River beds are overlain unconformably by the Lake Surprise Sandstone (Figure 3), which is restricted in distribution to the Lander Trough. Although no fossils have been found, the unit is lithologically very similar to the Dulcie Sandstone of the adjacent Georgina Basin and occurs in a very similar tectonic setting to the Dulcie Syncline. The southern bounding fault has been interpreted as a steeply south-dipping thrust with over 2000 m of uplift (Kennewell & Huleatt 1980). Thrusting is believed to have been synchronous with the Alice Springs Orogeny and deposition of the Lake Surprise Sandstone (Pegum & Loeliger 1990).

Eastern Officer Basin

The 'Munda sequence' of the eastern Officer Basin comprises the Byilkaoora Formation, Mt Chandler Sandstone, Indulkana Shale, Blue Hills Sandstone, and Cartu and Mintabie beds (Gravestock *et al.* 1995) (Figure 2). Although these units lack age-diagnostic fossils they are assumed to be of Cambro-Ordovician age and considered as essentially equivalent to the Larapinta Group of the Amadeus Basin (Gravestock *et al.* 1995). The supermature, trace fossil-rich Mt Chandler Sandstone would seem a reasonable equivalent of similar sandstones in the Larapinta Group. Webb (1978) and Womer *et al.* (1987) reported Rb–Sr whole-rock ages of 460 ± 15 Ma and 438 ± 10 Ma, respectively, for the abruptly overlying Indulkana Shale, together suggesting a mid- to Late Ordovician age. The overlying 800 m-thick red-brown clastics of the Blue Hills Sandstone mark a change in depositional style similar to that involving the incoming of the Carmichael Sandstone in the Amadeus Basin. The unit is probably of mixed marginal marine (deltaic) and fluvial origin (Gravestock *et al.* 1995). The Cartu and Mintabie beds are either lateral equivalents of, or overlie, the Blue Hills Sandstone. The immature clastics comprising these units are considered by Gravestock *et al.* (1995) to reflect a more proximal detrital source than that of the Blue Hills Sandstone. The only minimum age constraint on the upper 'Munda sequence' is provided by the overlying Devonian succession in the Munyarai Trough.

Approximately 1000 m of sandstone and redbeds disconformably overlie the Blue Hills Sandstone in drillhole Munyarai 1 in the Munyarai Trough near the northern margin of the eastern Officer Basin (Gravestock *et al.* 1995) (Figure 1). This succession, identified as the Mimili Formation by Morton (1997), lies in the depocentre of the eastern Officer Basin and has not been located elsewhere or known to crop out at the surface (Figure 3). The lower part of the formation contains fossil fish (Long *et al.* 1988) and Devonian palynomorphs (Gravestock *et al.* 1995). The fish assemblage has been correlated with the widespread *Wuttagoonaspis* fauna (Long *et al.* 1988), suggesting correlation with the basal Pertnjara Group and a Pragian–Emsian (Early Devonian) age (Young 1996). Significant overthrusting by basement of the Musgrave Inlier occurs along the northern margin of the Officer Basin (Milton & Parker 1973) and south-directed thrusting and local open folding about east–west axes occur within the basin itself in the northeast. This deformation has effected the Late Devonian sediments and although its exact age is not known, it is generally considered to be contemporaneous with the Alice Springs Orogeny (Gravestock *et al.* 1995).

Western Officer Basin

The western Officer Basin is briefly discussed because of claims that structures of Alice Springs Orogeny-age are present in the area. The current northern margin of the western Officer Basin has been interpreted as a major homocline similar to that of the northern Amadeus Basin and the thickest sediments occur immediately south of this structure (Jackson & van der Graaff 1981). However, the age of uplift along this margin is very poorly constrained and no syntectonic deposits have been recognised. In fact, any established pre-Permian Palaeozoic sediments are sparse in the western part of the basin. Two unfossiliferous clastic

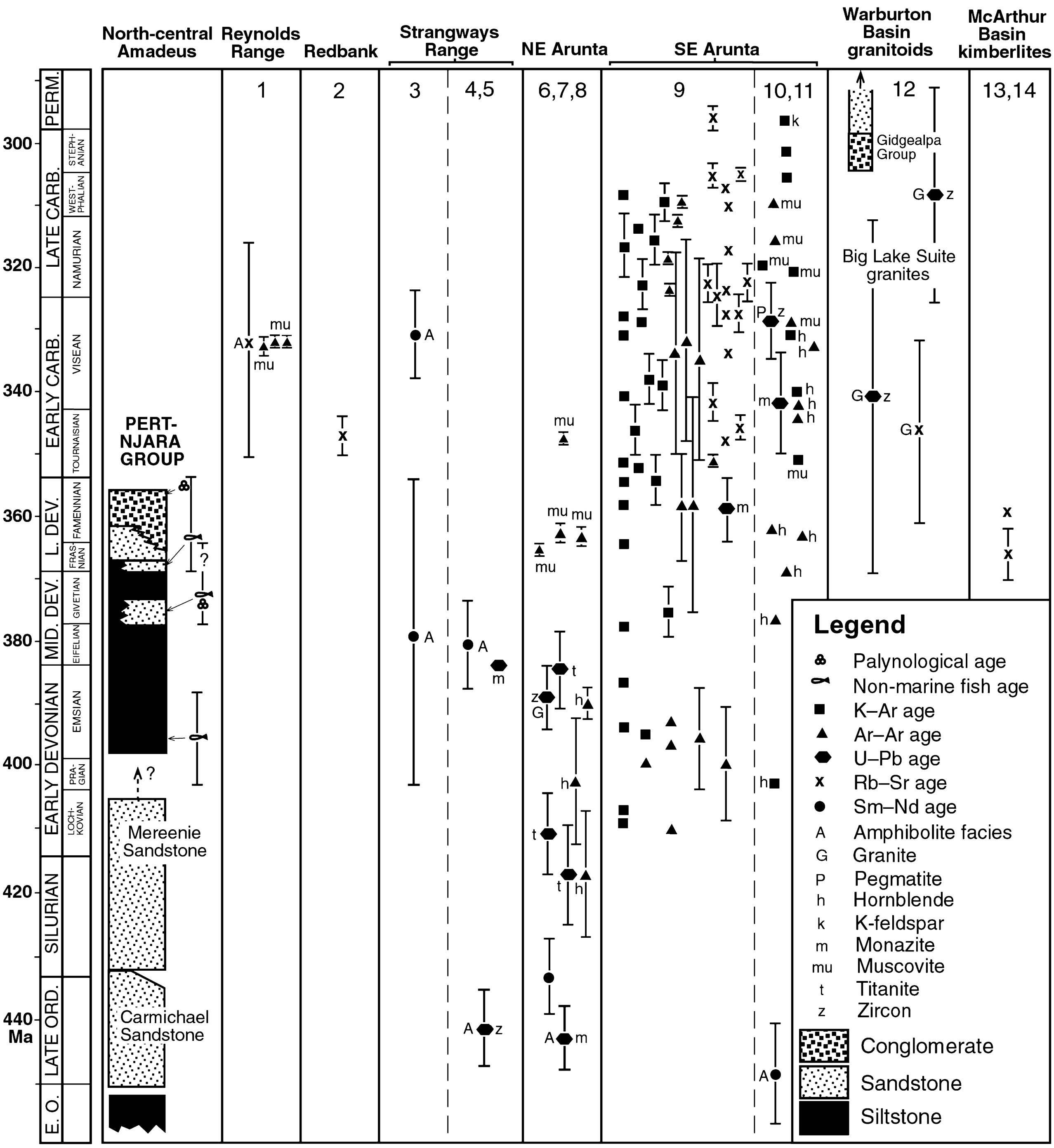

Figure 4 Comparison between the timing of Late Ordovician to Carboniferous synorogenic sedimentation in the Amadeus Basin (from Figure 3) and geochronological data from the Arunta Inlier. Data sources: 1, Cartwright *et al.* (1999); 2, Shaw and Black (1991); 3, Bendall *et al.* (1998); 4, Ballèvre *et al.* (2000); 5, Möller *et al.* (1999); 6, Scrimgeour and Raith (2001); 7, Scrimgeour *et al.* (2001); 8, Buick *et al.* (2001); 9, Dunlap and Teyssier (1995); 10, Mawby *et al.* (1998); 11, Mawby *et al.* (1999); 12, Gatehouse *et al.* (1995); 13, Lee *et al.* (1998); 14, Atkinson *et al.* (1990).

units, the Lennis Sandstone and the Wanna beds, together generally less than 400 m in thickness, unconformably overlie flood basalts of the Table Hill Volcanics and are overlain by Early Permian glacial sediments (Jackson & van der Graaff 1981). The Table Hill Volcanics are generally correlated with the Antrim Plateau Volcanics and equivalents of the Northern Territory and northern Western Australia, implying a Cambrian age (Hanley & Wingate 2000). Thus, the Lennis Sandstone and the Wanna beds are potentially anywhere from Cambrian to Early Permian in age. From published descriptions, the red feldspathic and micaceous Lennis Sandstone resembles other non-marine synorogenic deposits related to either the Petermann Ranges or Alice Springs Orogenies in central Australia and may represent distal foreland deposits related to the undated tectonic event that deformed the northern basin margin. Walter and Gorter (1994) noted that several authors have referred to reverse faults related to the Alice Springs Orogeny in the western Officer Basin. However, these authors considered the various statements made to be contradictory and assert that there is no evidence of the Alice Springs Orogeny in the western Officer or adjacent Savory Basin. They ascribed all tectonism to the latest Neoproterozoic – Early Cambrian Petermann Ranges/Paterson Orogeny. Townson (1985) presented evidence that the main folding event in the basin itself pre-dates the Table Hill Volcanics, which are only very gently warped. A lack of Alice Springs-aged orogenic activity and associated sedimentation in the western Officer Basin would be consistent with the interpretation of Braun *et al.* (1991) that the convergent deformation of the Alice Springs Orogeny was restricted to areas east of their proposed Lasseter Shear Zone.

Warburton Basin

The Warburton Basin lies to the immediate southeast of the Amadeus Basin and straddles the Tasman Line in its eastern part. It is not exposed at the surface, being variously concealed beneath the younger Pedirka, Cooper and Eromanga Basins. The exact location of the Amadeus Basin – Warburton Basin boundary is ill-defined and varies somewhat between authors. The discovery of typical upper Amadeus sequences (Mereenie Sandstone and Finke Group) in drillholes beneath the Pedirka Basin in northern South Australia suggests that the Amadeus Basin should be extended further east than once suggested (Gravestock *et al.* 1995).

Folding and mainly northwest-directed thrusting have affected Cambrian and Ordovician rocks in the eastern part of the basin. The age of deformation is poorly constrained between Late Ordovician and Late Carboniferous and various authors have suggested different ages and diverse correlations with tectonic events elsewhere. Gravestock *et al.* (1995) preferred a Carboniferous age and suggested a relationship with the Alice Springs Orogeny. Apak *et al.* (1995) also preferred a (Middle) Carboniferous age, but considered a correlation with the Kanimblan Orogeny of eastern Australia. A Carboniferous age for deformation is consistent with both the Carboniferous age (342 ± 28 Ma and 310 ± 7 Ma) of granites that intrude the sequence (Gatehouse *et al.* 1995), and the evidence for an *ca* 330 Ma thermal overprinting of Cambrian volcanics low in the sequence (Wopfner 1972). If we exclude Amadeus Basin-type sequences in the west, the only possibly late Alice Springs-aged synorogenic sediments known are non-marine conglomeratic and partly glacial sediments (basal Gidgealpa Group) of Late Carboniferous age that locally form the basal fill of the overlying Cooper Basin (Figure 4). This succession extends up into the Permian. The presence of associated granites, which incidentally lie east of the inferred position of the Tasman Line, are uncharacteristic of the Alice Springs Orogeny and seem more akin to Late Palaeozoic tectonism in eastern Australia. Meanwhile, northwest-directed thrusting suggests that the Warburton Basin may lie in a transitional domain between east–west compression in eastern Australia and predominantly north–south compression characteristic of the Alice Springs Orogen. Compressive reactivation of faults in the Warburton Basin continued during deposition of the Cooper Basin and affected sediments up to Jurassic in age (Sun 1997).

Ord Basin

The Ord Basin comprises a structurally controlled remnant of volcanics (Antrim Plateau Volcanics) and overlying sediments situated along the central Halls Creek Mobile Zone in Western Australia and adjacent border regions of the Northern Territory (Figure 1). Most of the basin is filled with Cambrian marine sediments. In some inliers, including the Hardman Syncline, the older succession is unconformably overlain by up to ~1000 m (minimum thickness, as the top is removed by erosion) of sandstone and conglomerate of the Mahony Group (Mory & Beere 1985) (Figures 2, 3). The age of the Mahony Group cannot be established biostratigraphically, but it is assumed to be Late Devonian because of very close similarities to the Cockatoo Creek Group of the nearby Bonaparte Basin (Mory & Beere 1985). Much of the succession is pebbly and one unit, the Boll Conglomerate, contains clasts measuring up to ~1 m in diameter. The Mahony Group was deposited mainly in alluvial fan, fluvial and aeolian environments (Mory & Beere 1988).

Bonaparte Basin

The Bonaparte Basin (Figure 1) comprises two main stratigraphic packages. The lower ranges from Late Neoproterozoic or Early Cambrian (Antrim Plateau Volcanics) to locally Early Ordovician in age (Figure 2). After a significant hiatus, the upper package extends from the Late Devonian to Late Carboniferous (Figure 3). In a basin margin zone this sequence comprises the Cockatoo (maximum thickness 2700 m), Ningbing, Langfield (maximum combined thickness 2000 m) and Weaber (maximum thickness 2400 m) Groups (Mory & Beere 1988). The Cockatoo and Weaber Groups were deposited in a variety of alluvial fan, fluvial and aeolian settings that interfinger in a basinward direction with a variety of marine environments (Mory & Beere 1988). Coarse detritus was periodically shed from active fault scarps and formed significant conglomeratic wedges into the basin. The intervening Ningbing and Langfield Groups are comprised mainly of shallow-marine carbonates and some clastics, which suggest a period of quiescence between two tectonic episodes. The marine sequences provide good biostratigraphic control. Deeper parts of the basin (Petrel Sub-basin) are dominated by fine-grained lateral equivalents, mainly assigned to the Bonaparte Formation. Significant unconformities occur at the base of the Cockatoo and Weaber Groups. Uplift, folding and erosion of the Devonian–Carboniferous syntectonic succession is evident prior to deposition of terminal Carboniferous–Permian marine to continental sediments (Keep Inlet Formation: up to 480 m thick onshore) that display some evidence of ongoing tectonism (Mory & Beere 1988).

McArthur – Mt Isa Basin regions

The existence of Alice Springs-aged deformation or syntectonic sedimentation has not been reported from the McArthur and Mt Isa Proterozoic sedimentary basins, which are generally considered to have undergone their last major phase of deformation during the Mesoproterozoic. However, outliers of Late Neoproterozoic and Cambrian sediments in this area have undergone local deformation of unknown age prior to deposition of thin Late Mesozoic sequences. A good example occurs in the Abner Range (Figure 1) of the southern McArthur Basin, in which the Late Neoproterozoic – Cambrian Bukalara Sandstone is folded in the keel of a northwest-trending syncline (Jackson *et al.* 1987; Pietsch *et al.* 1991). It seems likely that the folding is of Palaeozoic age and the vergence is similar to the nearest confirmed Alice Springs structures. It may be worth noting that nearby diamondiferous kimberlites are of Late Devonian age. A cluster of pipes known as the Merlin field (Lee *et al.* 1998) includes the earlier discovered E.Mu pipes (Atkinson *et al.* 1990; Smith *et al.* 1990). One pipe in the Merlin field has an Rb–Sr mica emplacement age of 367 ± 4 Ma (Lee *et al.* 1998), whereas Atkinson *et al.* (1990) reported an age of *ca* 360 Ma (method not specified) for the E.Mu pipes. Any connection to the Alice Springs Orogeny is speculative, but it is interesting to note that the Late Devonian age of these kimberlites coincides well with the period of rapid exhumation during the Alice Springs Orogeny, which is marked by deposition of the Brewer Conglomerate in the Amadeus Basin. The pipes discovered thus far lie within a west-northwest-trending zone of surficial microdiamonds that runs across the northern half of the Northern Territory (Smith *et al.* 1990), crudely paralleling the northern margin of the Alice Springs Orogen.

COMPARISON BETWEEN THE BASEMENT AND BASINAL RECORD IN CENTRAL AUSTRALIA DURING THE ALICE SPRINGS OROGENY

While it is clear that the Alice Springs Orogeny had a significant impact on the evolution of a number of intracratonic basins in Australia, significant tectonism is restricted to the Arunta Inlier, in particular the southeastern part of the inlier. In the following section we briefly review radiometric data from the Arunta Inlier relevant to the Alice Springs Orogeny in the context of the biostratigraphically constrained synorogenic sequences in the surrounding basins.

In the Arunta Inlier the Alice Springs Orogeny caused widespread reactivation of shear zones (Shaw & Black 1991; Hand *et al.* 1999a), producing a thick-skinned bivergent

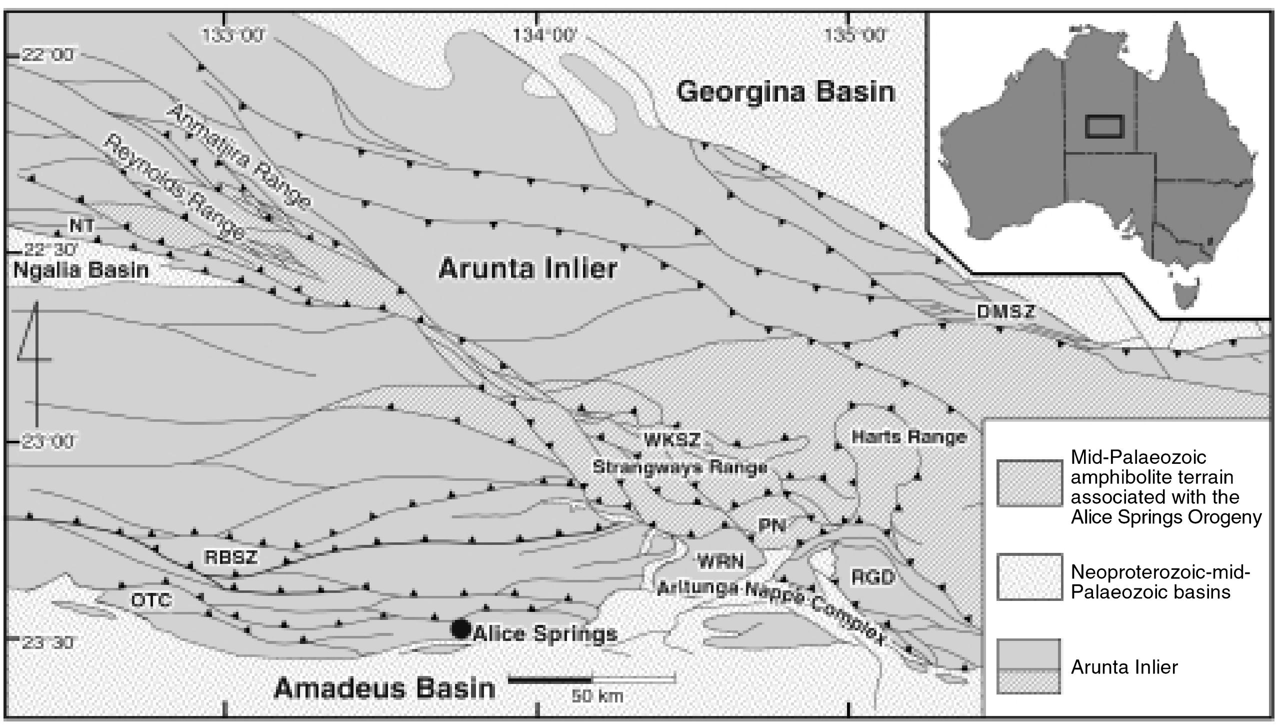

Figure 5 Generalised structural map of the eastern Alice Springs Orogen showing the distribution of Early to mid-Palaeozoic amphibolite facies metamorphism and shear zones interpreted to have been active during the Alice Springs Orogeny. RBSZ, Redbank Shear Zone; DMSZ, Delny–Mt Sainthill Shear Zone; WKSZ, Wallaby Knob Shear Zone; NT, Napperby Thrust; PN, Paradise Nappes; RGD, Ruby Gap Duplex; OTC, Ormiston Thrust Complex; WRN, White Range Nappe.

thrust system (Figure 5) that shed sediment northward into the Georgina and Wiso Basins and southward into the Amadeus Basin. Total shortening across the Arunta Inlier was in the order of 60–125 km (Dunlap *et al.* 1995; Flöttmann & Hand 1999) and resulted in the development of dramatic gravity gradients (Mathur 1976) associated with some of the largest amplitude (~150 mgal) gravity anomalies known from continental interiors. In the Amadeus Basin, shortening was accommodated via a system of 'Jura-style' forward and backthrusts and associated folds with detachments located in evaporite-bearing Neoproterozoic and Cambrian units.

Figure 4 is a compilation of available radiometric data from the eastern and central Arunta Inlier. While the data show a clear clustering of Devonian to Carboniferous ages, their interpretation in the context of the basinal record is hampered to some extent by the lack of distinction between inferred deformational and cooling ages. Figure 6 shows the geographical spread of selected radiometric data and the distribution of amphibolite facies (500–600°C; 500–700 MPa) metamorphism inferred to be associated with the Alice Springs Orogeny. Although the data are still somewhat sparse given the size of the Arunta Inlier, it is clear that the radiometric ages are relatively young within the high-grade Palaeozoic core of the Arunta Alice Springs Orogen, suggesting that significant exhumation occurred during the terminal stages of orogenesis. In Figure 6 we also distinguish inferred deformational ages from inferred cooling ages. Deformational ages are identified on the basis that: (i) the closure temperature of the applied thermochronometer is greater than the temperature at which the sampled structural fabric apparently formed; and (ii) the microstructural relationships are clear. While these criteria greatly reduce the amount of data that can be effectively used, they do allow some useful comparisons to be made between the structural and metamorphic record in the exhumed Arunta Inlier and the stratigraphic record in the surrounding basins.

Late Ordovician deformation

The earliest convergent structures that can be plausibly linked to the Alice Springs Orogeny occur in the Harts Range region of the eastern Arunta Inlier, in which regional-scale, reverse-sense shear zones reworked structures associated with Early Ordovician extension (Hand *et al.* 1999b; Mawby *et al.* 1999). Sm–Nd garnet (Mawby *et al.* 1999) and U–Pb monazite (Scrimgeour & Raith 2001) data give Late Ordovician (450–445 Ma) ages from major (≥500 m thick) upper amphibolite (≥650°C, 600 MPa) mylonite zones. In addition, Möller *et al.* (1991) reported U–Pb evidence for zircon growth at 443 ± 6 Ma in the Strangways Metamorphic Complex. Deformation was partitioned into south-directed thrusting (Mawby *et al.* 1999) and sinistral strike-slip movement (Scrimgeour & Raith 2001). The deformation apparently led to basin inversion and disruption of the seaway (Larapintine Seaway), which had previously linked the eastern and western margins of Australia, in part via these two basins. Starting at approximately 450 Ma, this inversion resulted in the deposition of the Carmichael Sandstone (Amadeus Basin) and the Ethabuka Sandstone (Georgina Basin)

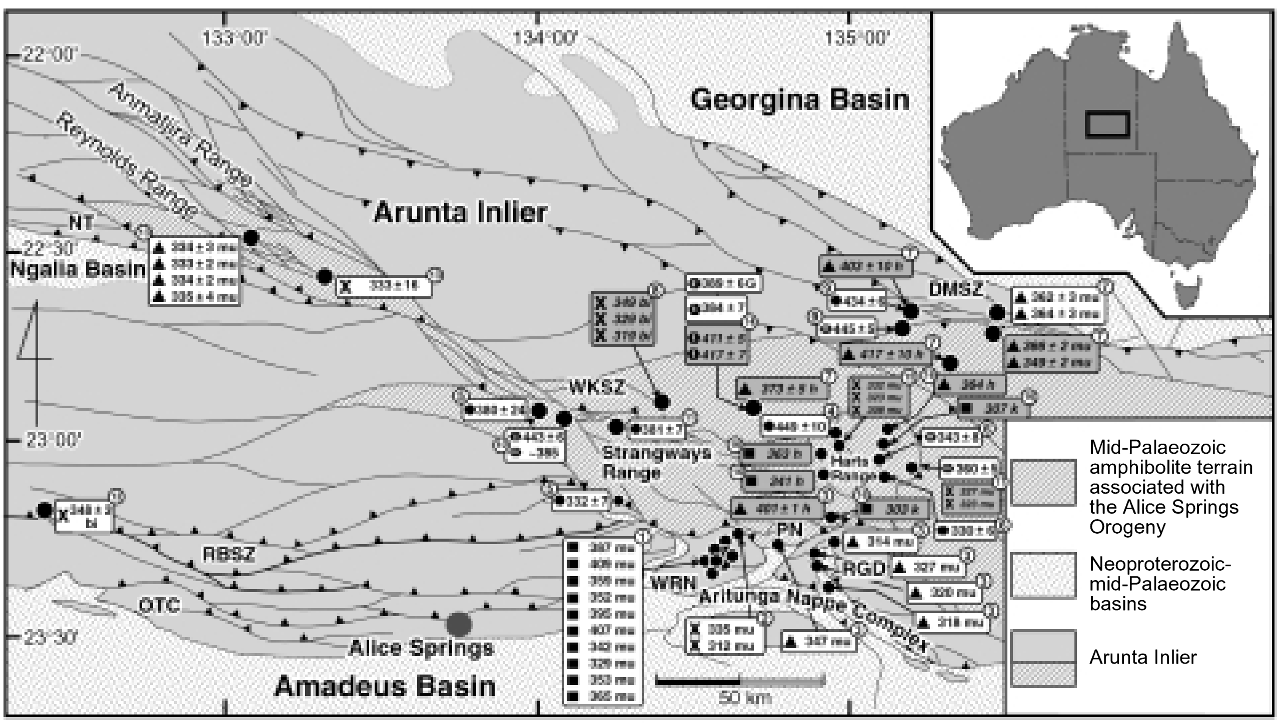

Figure 6 Geographical distribution of metamorphic age data in the Arunta Inlier. No-fill boxes indicate interpreted deformational ages; grey-filled boxes indicate interpreted cooling ages. Abbreviations of structural zones are the same as Figure 5. Symbols indicating the isotopic system employed for each data point are the same as Figure 4. Data sources: 1, Stewart (1971); 2, Armstrong and Stewart (1975); 3, Dunlap *et al.* (1995); 4, Mawby *et al.* (1999); 5, Bendall *et al.* (1998); 6, Hand *et al.* (1999b); 7, Scrimgeour *et al.* (2001); 8, Black and Gulson (1978); 9, Scrimgeour and Raith (2001); 10, Möller *et al.* (1999); 11, Ballèvre (2000); 12, Shaw and Black (1991); 13, Cartwright *et al.* (1999); 14, Buick *et al.* (2001); 15, Mortimer *et al.* (1987); 16, Mawby *et al.* (1998); 17, Cooper *et al.* (1988).

(Figure 7). A similar phase of deposition may be present in the Ngalia (Djagamara Formation) and eastern Officer Basins (Blue Hills Sandstone, Cartu and Mintabie beds). In the central Amadeus Basin, the Carmichael Sandstone conformably overlies marine sediments belonging to the mid-Ordovician Stokes Siltstone. However, to the northeast this contact becomes increasingly discordant with progressively greater loss of section. This tectonic influence in the northeast Amadeus Basin, termed the Rodingan Movement (Wells *et al.* 1970), heralds the beginning of Palaeozoic convergent deformation in central Australia.

Silurian deformation

At present, the existence of Silurian-aged deformation in the Arunta Inlier is not well demonstrated. A garnet Sm–Nd age of 434 ± 6 Ma (straddling the Ordovician–Silurian boundary) has been obtained from amphibolite-grade shears along the Delny–Mt Sainthill Shear Zone (Scrimgeour & Raith 2001) (Figure 6). Silurian cooling ages have been reported from the northern Harts Range area and further northeast (Buick *et al.* 2001; Scrimgeour *et al.* 2001) (Figure 4), implying that exhumation was occurring at least locally at this time. The Silurian interval in the Amadeus Basin is most probably spanned by the deposition of the Mereenie Sandstone (Li *et al.* 1991), the accumulation of which has been interpreted to reflect a period of tectonic stability (Jones 1991; Nicoll *et al.* 1991; Shaw *et al.* 1992). However, the thinning and disappearance of the Mereenie Sandstone over an unconformity towards the northeast Amadeus Basin (Wells *et al.* 1970; Young *et al.* 1987), suggests that the Mereenie Sandstone was synchronous with some basement uplift, possibly reflecting the continued development of the depositional system initiated in the Late Ordovician. The Mereenie depositional system does not appear to be present elsewhere, with the possible exception of the Ngalia and eastern Officer Basins.

Devonian deformation

In the Amadeus, Georgina and Wiso Basins, the Alice Springs Orogeny is most obviously expressed by the

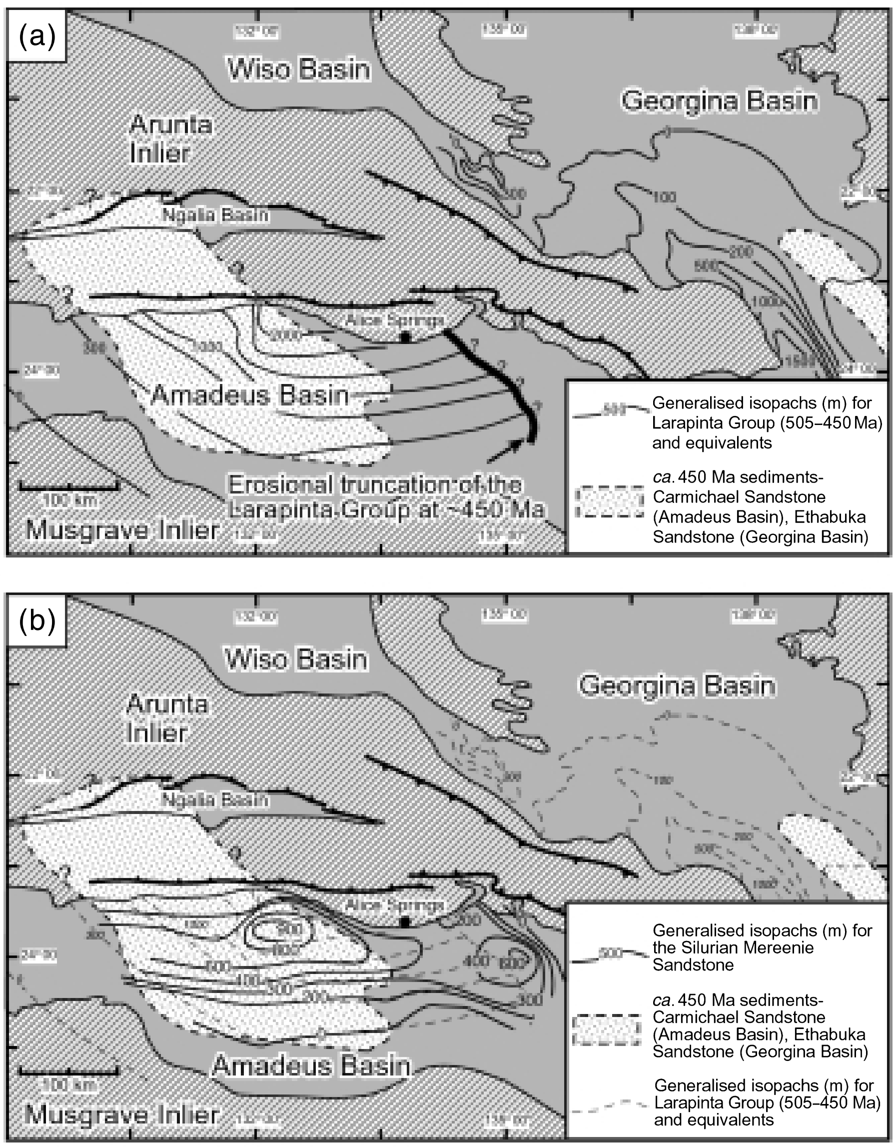

Figure 7 (a) Change in sedimentation pattern in the mid-Ordovician marked by the deposition of the Carmichael Sandstone (Amadeus Basin) and Ethabuka Sandstone (Georgina Basin) in northwest-trending depocentres that parallel the major system of northwest-trending structures (see Figure 6) that were active during the Alice Springs Orogeny. The Cambro-Ordovician Larapinta Group was deposited in a slowly subsiding marine basin that was inverted at approximately 450 Ma. The inversion was associated with deposition of clastic sediment in part derived from erosion of the Larapinta Group in the northeast Amadeus Basin (Nicoll *et al.* 1991). In the Amadeus Basin the Carmichael Sandstone is up to 15 m thick whereas in the Georgina Basin, the Ethabuka Sandstone is >1400 m thick, indicating rapid deposition in the mid-Ordovician, and marking a major change from the very slow sedimentation rates through the Early to mid-Ordovician. (b) Distribution of the Mereenie Sandstone (modified from Wells *et al.* 1970; Lindsay 1993). This probable Silurian-aged unit occupies an east-trending trough that was bounded by an elevated region in the northeast Amadeus Basin.

deposition of extensive synorogenic sequences in troughs that developed along the margins of the Arunta Inlier (Figure 1). Although there is little direct evidence of the distribution of Devonian deformation throughout the Arunta Inlier in general, the broad distribution of Devonian synorogenic sediments in central Australia implies the existence of a regionally extensive orogenic belt. Therefore, it seems likely that many of the shear zones shown in Figure 4 were active during the Devonian.

In the eastern Arunta Inlier, Early Devonian tectonism produced locally derived granites at approximately 390 Ma (Buick *et al.* 2001) and mid-upper amphibolite grade metamorphism. On a macroscopic scale the Devonian deformation system produced a bivergent orogenic belt, with north- and south-directed deformation producing forelands on both sides of the orogen (Figure 1). On the northern side of the orogen the major active shear zones were the Delny–Mt Sainthill Shear Zone, which juxtaposed Ordovician granulites against essentially unmetamorphosed sediments belonging to the Georgina Basin (Scrimgeour *et al.* 2001). On the southern side of the orogen south-directed Early – Middle Devonian thrusting, principally along the Ormiston Thrust Zone and associated faults in the footwall of the Redbank Shear Zone (Flöttmann & Hand 1999) formed the Macdonnell Homocline, and led to progressive titling of successive synorogenic sequences in the Pertnjara Group (Jones 1991).

Shear zones along the northern margin of the Strangways Metamorphic Complex (Strangways Range region) that link with the Delny–Mt Sainthill Shear Zone accommodated sinistral transpressional deformation with a northeast-directed vertical component, resulting in partial exhumation of the amphibolite-grade 'core' of the Arunta Alice Springs Orogen (Bendall *et al.* 1998; Ballèvre *et al.* 2000). Mineral-reaction textures in shear zones in the Strangways Metamorphic Complex indicate that exhumation of the amphibolite-grade central zone began at or before 380 Ma (Bendall *et al.* 1998; Ballèvre *et al.* 2000).

In a review of existing thermochronological data, Dunlap and Teyssier (1995) concluded that the southeastern part of the Arunta Inlier, in the vicinity of the Paradise Nappes (Figure 5), cooled through 500°C at approximately 400 Ma and continued to cool through 350°C at approximately 350 Ma, implying regional average cooling rates during the Devonian in the order of $3°C/10^6$ y. Given the existence of active Devonian shear zones and the voluminous Devonian synorogenic sediment, it seems likely that the Devonian cooling history of the southeast Arunta Inlier was strongly influenced by exhumation assisted by deformation along major shear zones.

Carboniferous deformation

Despite the rarity of Carboniferous synorogenic sediments in central Australia, the isotopic record from the Arunta Inlier indicates widespread deformation and cooling during the Carboniferous associated with exhumation of large regions of the mid-crust. Deformation was principally centred along the northwest–southeast-trending southern margin of the amphibolite-grade core of the orogen (Figure 5). In contrast to Devonian deformation, Carboniferous deformation appears to have been principally south-directed, with local 'pop-up' style domains (e.g. Anmatjira Range: Figure 5) bounded by steeply dipping structures indicating a sinistral transpressional regime.

In the Reynolds–Anmatjira Ranges region in the central Arunta Inlier, along the southern margin of the Strangways Metamorphic Complex (Figure 5), and in the Harts Range Metamorphic Complex, amphibolite-grade (500–600°C, 450–600 MPa) shear zones were active at approximately 340–320 Ma (Bendall *et al.* 1998; Cartwright *et al.* 1999; Hand *et al.* 1999b). In the northern Ngalia Basin, the Late Devonian to mid-Late Carboniferous Mt Eclipse Sandstone was derived from thrust-generated relief in the region that includes Reynolds–Anmatjira Ranges. Given the loss of at least 2 km of section from uppermost Mt Eclipse Sandstone (Wells & Moss 1983) and folding during the Early Permian Waite Creek Movement (Bradshaw & Evans 1988) it seems probable that shear zones in the Reynolds–Anmatjira region were active until at least 295 Ma.

Rb–Sr and $^{40}Ar–^{39}Ar$ ages from greenschist-grade mylonites associated with south-directed thrusting in the White Range Nappe and the Ruby Gap Duplex in the Arltunga Nappe Complex also yield Middle to Late Carboniferous deformational ages (Armstrong & Stewart 1975; Dunlap *et al.* 1995). The Arltunga Nappe Complex accommodated ≥80 km of shortening during the Carboniferous (Kirschner & Teyssier 1992; Dunlap *et al.* 1995). Given the presence of pervasive Carboniferous deformation in the Harts Range Metamorphic Complex (Hand *et al.* 1999b), the total Carboniferous shortening in the eastern Alice Springs Orogen must have been in excess of 90 km, thus representing a significant fraction of the total estimated shortening associated with the Alice Springs Orogeny.

Regional cooling of the southeast Arunta Inlier to <250°C had occurred by *ca* 290 Ma with the suggestion of rapid cooling through 300°C at *ca* 300 Ma (Dunlap *et al.* 1995; Mawby *et al.* 1998). Further west, south-directed reactivation of Devonian-aged thrusts in the Ormiston Nappe Complex resulted in rapid cooling from around 300°C to <110°C over the interval 320–300 Ma (Shaw *et al.* 1992).

DISCUSSION AND CONCLUSIONS

Orogenies can be dated both internally and externally and the two methods may not yield identical results. Internally, synorogenic metamorphic and intrusive rocks, and fault and shear zones may be dated using a variety of isotopic systems. The significance placed on any such date will depend on the method used, as the closure temperatures of different systems vary widely. Externally, synorogenic sediments eroded from orogenic topography and deposited in the foreland may be dated by a variety of means, most typically by biostratigraphic methods. As sedimentation is very sensitive to changes in topography, such studies offer the best chance for pinning down the time of initiation of orogenic uplift or identifying discrete phases of reactivation. However, synorogenic sediments may be later eroded and the chance of preservation decreases for sediments related to late stages of the orogeny. In contrast, isotopic systems will record less of the prograde phase of the orogeny unless samples are somehow removed from the system (e.g. as clasts). Any material that underwent isotopic closure during the earliest stages of the orogeny has probably been exhumed and removed by erosion. Thus, isotopes potentially provide details of the timing of peak thermal activity and a history of later exhumation and cooling. As argued by Haines and Flöttmann (1998), combining information from both sources should provide a more complete picture of the timing and duration of orogenic events.

The sedimentary record from central Australia suggests that the earliest phase of uplift, presumably related to convergent activity, dates from the Late Ordovician (*ca* 450 Ma). This is marked by the sudden incoming of the immature deltaic Carmichael Sandstone in the central and western Amadeus Basin and erosion in the northeast. Simultaneously the thick Ethabuka Sandstone began to accumulate in the Toko Syncline to the northeast of the eastern Arunta Inlier. Although not as well age constrained, it is suggested here that this event is also recorded by the Blue Hills Sandstone, Cartu and Mintabie beds of the Eastern Officer Basin and possibly the Djagamara Formation of the Ngalia Basin. All of these units seem to be at least marginally or locally marine (deltaic) and are notably less mature than the sandstone units below. This is the last evidence of marine sedimentation in the central Australian basins. The Silurian to Early Devonian is marked by a significant break in the record in most areas, indicating that the region was at this time above sea-level. The sedimentary record is apparently restricted to the Amadeus Basin, where the Mereenie Sandstone accumulated in very arid and predominantly aeolian conditions. For accumulation of such a thick non-marine sequence, ongoing tectonic control of accommodation space is required. The widespread lack of coarse detritus may be a reflection of the very dry climate, as much as an indicator of lack of significant tectonic relief.

The main phase of widespread syntectonic deposition appears to start synchronously in most basins in the late Early Devonian, at least in areas where there is reasonable biostratigraphic control. Initial deposits are sandstone and mudstone of fluvial and lacustrine origin. The start of this phase coincides with the widespread *Wuttagoonaspis* fossil assemblage and occurred at approximately 400 Ma. The start of the sedimentary pulse coincides well with the first uplift and cooling event recognised in the southeast Arunta Inlier (Dunlap & Teyssier 1995; Dunlap *et al.* 1995). However, an alternate argument could be made that it simply represents a climatic shift to a wetter regime, as required by the presence of freshwater lakes. The Devonian syntectonic package tends to coarsen upwards (except for the Finke Group), particularly in the Amadeus and Ngalia Basins in which it culminates in thick fan-deposited conglomerates, suggesting a peak in the rate of exhumation in the latest Devonian. This is also the time of the first phase of transcurrent movement in the Ord and Bonaparte Basins. The top of this sedimentary package also appears to be fairly synchronous between most basins, being of latest Devonian age (*ca* 355 Ma), although this is less well constrained than the base because of the sparsity of good palaeontological data. This coincides well with the beginning of the second inferred phase of accelerated uplift in the southeast Arunta Inlier (Dunlap & Teyssier 1995; Dunlap *et al.* 1995).

The biggest incongruence between the sedimentological and the isotopic data is the lack of any known Carboniferous sediments in the Amadeus Basin. In fact, the only known Carboniferous sediments anywhere in central Australia are represented by the upper Mt Eclipse Sandstone of the Ngalia Basin, although a major phase of transcurrent activity is apparently recorded by the

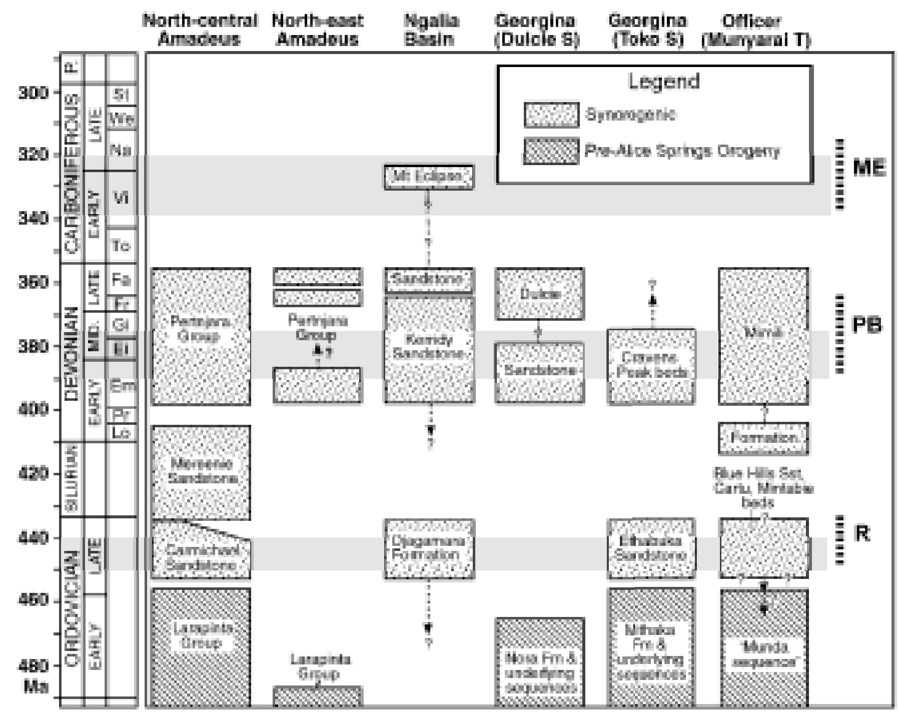

Figure 8 Comparison between stratigraphically constrained 'movements' (Shaw *et al.* 1992) and prograde metamorphic and deformational ages from the Arunta Inlier (grey bands). R, Rodingan Movement; PB, Pertnjara–Brewer Movements; ME, Mt Eclipse Movement. Age data are from Ballèvre (2000); Bendall *et al.* (1998); Mawby *et al.* (1999); Scrimgeour and Raith (2001); Möller *et al.* (1999). Fm, formation; Sst, sandstone; S, syncline; T, trough.

Carboniferous sediments of the Bonaparte Basin. It should be noted, however, that the palynological age for the upper Brewer Conglomerate was obtained from the north-central Amadeus Basin and no independent evidence of age is available for the eastern Amadeus Basin adjacent to the region from which Carboniferous cooling ages have been obtained. It is possible that the Brewer Conglomerate extends into the Carboniferous in this area. The spatial limitation of isotopic studies must also be remembered. The lack of isotopic data from basement-involved areas other than the southern and central Arunta Inlier makes it unclear if Carboniferous exhumation and sedimentation should be expected in other areas. It is possible that the Alice Springs Orogeny was most regionally extensive during the Devonian, but deformation became more locally focused during the Carboniferous.

That some younger sediment has been subsequently eroded in most areas is supported by fission track studies in the central-northern part of the Amadeus Basin, which suggest that a phase of rapid cooling occurred around 280–260 Ma (Permian), presumably related to erosive removal of overlying sediments (Tingate *et al.* 1986). However, the total section removed at this time appears to be no greater than approximately 2 km (Tingate 1991). This implies that the bulk of sediment sourced from regional Carboniferous denudation of the Arunta Inlier was not accommodated in the immediately surrounding basins. Thus, by Carboniferous times any foreland depressions must have been essentially full, with an efficient sediment bypass system, most likely directing detritus towards basins in eastern and/or Western Australia.

A number of previous workers (Shaw *et al.* 1992) have suggested that the Alice Springs Orogeny contained several phases, referred to as 'movements'. The timing of the movements was based on stratigraphic evidence. Figure 8 shows the relationship between stratigraphically constrained movements and inferred ages of deformation within the deeper parts of the orogen. Although the radiometric data are still comparatively sparse, they reveal a general correspondence between intervals of deformation and associated metamorphism, and the timing of deformation from stratigraphic criteria. This review supports the notion that deformation rates were not constant during the overall duration of the Alice Springs Orogeny, with the fastest inferred relative bulk strain rates during the Carboniferous.

With regard to the duration of the Alice Springs Orogeny, the sedimentological record suggests that convergence-related uplift occurred episodically from the Late Ordovician to the Late Devonian–Carboniferous. This agrees reasonably well with isotopically recorded events, which extend orogenic uplift through most of the Carboniferous. We see little reason to set an arbitrary beginning to the Alice Springs Orogeny within a protracted period of convergence, and in this review we adopt a broad definition of the Alice Springs Orogeny similar to that used by Forman *et al.* (1967) and Bradshaw and Evans (1988), but extend the definition spatially well beyond the Arunta Inlier and immediate surrounds. As such we include all Palaeozoic convergent and associated transcurrent deformation across central to northern Australia that post-dates the inferred Early Ordovician extensional episode (Hand *et al.* 1999a, b). In some areas the recognition of orogenic activity is solely from the presence of proximal syntectonic style sedimentation of appropriate age.

The prolonged duration of the Alice Springs Orogen (~150 million years), together with the relatively limited total shortening (60–125 km in the central Australian region) implies time-integrated shortening rates of <1 mm/y. This is several orders of magnitude slower than typical rates of convergence across plate-margin orogens, and may have impacted on the long-term thermal and mechanical evolution of the orogenic system (Sandiford *et al.* 2001). In particular, at such low rates, the thermal structure of the orogenic system will respond to the evolving redistribution of thermal properties at the lithospheric scale, with deep levels of denudation leading to long-term cooling and progressive strengthening of the orogen. In detail, the combined sedimentological and isotopic records point to a marked episodicity in the tectonic activity over the interval 450–300 Ma, with activity peaking apparently in the periods 450–440 Ma, 390–375 Ma and 340–320 Ma (Figure 8). It is not yet clear to what extent this temporal variation is reflected in spatial variations, although the available biostratigraphic evidence for restricted Carboniferous sedimentation in the Ngalia Basin, suggests that deformation was markedly heterogeneous in space as well as time. Future studies focusing on the temporal and spatial distribution of deformation in central Australia have the potential to yield important insights into the feedback between surface processes and tectonic activity in continental interiors.

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