[AMERICAN JOURNAL OF SCIENCE, VOL. 290-A, 1990, P. 295–332]

WORKING HYPOTHESES FOR THE ORIGIN OF THE WONOKA CANYONS (NEOPROTEROZOIC), SOUTH AUSTRALIA

NICHOLAS CHRISTIE-BLICK,* C. C. von der BORCH,** and P. A. DiBONA***

ABSTRACT. **Recent attempts to apply concepts of sequence stratigraphy to the Neoproterozoic[1] Wilpena Group of the Adelaide "geosyncline" in South Australia have provided an important new method for improving the resolution of intrabasinal correlation in sparsely fossiliferous and unfossiliferous strata. Eight regional unconformities are now recognized within or bounding the Wilpena Group. The most prominent of these, at or near the base of the Wonoka Formation, is expressed by a series of spectacular incised valleys or canyons, some more than 1 km deep and dated as approx 630 to 580 Ma. The canyons developed following an interval of continental rifting that took place between about 800 and 700 Ma and prior to a second phase of accelerated subsidence of uncertain origin in Early Cambrian time (after about 560 Ma). Subsidence during the intervening span of more than 140 my was in part of thermal origin and in part due to the withdrawal of buried salt at depth, but it may also have involved additional extension for which little direct structural evidence is preserved. The canyons are incised into a succession of shallow marine mainly terrigenous strata that accumulated in a broad north- and east-facing ramp. They are exposed in two distinct belts within and east of the Flinders Ranges, in an area that is about 275 km in a north-south direction and about 175 km east-west. The canyons are inferred to have been filled by shallow marine sediments primarily on the basis of sedimentary structures interpreted as combined-flow and oscillation ripples and hummocky cross-stratification. If this is correct, development of the canyons was related to regional lowering of depositional base level by more than 1 km. Recent work also indicates a second phase of valley incision at an unconformity immediately above the main canyons and involving a relative sealevel fall of at least 200 m.**

Two working hypotheses are advanced to account for the origin of the Wonoka canyons: regional uplift and an evaporitic lowering of sealevel in an isolated basin, analogous to the Messinian event in the Mediterranean. Any regional uplift would likely have been of tectonic origin. Diapirism associated with buried salt cannot account for the wide distribution of erosion or for pronounced uplift in an extensional setting lacking evidence for basin inversion or compressional deformation coeval with sedimentation. One possible mechanism for

* Department of Geological Sciences and Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

** School of Earth Sciences, The Flinders University of South Australia, Bedford Park, South Australia 5042, Australia

*** Western Australia Centre for Petroleum Exploration, Department of Geology, Curtin University, GPO Box U 1987, Perth, Western Australia 6001, Australia

[1] The subdivision of the Proterozoic into Paleoproterozoic, Mesoproterozoic, and Neoproterozoic for intervals delimited by ages of 2500, 1600, and 1000 Ma and the base of the Cambrian (approx 560 Ma; Benus, 1988) is from Cowie, Ziegler, and Remane (1989).

tectonic uplift involves inhomogeneous extension of the lithosphere, with the amount of extension balanced at all levels on a regional scale possibly by means of detachment faults. Possible difficulties with this hypothesis are the requirement of relatively uniform uplift over distances of hundreds of kilometers and the fact that repeated large-scale lowering of base level implies oscillatory vertical motions that are not readily explained. An evaporitic drawdown accounts for the wide distribution and scale of the canyons and for repeated lowering of base level. Possible difficulties in this case are the presence within the canyon fill of facies that have been interpreted to be of tidal origin; the fact that unlike the Messinian crisis in the Mediterranean, the Wonoka canyons do not appear to have been drowned rapidly; and the lack of direct evidence for evaporities of appropriate age. Neither hypothesis accounts for the apparent absence of appreciable meteoric diagenesis in areas far removed from sites of canyon incision.

Two additional conclusions are as follows. First, neither of the hypotheses precludes eustasy as an important control on sedimentation. Sequence stratigraphic comparisons with other basins of the same general age should focus primarily on the time of formation of sequence boundaries not on the geometry of the boundaries or the facies involved. Second, a drawdown in excess of 1 km implies that the adjacent basin was originally at least this deep and hence likely underlain at least locally by highly attenuated continental crust or oceanic crust. Either hypothesis therefore has important implications for the tectonic development of the Adelaide geosyncline.

INTRODUCTION

It is now widely recognized that sediments and sedimentary rocks are divisible at a variety of scales into relatively conformable successions bounded by unconformities and their correlative conformities, units that are generally termed depositional sequences (Sloss, 1963, 1988; Vail and others, 1977; Vail, Hardenbol, and Todd, 1984; Berg and Woolverton, 1985; Vail, 1987; van Wagoner and others, 1987, 1988; Christie-Blick, Grotzinger, and von der Borch, 1988; James and Leckie, 1988). Like most depositional surfaces, sequence boundaries may pass laterally through changes in facies and in places may be subtle or even cryptic where similar facies are superposed or the hiatus is small. Sequence boundaries do not necessarily correspond with conventional lithostratigraphic contacts and are commonly present even where the boundaries of lithostratigraphic units appear to be gradational or interfingering.

Most sequence boundaries have time-stratigraphic significance because with few exceptions (Christie-Blick, Mountain, and Miller, 1990) strata overlying an unconformity in a given sedimentary basin are everywhere younger than strata underlying it, at the resolution of available dating methods. Although the duration of a hiatus may vary laterally, few unconformities are themselves diachronous. Some sequence boundaries appear to persist from one basin to another and perhaps even globally, and this has led to the idea that some or even most such boundaries are of eustatic origin (Vail and others, 1977; Vail, Hardenbol, and Todd, 1984; Haq, Hardenbol, and Vail, 1987, 1988). However, the relative roles of eustasy, tectonics, sediment supply, climate, and oceanographic conditions in the development of unconformity-bounded sequences have yet to be worked out satisfactorily. Insufficient data are available to evaluate the synchroneity of most unconformities at a global scale (Miall, 1986; Christie-Blick, Mountain, and Miller, 1988, 1990; Gradstein and others, 1988; Matthews, 1988), and serious questions remain about precisely how and at what timescales patterns of sedimentation respond to variations in any of the principal controls (Posamentier, Jervey, and Vail, 1988; Cross, 1989; Christie-Blick, Mountain, and Miller, 1990; Jordan and Flemings, 1990).

Recent attempts, mainly in North America and Australia, to apply concepts of sequence stratigraphy to rocks of Proterozoic and earliest Phanerozoic age (Christie-Blick and Levy, 1985, 1989; Lindsay, 1987, 1989; Link and others, 1987; Christie-Blick, Grotzinger, and von der Borch, 1988; von der Borch, Christie-Blick, and Grady, 1988; von der Borch and others, 1989; DiBona, ms; Grotzinger and others, 1989; Lindsay and Korsch, 1989; Mount, 1989; DiBona, von der Borch, and Christie-Blick, 1990; Harris and Eriksson, 1990) have provided an independent and potentially important new method for improving the resolution of intrabasinal correlation in sparsely fossiliferous and unfossiliferous strata. The lateral persistence of some Paleoproterozoic sequence boundaries between basins of different origin (Grotzinger and others, 1989) and widespread occurrence of continental glaciation during Neoproterozoic time (Hambrey and Harland, 1981, 1985) suggest that some of the boundaries are of eustatic origin and hence of global extent, but as in the younger strata, it is generally difficult to determine the origin of specific unconformities.

The purpose of this article is to focus on the origin of a single sequence boundary at or near the base of Wonoka Formation (Neoproterozoic) in the Adelaide geosyncline of South Australia (figs. 1-3; table 1). The boundary is expressed by a series of spectacular incised valleys or canyons, some more than 1 km deep. These were initially interpreted by Thomson (1969a), by von der Borch, Smit, and Grady (1982), and by von der Borch and others (1985) as submarine canyons, cut and filled in a relatively deep marine setting, perhaps analogous to the Neogene canyons of modern continental margins. Recent papers by Eickhoff, von der Borch, and Grady (1988) and by von der Borch and others (1989) describe features of the sedimentary fill that cast doubt on this interpretation, specifically the presence of sedimentary structures such as combined-flow and oscillation ripples and hummocky cross-stratification, structures that have been taken to imply sedimentation above storm wave base. If correctly interpreted, these structures pose a problem because they seem to require base-level changes that are implausibly large for a simple eustatic control, and the postulation of large-scale regional uplift is inconsistent with the prevailing view of the tectonic

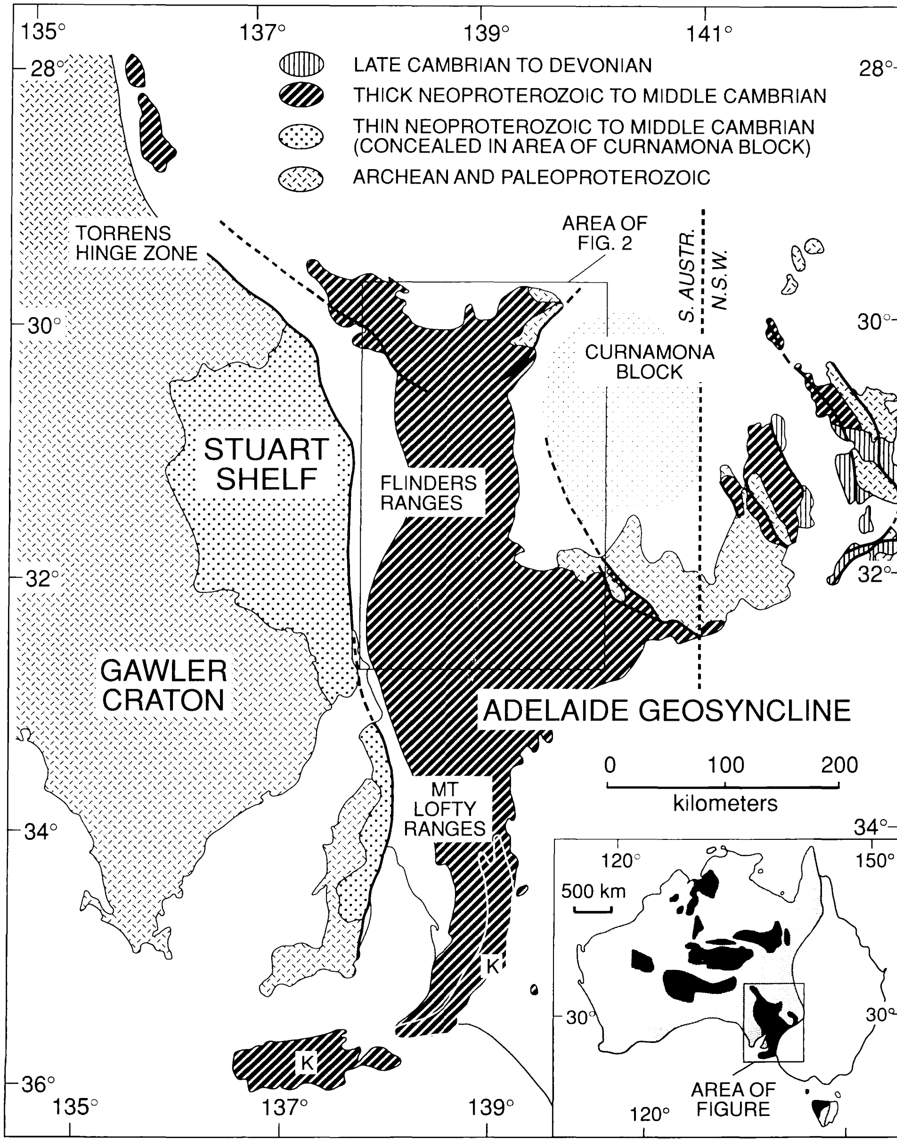


Fig. 1. Location map of the Adelaide geosyncline (from Priess, 1987). K, area of outcrop of the Kanmantoo Group (Early to Middle Cambrian). Bold lines indicate selected prominent faults. The inset (modified from Preiss and Forbes, 1981) shows the distribution in Australia of Archean to mid-Proterozoic crust (shaded) and of basins with appreciable thicknesses of Neoproterozoic sedimentary rocks (black). The final assembly of this crustal block appears to overlap in time with the development of the Adelaide geosyncline (Myers, 1990; P. F. Hoffman, personal commun., 1990).

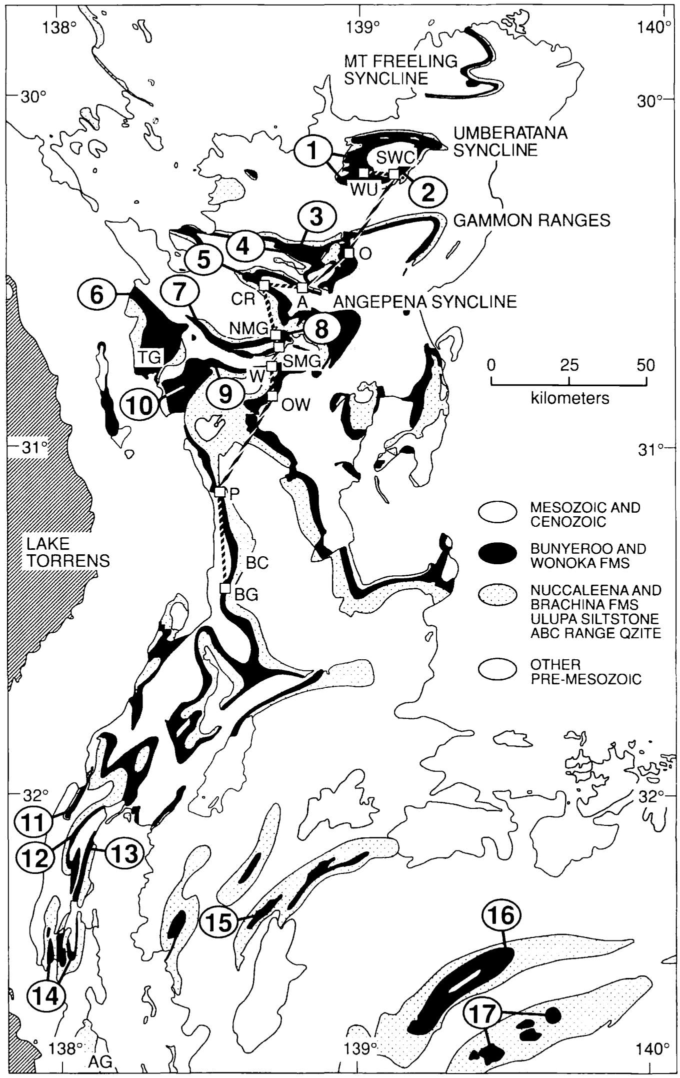


Fig. 2. Map showing outcrops of the lower part of the Wilpena Group (Nuccaleena Formation to Wonoka Formation), together with the location of surface exposures of the Wonoka canyons and other localities mentioned in the text (modified from Dalgarno and Johnson, 1966; Binks, 1968; Coats, 1973; and Preiss, 1986). The location of the map area within the Adelaide geosyncline is indicated in figure 1. Canyon exposures (modified from Haines, ms): 1, Fortress Hill canyon complex; 2, shallow incised valley north of "Umberatana" station; 3, Oodapanicken canyon; 4, Depot Springs canyon; 5, Patsy Springs Canyon; 6, Nankabunyana canyon; 7, Salt Creek canyon; 8, Mocatoona canyon; 9, Puttapa canyon; 10, Beltana canyon; 11, shallow incised valley west of Buckaringa Hill; 12, Buckaringa Gorge canyon; 13, Yarra Vale canyon; 14, Waukarie Creek canyon complex; 15, Pamatta Pass canyon complex; 16, possible canyon at the eastern end of Waroonee syncline; 17, Yunta canyon complex. Stratigraphic sections used to construct figure 4 (open squares): BG, Bunyeroo Gorge; P, Parachilna; OW, Old Warraweena; W., Warraweena; SMG, south Mount Goddard syncline; NMG, north Mount Goddard syncline; CR, Castle Rock; A, Angepena syncline; O, Owieandana; SWC, Salt Well Creek; WU, western Umberatana syncline. Other abbreviations: AG, Alligator Gorge; BC, Brachina Creek; TG, Trebilcock Gap.

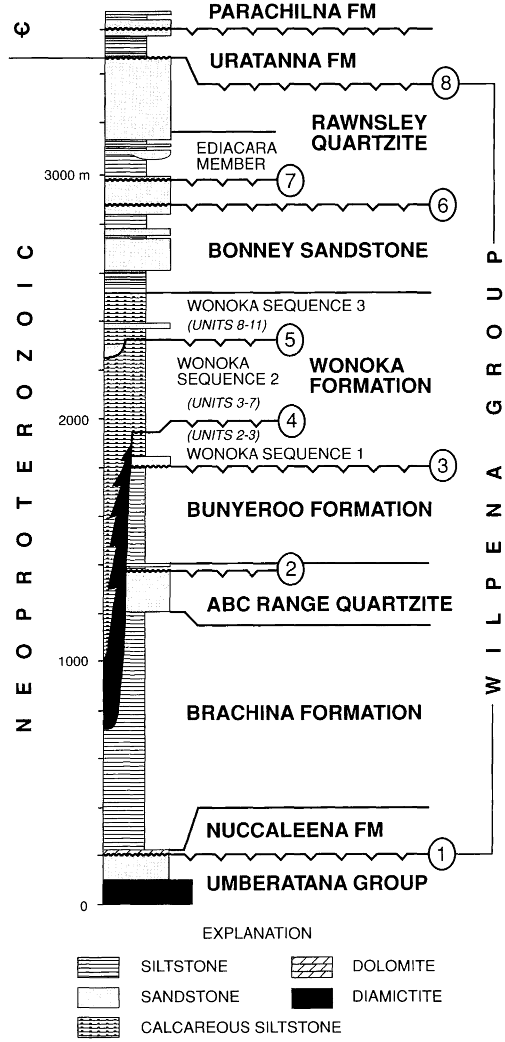
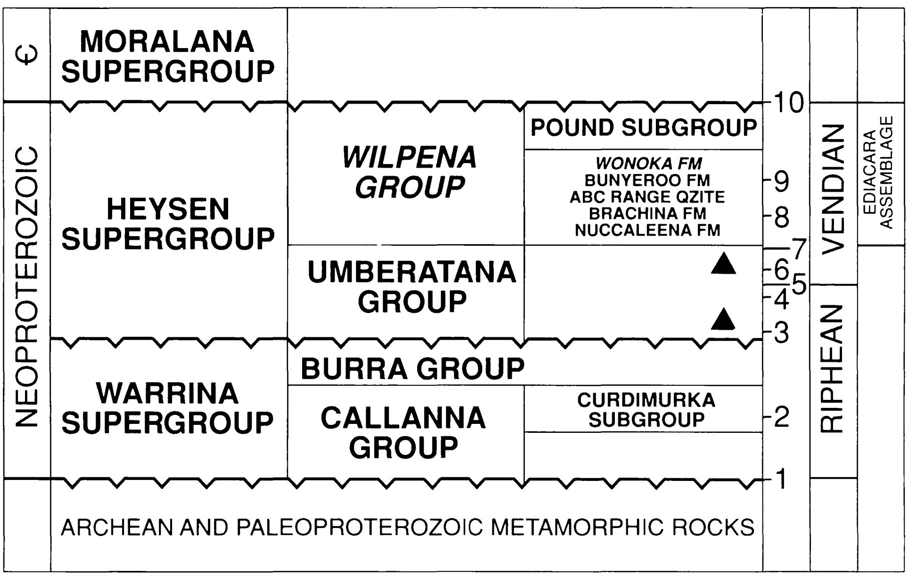


Fig. 3. Generalized stratigraphic section for the Wilpena Group of the central and northern Flinders Ranges. The locations of the main sequence boundaries (numbered) are modified from data and interpretations presented by Gehling (ms); Jenkins, Ford, and Gehling (1983), von der Borch, Christie-Blick, and Grady (1988); von der Borch and others (1989), DiBona (ms), Mount (1989), DiBona, von der Borch, and Christie-Blick (1990), and J. F. Mount (personal commun., 1989). The Wonoka canyons correspond with sequence boundary 4. Thicknesses shown are approximate.

TABLE 1

The stratigraphic position of the Wonoka Formation with respect to selected lithostratigraphic units of the Adelaide geosyncline and summary of available calibration. Triangles in the Umberatana Group indicate units of glacial origin. Specific horizons are as follows (summarized by Preiss, 1987): (1) 1424 ± 51 Ma, Rb-Sr on siltstone, Pandurra Formation, the oldest undeformed cover of the Stuart shelf (Fanning, Flint, and Preiss, 1983), and probably pre-Adelaidean (Rutland and others, 1981); 1200 to 1080 Ma, Rb-Sr, Beda volcanics of Stuart shelf, correlative with lower part of Callana Group or, more likely, pre-Adelaidean (Webb and others, 1983); (2) 802 ± 10 Ma, U-Pb on zircon, Rook Tuff (Fanning and others, 1986); (3) Sturtian glacial strata; (4) 750 ± 53 Ma, Rb-Sr on siltstone, Tapley Hill Formation (Webb and Coats, unpublished report, 1980); (5) Riphean-Vendian boundary, best located in the interval between the Brighton Limestone and the Wundowie Member of the Angepena Formation (Preiss, 1987); approx 700 to 680 Ma (Glaessner, 1984); (6) 724 ± 40 Ma, Rb-Sr on siltstone, Willochra Subgroup (Webb and Coats, unpublished report, 1980); 614 ± 98, Rb-Sr on siltstone, Angepena Formation (Webb, ms, 1980 and ms 1981); (7) Marinoan glacial strata; (8) 676 ± 240 Ma, Rb-Sr on siltstone, Woomera Shale Member, correlative with the Brachina Formation (Thomson, 1980); 601 ± 68 Ma, Rb-Sr on siltstone, Brachina Formation (Webb, ms, 1980 and ms, 1981); (9) 588 ± 35 Ma, Rb-Sr on siltstone, Yarloo Shale, correlative with the Bunyeroo Formation (Webb, unpublished report); (10) Proterozoic-Cambrian boundary approxi 560 Ma (Benus, 1988)



setting, that of a thermally subsiding basin related to lithospheric extension earlier in Neoproterozoic time (Preiss, 1987). Here we extend the work of Eickhoff, von der Borch, and Grady, (1988) and von der Borch and others (1989) by taking a broader perspective of the depositional setting of the Wonoka canyons, integrating an assortment of observations that must be accommodated by hypotheses for their origin (table 2). The interpretation of the canyons bears directly on the interpretation of all the sequence boundaries in the Adelaidean succession (von der Borch, Christie-Blick, and Grady, 1988; Mount, 1989; von der Borch and others, 1989) and is critical to the quest for unconformities of eustatic origin that might be useful in global correlation of Neoproterozoic rocks. The canyons also have special relevance to a volume dedicated to Preston Cloud because they are located stratigraphically within the type Ediacarian[2] of Cloud and Glaessner (1982), a remarkable interval in the history of life that has long fascinated biogeologists and for which evidence was first discovered in South Australia (Sprigg, 1947).

STRATIGRAPHIC AND TECTONIC SETTING

The Wonoka canyons are present in the upper part of a succession of Neoproterozoic and Cambrian age that is as much as 15 km thick (table 1; Preiss, 1983) and widely exposed in the Flinders and Mount Lofty Ranges of South Australia (fig. 1). The sedimentary basin containing these strata is commonly referred to as the Adelaide geosyncline (Mawson and Sprigg, 1950), a term that is retained here, although without genetic connotations. Today, the rocks crop out as a series of plunging folds, and individual stratigraphic units can be traced continuously through superb outcrop for many tens of kilometers along strike (fig. 2). The deformation is generally attributed to the Cambro-Ordovician Delamerian orogeny (Thomson, 1969b; Rutland and others, 1981; Clark and Powell, 1989), but in the absence of overlapping younger Paleozoic strata, the possible contribution of the younger deformational events is difficult to assess. Outliers in the northwestern part of the Flinders Ranges of Triassic and Jurassic beds with dips as great as 50° (Copley map area; Coats, 1973) suggest a more complex history than is generally assumed. The fold belt was uplifted during late Cenozoic time as a result of renewed lithospheric extension following the separation of Australia from Antarctica during mid-Cretaceous time (Rutland and others, 1981; Hegarty, Weissel, and Mutter, 1988).

Stratigraphy and Geochronology of the Adelaide Geosyncline

The stratigraphy of the Adelaide geosyncline has been divided into three major lithostratigraphic units bounded by regional unconformi-

[2] The canyons are also located near the base of the stratigraphically more restricted Ediacaran of Jenkins (1981). We concur with Preiss (1987) that while the longer stratigraphic range suggested by Cloud and Glaessner (1982) is probably closer to the true range of the Ediacara assemblage, the spelling "Ediacaran" is preferred for etymological reasons.

TABLE 2

Interpretations concerning the origin of the Wonoka canyons, with comments summarized from the text. Working hypotheses are indicated in bold italics

INTERPRETATION OF PALEO-WATER DEPTH OF CANYON FILL	EVIDENCE OR RATIONALE
1. Relatively deep	Limited evidence for subaerial exposure of canyon shoulders. Evidence for shallow-water deposition of canyon fill may not be diagnostic. Kilometer-scale base-level changes are unusually large.
2. ***Above storm-wave base***	Consistent with an association of structures interpreted as combined-flow and oscillation ripples and HCS

HYPOTHESES ASSUMING SHALLOW-MARINE CANYON FILL	COMMENTS
BASE-LEVEL CHANGES OVERESTIMATED	
1. Brachina Formation was tilted prior to canyon cutting	Canyon fill locally exceeds 1 km in thickness (not simply erosional relief in the Brachina)
2. Detached normal faults or distributed deformation within the Brachina Formation permits shallow-marine sediments to be lowered with respect to adjacent "wall rocks" (i.e., the "canyons" are deformational not erosional features)	Inconsistent with mapped relations at canyon walls
LARGE-SCALE UPLIFT	
1. Uplift related to salt diapirism	Inconsistent with the regional distribution of the canyons and the absence of basin inversion
2. Tectonic mechanisms	
a. Uplift related to compressional deformation	No independent evidence in basin
b. ***Regional uplift related to epeirogeny or inhomogeneous lithospheric extension***	Difficult to explain uniform uplift on a regional scale and large base-level changes at two closely spaced stratigraphic levels
LARGE-SCALE SEA-LEVEL FALL	
1. Eustasy	Eustasy alone cannot explain kilometer-scale changes in base level
2. ***Messinian-style sea-level change, in an isolated basin***	Accounts for wide distribution of canyons, for pronounced and repeated lowering of base level, and for the absence of evidence for shoaling in the underlying sequence. Difficulties are the presence locally of facies of possible tidal origin, absence of evidence for rapid drowning of the canyons, and absence of evidence for evaporites of appropriate age.

ties (table 1; Preiss, 1987). Beginning at the base these are (1) the Warrina Supergroup (Neoproterozoic), an assemblage of non-marine to shallow marine terrigenous, carbonate, and evaporitic sedimentary rocks and mafic volcanic rocks; (2) the Heysen Supergroup (also Neoproterozoic), an assemblage of predominantly shallow marine terrigenous and minor carbonate rocks, including diamictites of glacial origin, and exposed both within the Adelaide geosyncline and in thinner sections on adjacent platforms such as the Stuart "shelf" (fig. 1); and (3) the Moralana Supergroup, consisting of shallow and somewhat deeper marine carbonate and terrigenous rocks of Early to Middle Cambrian age. The term "Adelaidean" is used in Australia in a chronostratigraphic sense for the interval represented by the Proterozoic portion of the Adelaide geosyncline. The Wonoka canyons are located in the Wilpena Group, in the upper part of the Heysen Supergroup (table 1; fig. 3).

Basal Adelaidean strata overlie Archean and Paleoproterozoic crystalline rocks of the Gawler craton and on the Stuart shelf (fig. 1) may correlate with or post-date the Beda volcanics, dated as about 1200 to 1080 Ma (Rb-Sr; Webb and others, 1983; Preiss, 1987). The most reliable age determination near the base of the main part of the basin appears to be a concordant U-Pb date of 802 ± 10 Ma on zircon from the Rook Tuff in the Curdimurka Subgroup (horizon 2 in table 1; Fanning and others, 1986). Numerous Rb-Sr isochrons have been reported from sedimentary rocks within the upper part of the Adelaidean, most younger than 750 Ma (Tapley Hill Formation; horizon 4 in table 1), but with large uncertainties. Studies of stromatolites, oncolites, and catagraphs indicate a probable Late Riphean to Vendian age for the Warrina and Heysen supergroups (younger than about 1000-950 Ma), with the Riphean-Vendian boundary (about 700-680 Ma) most likely located within the upper part of the Umberatana Group and well below the Wonoka Formation (Preiss, 1987). Apart from the enigmatic trace fossil *Bunyerichnus* discovered near the middle of the Brachina Formation (fig. 3), Ediacara assemblage metazoan fossils are found exclusively in the Pound Subgroup (table 1; Jenkins, 1981; Cloud and Glaessner, 1982; Mount, 1989; Walter, Elphinstone, and Heys, 1989). The true range of this assemblage and particularly whether it includes or is entirely younger than the Wonoka canyons remains uncertain. Taken together, however, available isotopic dating and biostratigraphic evidence suggest that the canyons are younger than 700 Ma and most likely about 630 to 580 Ma.

Origin of the Adelaide Geosyncline

Stratigraphic evidence for rifting during deposition of the lower part of the Adelaidean succession is compelling (summarized here largely from Preiss, 1987). The Warrina Supergroup appears to have accumulated at least in part in restricted fault-bounded basins, a setting consistent with the presence of alkalic volcanic rocks and evaporites, now preserved largely as pseudomorphs within bodies of diapiric breccia. Rifting continued, probably episodically, through deposition of the lower part of the Umberatana Group (table 1), as indicated by pronounced stratigraphic thickening across growth faults and by the development of angular unconformities. In contrast, deposition of the upper part of the Umberatana Group (beginning with the Tapley Hill Formation; horizon 4 in table 1) and the overlying Wilpena Group was for the most part not influenced by basement-involved faulting, suggesting that subsidence during this interval was in part of thermal origin and in part due to salt withdrawal at depth (Lemon, 1985). In that these rocks represent nearly half the Proterozoic section (in excess of 5 km) and a time span of more than 140 my (that is, long in comparison with the thermal time constant for lithospheric cooling, about 60 my; Parsons and Sclater, 1977), we cannot exclude the possibility that at least some of the later Adelaidean subsidence was due to continued lithospheric extension. If this is the case, extension must have been distributed inhomogeneously within the crust and upper mantle, with minimal extension of the upper crust in the area of outcrop.

Permissive evidence for renewed rifting is present in rocks of Cambrian age. Neoproterozoic to Early Cambrian volcanic rocks are widespread in Australia, and preliminary attempts at analyzing the early Paleozoic tectonic subsidence of several intracratonic basins are consistent with an acceleration of thermally driven subsidence in Early Cambrian time, perhaps due to continental fragmentation and dispersal (Bond, Nickeson, and Kominz, 1984; Lindsay, Korsch, and Wilford, 1987; N. Christie-Blick, unpublished results presented at the Australian Geological Convention in 1986). Unfortunately, none of the sedimentary sections is thick enough for confident interpretation of the tectonic subsidence, and in the Adelaide geosyncline a significant portion of the observed Early and Middle Cambrian subsidence may be related to salt withdrawal and detached normal faulting (for example, in the northern part of Parachilna map area; Dalgarno and Johnson, 1966).

A relatively thick assemblage of clastic sedimentary rocks of Early to Middle Cambrian age (Kanmantoo Group) is exposed along the eastern and southern parts of the Mount Lofty Ranges and their westward continuation on Kangaroo Island (K in fig. 1; Gatehouse, 1988). In places these rocks are associated with mafic to intermediate-composition volcanic rocks (Truro volcanics; Forbes, Coats, and Daily, 1972), inviting the possibility of a rift origin (Thomson, 1969b). However, the true thickness and site of deposition of the Kanmatoo Group are uncertain because the rocks are strongly deformed and at the highest structural levels are metamorphosed to upper amphibolite facies (Clark and Powell, 1989). Furthermore, although the Truro volcanics are said to rest uncomformably on rocks as old as the Umberatana Group, the nature of this contact is obscured by poor outcrop, and the volcanic rocks may instead represent a tectonic slice of an oceanic arc emplaced during collision in Late Cambrian and Ordovician time with the passive continental margin. These complexities leave open the question as to whether the Adelaide geosyncline represents the development of a single continental margin either at 750 to 700 Ma (the stratigraphic level of the Tapley Hill Formation; horizon 4 in table 1; for example, Preiss, 1983, 1987) or in Early Cambrian time (for example, von der Borch, 1980; Lindsay, Korsch, and Wilford, 1987), or perhaps at both times. We do not know, therefore, whether the Wonoka Formation accumulated in a passive margin or intracratonic setting.

SEQUENCE STRATIGRAPHIC FRAMEWORK

The sequence boundary associated with the Wonoka canyon is one of eight regional unconformities now recognized within or bounding the Wilpena Group (fig. 3; updated from von der Borch, Christie-Blick, and Grady, 1988; Mount, 1989; von der Borch and others, 1989; DiBona, ms; and DiBona, von der Borch, and Christie-Blick, 1990). These are located as follows: (1) at the base of the Nuccaleena Formation, and perhaps in places within the underlying Umberatana Group; (2) at or near the top of the ABC Range Quartzite or the top of the Brachina Formation (Ulupa Siltstone), where the ABC Quartzite pinches out toward the north and east; (3) at the base of unit 2 of the Wonoka Formation (unit terminology from Haines, ms and 1988); (4) within unit 3 of the Wonoka Formation (the boundary associated with large-scale canyons, and which in places cuts downward almost to the level of the Nuccaleena Formation); (5) at or near the base of unit 8 of the Wonoka Formation; (6) at or near the base of the Rawnsley Quartzite; (7) at the base of the Ediacara Member of the Rawnsley Quartzite; and (8) at the base of the Uratanna Formation (for most of the Early Cambrian age, but with trace fossils of possible Vendian affinity near the base: J. F. Mount, personal commun., 1989). Of these boundaries, six are associated at least in places with erosional relief of tens to hundreds of meters. In the case of the other two (near the top of the ABC Range Quartzite and at the base of Wonoka unit 2), stratal discordance has not yet been observed, and the presence of a sequence boundary is inferred on the basis of regional facies discontinuities. Here we review briefly the sequence stratigraphy between the Nuccaleena Formation and unit 3 of the Wonoka Formation, to provide a framework for discussing the origin of the canyons. Further details will be published elsewhere. Sequence stratigraphic terminology is from van Wagoner and others (1987, 1988), as modified by Christie-Blick and Levy (1989) and Christie-Blick (1990).

Nuccaleena-Brachina-ABC Range Sequence

The Brachina Formation is composed of a thick succession of brown, grayish red, and olive-drab siltstone, with minor fine- to very fine-grained argillaceous sandstone especially in the upper part (Plummer, 1978 and ms). At least 1200 m is reported in the type section at Brachina Creek (BC in fig. 2; Dalgarno and Johnson, 1964). Sedimentary structures include even and wavy parallel to non-parallel laminae, current and combined-flow ripples, climbing ripples, interference and ladderback ripples, channels, gutter marks, groove marks, flute casts and load structures, deformed sandstone dikelets, and other evidence for soft sediment deformation. The abundance of particular structures varies both within any given section and from one section to another. The siltstone grades downward into the Nuccaleena Formation, a regionally persistent marker unit no more than a few meters thick, and composed of pink to buff-colored laminated dolomite unconformably to disconformably overlying various glacial strata of the Umberatana Group. Stromatolites, tepee structures, and intraclast breccias are present locally within the Nuccaleena (Plummer, 1978c; Williams, 1979). The Brachina Formation interfingers with the overlying ABC Range Quartzite, which is composed of grayish red to white, coarse- to very fine-grained quartzite, cyclically interstratified with very fine-grained sandstone and siltstone. Quartzite beds commonly contain fragments of siltstone, indicative of erosional contacts. The ABC Range Quartzite is about 70 m thick at a reference section near Bunyeroo Gorge (BG in fig. 2; Plummer, 1978 and ms), and thickens to over 2000 m in the vicinity of Alligator Gorge in the southwestern Flinders Ranges (AG in fig. 2; Plummer, 1978 and ms; Preiss, 1987). The unit becomes finer-grained and pinches out toward the north and east, presumably by interfingering with the underlying Brachina Formation (Plummer, 1978 and ms). Common sedimentary structures are cross-stratification in coarser-grained units, and current and combined-flow ripples, together with larger-scale structures resembling hummocky and swaley cross-stratification in finer-grained ones. Other structures include channels, reactivation surfaces, parting lineation, oscillation ripples, interference ripples, and desiccation cracks. Our limited measurements of paleocurrents in the ABC Range Quartzite confirm that they are typically dispersed to polymodal even within stratigraphic intervals of a few meters or less (Plummer, ms). In the northern part of the Flinders Ranges (Gammon Ranges and Umberatana syncline; fig. 2), paleocurrents in the Brachina Formation are directed approximately toward the north and more or less down the regional paleoslope suggested by regional facies relations with the ABC Range Quartzite.

Interpretation.—The Nuccaleena Formation and lowest part of the Brachina Formation are interpreted to represent a marine transgression across a nearly planar erosion surface developed on the top of the Umberatana Group (von der Borch, Christie-Blick, and Grady, 1988). The remainder of the Brachina Formation and the overlying ABC Range Quartzite represent overall shoaling of a broad terrigenous ramp (for the most part highstand systems tract of van Wagoner and others, 1987, 1988) from shallow subtidal/offshore to shoreface, intertidal, braid-delta and possibly fluvial environments (see Plummer, 1978 and ms). These environments appear to have formed a complex mosaic, subject to high-frequency cyclic variation. Even in the relatively distal northern part of the Adelaide geosyncline (Gammon Rangers; fig. 2), abundant combined-flow ripples through the section indicate that the water was probably never more than a few tens of meters deep. Dispersed and polymodal paleocurrents in the ABC Range Quartzite suggest strongly that the basin was tidally influenced and therefore connected with the open ocean. This observation is relevant to the overall paleogeographic interpretation of the Wilpena Group, including the Wonoka canyons, because one explanation for the canyons involves the partial desiccation of an isolated marine basin (von der Borch and others, 1989).

In many sections, the upper few meters of the ABC Range Quartzite consists of dark grayish red granule-bearing, cross-stratified sandstone and siltstone, overlain with either sharp or interfingering contact by distinctive reddish-brown siltstones of the Bunyeroo Formation. In most places, the lower contact of this upper unit of the ABC Range Quartzite is probably a sequence boundary amalgamated with a marine flooding surface (von der Borch, Christie-Blick, and Grady, 1988). However, recent work by N. Christie-Blick suggests that at Trebilcock Gap in the Mount Bayley Range (TG in fig. 2) the sequence boundary may be located about 15 m below the flooding surface, corresponding to abrupt coarsening of the quartzite (from very fine-grained to very coarse- to fine-grained) and to the development of erosion surfaces with tens of centimeters of relief.

Bunyeroo Sequence

The Bunyeroo Formation consists of reddish brown to bluish gray parallel-laminated to structureless siltstone. Thin beds of sandstone and conglomerate are present locally, especially in the vicinity of diapirs (Plummer, 1978a; von der Borch, Christie-Blick, and Grady, 1988), together with yellowish-brown concretionary dolomite at various horizons (Haines, ms; Eickhoff, von der Borch, and Grady, 1988; von der Borch, Christie-Blick, and Grady, 1988; DiBona, ms). A layer of meteorite-impact ejecta is present about 80 m above the base of the formation over much of the western part of the Flinders Ranges (Gostin and others, 1986). The contact with the overlying Wonoka Formation has been revised downward by Gostin and Jenkins (1983[3]) to beneath a regionally persistent interval of dolomitic beds, in places parallel-laminated or composed of intraclast breccia, and from a few meters to as little as few tens of centimeters thick (unit 1 of the Wonoka Formation; Haines, ms and 1988). These beds of dolomite are overlain abruptly by a distinctive unit of sandstone and siltstone (unit 2 of the Wonoka Formation, described below; fig. 3). The Bunyeroo Formation (restricted) is about 500 m thick at its type section at Brachina Creek (BC in fig. 2; Dalgarno and Johnson, 1964; Gostin and Jenkins, 1983) and thins irregularly toward the north (fig. 4; Priess, 1987; DiBona, ms).

[3] The arguments for changing the definition of the Bunyeroo-Wonoka contact are not universally accepted (Preiss, 1987), but here we follow the recommendation of Gostin and Jenkins (1983) on the grounds that the new boundary can be more precisely located in the field than the original one of Dalgarno and Johnson (1964).

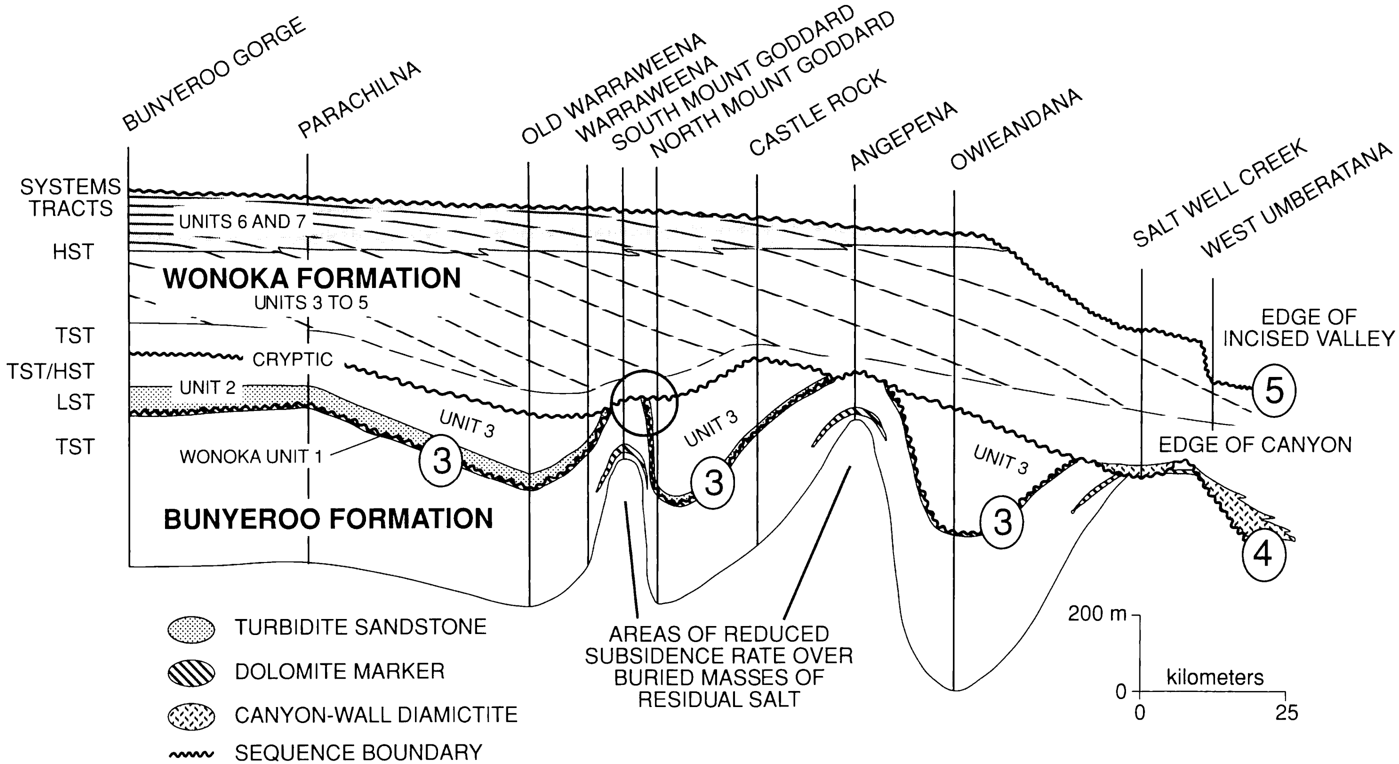


Fig. 4. Regional cross section of the Bunyeroo-Wonoka interval (modified from DiBona, ms). Stratigraphic sections used to construct the cross section are located in figure 2. Data for sections between the Bunyeroo Gorge and Mount Goddard syncline are from Haines (ms). Thicknesses for the Bunyeroo Formation are approximate. Clinoforms within Wonoka sequence 2 emphasize that lithostratigraphic units within Wonoka Formation are probably time-transgressive. The critical area of the Mount Goddard syncline shown in figure 5 is circled. Abbreviations for systems tracts: HST, highstand systems tract; TST, transgressive systems tract; LST, lowstand systems tract.

Interpretation.—The Bunyeroo Formation is thought to represent deposition in an offshore marine environment (transgressive systems tract) that unlike the Brachina Formation was sufficiently deep not to have been influenced significantly by surface waves even under storm conditions. Through most of the Flinders Ranges, little or no evidence for shoaling is present at the top of the formation, even in areas where the underlying sequence is dominated by considerable thicknesses of shallow marine to non-marine sedimentary rocks. Unit 1 of the Wonoka Formation is therefore interpreted as an interval of sediment starvation (marine hardground; Haines, ms and 1988; von der Borch, Christie-Blick, and Grady, 1988) corresponding to the upper part of the transgressive systems tract and perhaps all of the highstand systems tract, and a sequence boundary is placed at the very prominent facies discontinuity at the base of unit 2 of the Wonoka Formation (compare fig. 13 of von der Borch and others, 1989). The possibility that unit 1 might represent subaerial deposition (discussed by von der Borch and others, 1989) is now rejected on the basis of regional continuity and lack of evidence for subaerial exposure in either unit 1 or overlying unit 2.

Wonoka Sequence 1

Wonoka sequence 1 consists of several tens of meters of sandstone and siltstone (unit 2) that grade upward into as much as 200 m of grayish red siltstones and minor thin-bedded limestones, in part current deposited (most of unit 3 of Haines, ms and 1988, except in the northern Flinders Ranges; figs. 3 and 4). Sandstone beds of unit 2 are characterized by flute casts, minor normal grading, and well developed hummocky cross-stratification and combined-flow ripples in their upper portions. In several sections, the sandstones are arranged into an overall thickening-upward sequence overlain by a relatively thin thinning-upward sequence, and the unit as a whole thins to both the north (fig. 4) and east. Paleocurrents in unit 2 are directed toward the east and northeast (Haines, ms).

Interpretation.—Unit 2 is thought to have accumulated above storm wave-base in a shallow-marine ramp setting as a result of storm induced underflows (turbidites with hummocky cross-stratification). Systematic thickening-upward of sandstone beds indicates overall progradation during deposition of a lowstand systems tract. The uppermost part of unit 2 and part or all of unit 3 are interpreted as transgressive to highstand systems tract, with sedimentation for the most part below wave base. Perhaps surprisingly, no direct evidence is present in unit 3 for shoaling upward below the horizon corresponding to the canyon-cutting unconformity (sequence boundary 4 in fig. 4).

STRATIGRAPHIC RELATIONS AT MOUNT GODDARD SYNCLINE

In some areas of the northern Flinders Ranges, where unit 2 is absent (for example, southern limb of Mount Goddard syncline and northern limb of Angepena syncline, SMG and A in fig. 2: and along the northern limb of Kate Hill syncline, west of loc. 3 in fig. 2), the base of unit 3 is characterized by an unusual bed of cherty intraclastic and tepee dolomite, containing quartz pseudomorphs after anhydrite and discoidal gypsum (Haines, ms; DiBona, ms). The dolomite is overlain by thinly bedded limestone containing microbial laminae and is thought by us to have accumulated in an intertidal to supratidal environment. On the southern limb of Mount Goddard syncline, the tepee dolomite overlies the Bunyeroo Formation at an erosion surface, which passes laterally toward the east into a sandstone-filled valley more than a 1 km wide and 100 m deep, and permits the Wonoka Formation to rest directly on the upper part of the Brachina Formation (fig. 5: DiBona,

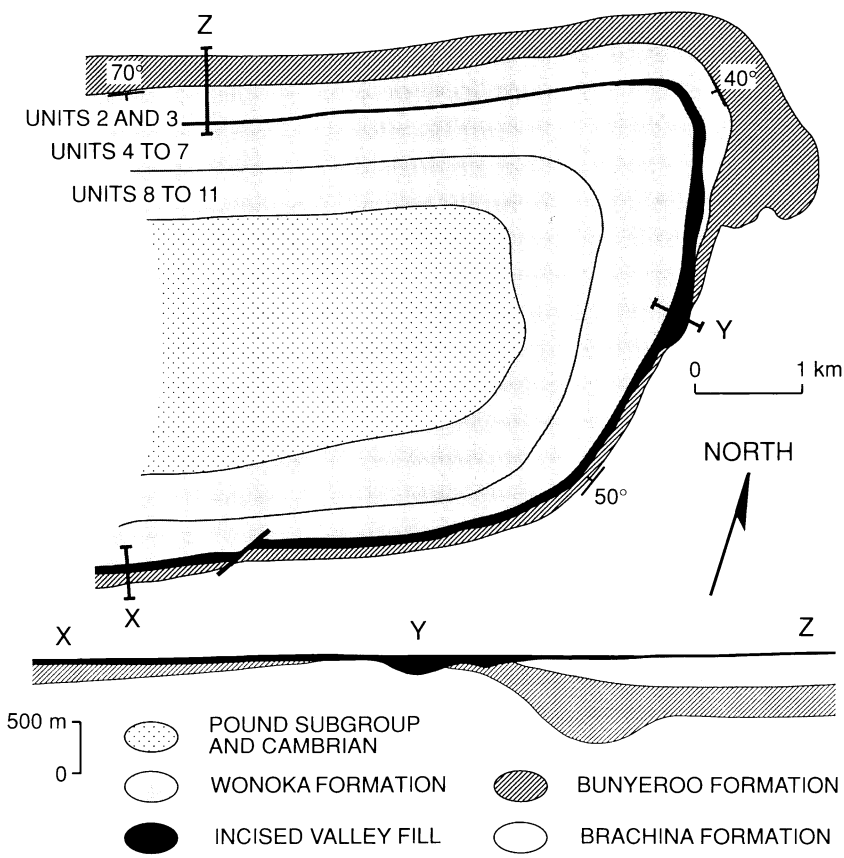


Fig. 5. Geological map and schematic cross section of the eastern part of the Mount Goddard syncline showing a prominent erosion surface within unit 3 of the Wonoka Formation.

1989). On the northern side of the valley, the erosion surface rises through the Bunyeroo Formation and units 1 to 3 of the Wonoka Formation to a horizon near the base of unit 4 of Haines (ms), demonstrating that the tepee dolomite overlies a subaerial erosion surface that on a regional scale is located stratigraphically within the Wonoka Formation, in places at the base of unit 3 of Haines (ms), in places within that unit, and in places near the top of it (compare fig. 13 of von der Borch and others, 1989). The erosion surface corresponds to the Wonoka canyons that form the subject of this paper (fig. 4). The observations at Mount Goddard syncline are important because they demonstrate that the shoulders of the Wonoka canyons were subaerially exposed at least locally even in the relatively distal northern Flinders Ranges. Where the canyons are absent in the more proximal central Flinders Ranges, we infer that a sequence boundary is present but cryptic in what initially appears to be a relatively conformable succession (Haines, ms).

Shallow-water facies appear to be preserved preferentially on the canyon shoulders in areas of reduced subsidence rate, perhaps due to the presence at depth of buried masses of residual salt (Warrina Supergroup; fig. 4). Evidence supporting this interpretation is provided by stratigraphic relations in the underlying Bunyeroo Formation. At Mount Goddard syncline and Angepena syncline, for example, the Bunyeroo Formation appears to be thinner than in adjacent areas (less than about 200 m), and in both places thin beds of orange-weathering ankeritic dolomite with microbial laminae, digitate stromatolites, and neptunian dikes are present in the lower part (DiBona, ms). These features are indicative of an intertidal to supratidal environment, a setting unusually shallow for the Bunyeroo Formation.

KEY ATTRIBUTES OF THE WONOKA CANYONS

Distribution and Geometry

Prominent incised valleys or canyons are present within or at the base of the Wonoka Formation at a number of localities in the northern Flinders Ranges and within and east of the southern Flinders Ranges, an area about 275 km in a north-south direction and about 175 km east-west (fig. 2). The best exposed and best studied examples are in the northern area: the Fortress Hill canyon complex (fig. 2, loc. 1; von der Borch and others, 1985; Eickhoff, von der Borch, and Grady, 1988) and Patsy Springs canyon (fig. 2, loc. 5; von der Borch, Smit, and Grady, 1982; von der Borch and others, 1989). These and the intervening Oodnapanicken canyon (fig. 2, loc. 3; Di Bona, ms) are also the deepest (in excess of 1 km of sedimentary fill; table 2) and the ones that erode to the deepest level within the underlying stratigraphy (almost to the Nuccaleena Formation; fig. 3). Other examples shown in figure 2 are discussed to varying degrees by Haines (ms). Regional geological mapping indicates that an erosional unconformity may be present at the same horizon over a still broader area (for example, in the Mount

Freeling syncline; fig. 2; Preiss, 1986), although not necessarily associated with the distinctive canyon-filling facies observed at the main localities. In addition to detailed studies at localities 1, 3, and 5 (fig. 2), one or more of the present authors have visited at least briefly each of the exposures in the northern area (loc. 2, 4, and 6 to 10), but with the exception of the outcrops west of Buckaringa Hill (loc. 11) and at Buckaringa Gorge (loc. 12), we have not examined the outcrops in the south (loc. 13 to 17).

The geographic separation of the two outcrops belts suggests they may be a part of two separate canyon systems: one feeding to the north and one feeding to the southeast (von der Borch and others, 1985; Haines, ms; Preiss, 1987; DiBona, ms). The northern canyons contain similar facies, and paleocurrents, while variable (fig. 6), are directed approximately in a northward direction, consistent with the paleogeography of the underlying Nuccaleena–Brachina–ABC Range sequence. The manner in which the present exposures are connected in three dimensions is uncertain, but paleocurrent evidence for a sinuous canyon system at locality 1 (fig. 6; von der Borch and others, 1985; Eickhoff and others, 1988) suggests that a relatively small number of distinct canyons (or their feeders) is represented. The orientation of the southern canyon system has not yet been worked out and is assumed from the distribution of outcrops (Preiss, 1987).

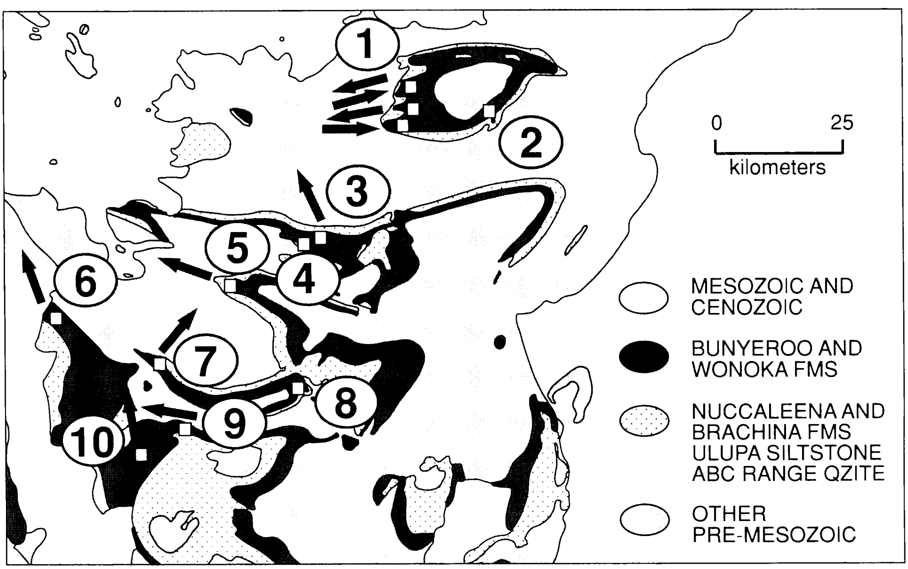


Fig. 6. Summary of overall sediment transport directions from paleocurrents in the Wonoka canyons of the northern Flinders Ranges (open squares; modified from Haines, ms) Outcrop patterns enlarged from figure 2.

Few direct measurements are available of the gradients of the canyon walls. Cross sections by Eickhoff, von der Borch, and Grady (1988) and DiBona (ms) and work in progress by N. Christie-Blick suggest that primary dips were typically a few degrees and locally as large as 30°. Markedly steeper slopes (near vertical) inferred in a restored cross section published by von der Borch, Smit, and Grady (1982) for the Pasty Springs canyon (fig. 2, loc. 5) are exaggerated because they do not take into account the effects during folding of layer-parallel slip and flow, deformation that was locally quite pronounced in fine-grained sedimentary rocks of the tightly folded Angepena syncline.

Wall Rocks

Wall rocks of the Wonoka canyons consist of various stratigraphic levels within the Brachina Formation (Ulupa Siltstone), ABC Range Quartzite (mostly very thin in the northern Flinders Ranges), Bunyeroo Formation, and, at least locally, parts of the lowermost Wonoka Formation. These rocks are thought to have been largely consolidated at the time of the canyon incision because relatively steep slopes were maintained at least locally, and because undeformed angular clasts of Brachina Formation are preserved in siltstone-clast diamictite within the canyon fill. The wall rocks were not necessarily lithified, however, because in places the Brachina Formation displays abundant evidence for soft sediment deformation and locally grades laterally over a distance of several tens of meters into diamictite deposited in the adjacent canyon (compare Eickhoff, von der Borch, and Grady, 1988).

With the exception of such gradational contact relations, the boundary between the canyon fill and the wall rocks is typically sharp and is inferred to be erosional with small-scale relief of as much as several meters. Key evidence for this interpretation is found in the Fortress Hill canyon complex in the axial region of the Umberatana syncline (fig. 2, loc. 1), where the rocks were little affected by Phanerozoic deformation. Here, the Brachina Formation dips gently toward the east and strikes at a high angle to the contact with the Wonoka Formation. Mapping in this area at 1:10,000 scale demonstrates that the contact is neither a fault nor the result of large-scale loading into unconsolidated sediment, the type of syn-sedimentary deformation that has characterized the Neogene development of the passive continental margin along the northern Gulf of Mexico (table 2).

Canyon Fill (Wonoka Sequence 2)

The Wonoka canyons are filled by a variety of depositional facies, described in considerable detail by von der Borch, Smit, and Grady (1982), von der Borch and others (1985, 1989), and Eickhoff, von der Borch, and Grady (1988) and only briefly summarized here. In the northern Flinders Ranges, the main components are a laminated carbonate veneer, best preserved on canyon shoulders; siltstone-clast diamictite, deformed masses of stratified sandstone and siltstone (olistostromes), and carbonate-clast conglomerate and breccia, deposited for the most part at the bottoms of canyons and adjacent to the walls; and various siltstones and sandstones, mostly fine- to very fine-grained, and which account for the bulk of the canyon fill. The carbonate veneer is composed of gray micritic to microsparry limestone and dolomite a few tens of centimeters thick, commonly with diffuse planar laminae, and locally containing possible stromatolites, tepee structures, and soft-sediment folds. The carbonate rocks tend to pinch out down the canyon walls and are present as abundant clasts in conglomerate and breccia. The diamictite facies is composed for the most part of fragments of siltstone as large as several meters in diameter and derived mainly from Brachina Formation and to a lesser extent from the Bunyeroo Formation. The diamictite is typically disorganized but in places contains stratified conglomerate, sandstone, and siltstone. The conglomerate and breccia facies consists of rounded to angular clasts of limestone and dolomite a few centimeters to as much as several meters across, together with clasts of quartzite and sandstone in a sandy to silty matrix. The rocks are disorganized to relatively well-stratified and locally cross-stratified, with sharp locally erosional lower contacts and sharp upper contacts. Sandstones and siltstones intertongue with the coarser-grained facies and range from relatively massive or diffusely stratified to well-stratified tabular to broadly channelized beds. Few beds contain systematic variations in grain size, although some are normally graded. Sedimentary structures include scours, flute casts, load structures and other evidence for soft sediment deformation, parallel to wavy laminae, low-angle cross-laminae, parting lineation, current and combined-flow ripples, climbing ripples, and rare hummocky cross-stratification, swaley cross-stratification, large-scale trough cross-stratification, and oscillation ripples. Examples of structures interpreted as combined-flow ripples and hummocky cross-stratification are illustrated in figure 7.

INTERPRETATION

Evidence for Shallow-Water Deposition

The shallow-water interpretation of the canyon fill is based primarily on the presence of sedimentary structures thought to indicate sedimentation above storm wave base, particularly combined-flow and oscillation ripples, and rare hummocky cross-stratification (HCS) with hummocks as much as 1 m in diameter (fig. 7A; table 2). HCS is present at several horizons including the lowest stratigraphic levels of each of the main canyon exposures (fig. 2, loc. 1,3, and 5; Eickhoff, von der Borch, and Grady, 1988; DiBona, ms; von der Borch and others, 1989). The interpretation of HCS is controversial in detail, but the present consensus is that it results primarily from some combination of undirectional and oscillatory flow above storm wave base (Dott and Bourgeois, 1982; Walker, Duke, and Leckie, 1983; Allen, 1985; Duke and Leckie, 1986; Nøttvedt and Kreisa, 1987; Southard and others, 1990).

A.

B.

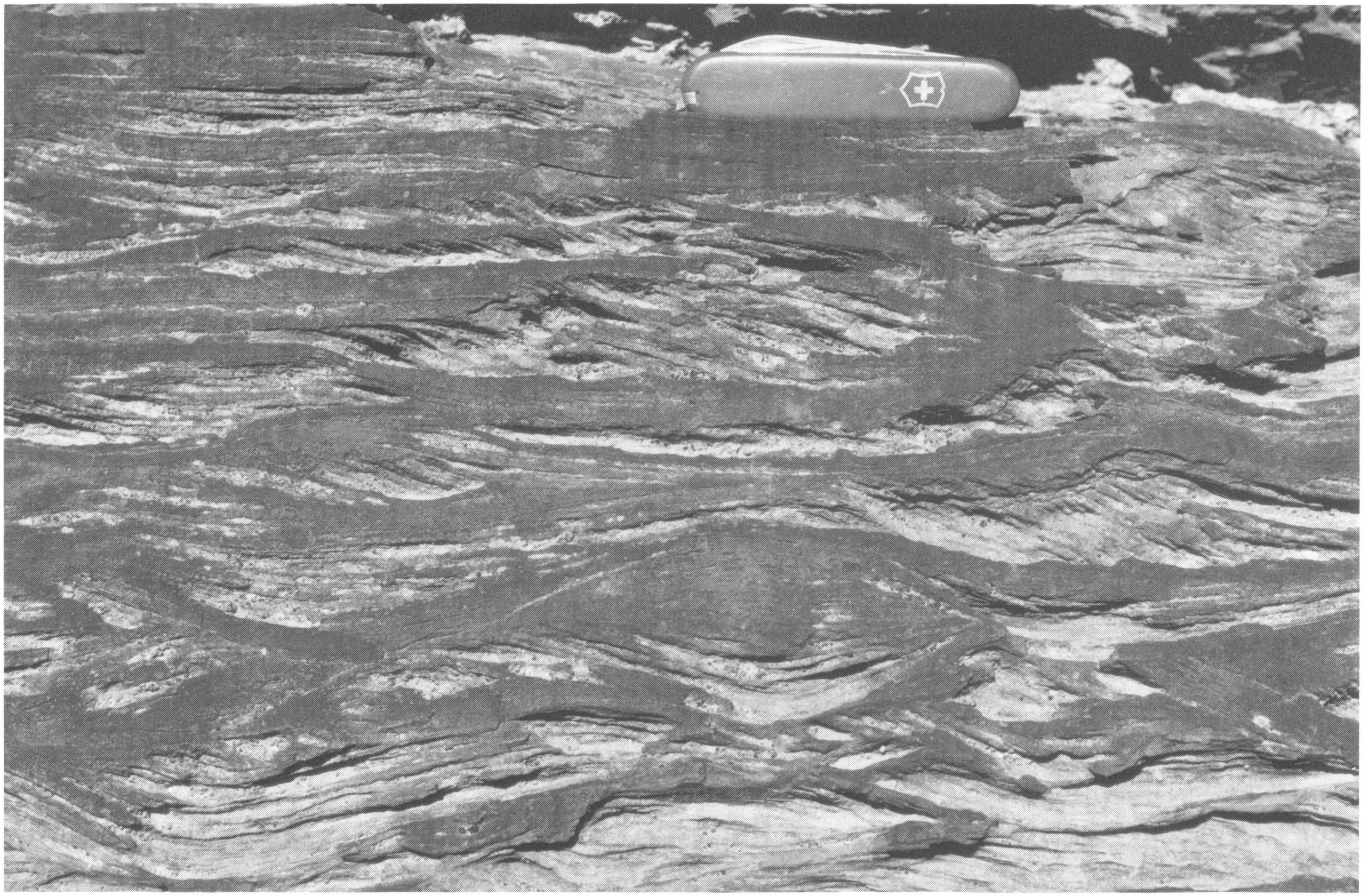


Fig. 7. Examples of hummocky cross-stratification (A) and combined-flow ripples (B) from the lower part of the Fortress Hill canyon complex.

Small-scale structures interpreted to represent a combination of unidirectional flow and oscillatory motion are present widely at all stratigraphic levels in the Wonoka canyons. In cross section, they display complex bundling of laminae and cross-stratal offshoots that pass through troughs to the flanks of adjacent ripples, features typical of wave-influenced sedimentation (fig. 7B; de Raaf, Boersma, and van Gelder, 1977; Reineck and Singh, 1980). Although cross-laminae typically indicate a strongly preferred direction of flow, in plan view these ripples are characterized by relatively symmetrical three-dimensional hummocks and swales with spacings of 8 to 14 cm and amplitudes of as great as 2 cm. Similar structures have been described by Prave (1985) and Prave and Duke (1990) from deep-water turbidites of the Behobie Formation (Late Cretaceous) in the western Pyrenees and interpreted by him as having been deposited from antidunes. Bundled laminae and low-relief scours and drapes are observed also in outer- to mid-fan turbidites of the Chalky Mount succession (Cenozoic) of Barbados, where they are ascribed by Larue and Speed (1983) and Larue and Provine (1988) to pulsating flows or to the influence of entrained organic matter on flow behavior. However, these interpretations appear to be inappropriate for the Wonoka Formation, in which combined-flow ripples are in some cases associated with relatively linear symmetrical ripples, some with flat, truncated tops or bifurcating geometry in plan view, features that are commonly produced by wave activity in shallow water. Moreover, combined-flow ripples are present in the Wonoka Formation not only in discrete sandstone beds but as thin veneers at the tops of conglomerate units, where they are most likely due to winnowing. Structures resembling those in the Wonoka Formation are found also throughout the underlying Brachina Formation and ABC Range Quartzite, units in which they are associated with numerous other shallow-water indicators (see above), and it seems implausible that similar structures in the Wonoka Formation have a markedly different origin.

We acknowledge that few of the sedimentary structures observed in the canyon fill are by themselves unequivocally diagnostic of a shallow marine depositional environment. In our view, it is the convergence of evidence toward this interpretation that is most persuasive. Indeed little doubt would exist were it not for the rather startling implications of this conclusion for large-scale changes in depositional base level.

Possible Evidence for Tidal Activity

An unusual facies locally developed between 200 and 400 m above the base of the Patsy Springs canyon (fig. 2, loc. 5) consists of intervals of sandstone-mudstone couplets arranged into thinning- and fining-upward sequences 8 to 10 cm thick, with approx 28 couplets per sequence. These cyclic sediments have been interpreted by von der Borch and others (1989) as indicative of some form of tidal influence, although the manner in which the cyclicity developed has not yet been determined. Rare examples of possible tidal bundles have also been noted about 130 m above the base of the canyon at the same locality. If correctly interpreted, these observations are potentially important to the interpretation of the canyons because quite apart from what they might indicate about water depth they may imply a connection between the sedimentary basin and the open ocean at the time the canyons were being filled.

Summary of Facies Interpretation

The carbonate veneer of the canyon shoulders is interpreted as a subaerial tufa, disrupted by downslope-sliding and flow during continued subaerial incision of the canyons. The diamictites, conglomerates, and breccias are thought to represent a variety of sliding and sediment gravity flow processes, with stratification and cross-stratification related to winnowing and redeposition of sediment by currents. The presence of combined-flow ripples on top of conglomerate beds indicates that much of the coarse-grained sediment accumulated in shallow water during flooding of the canyons (transgressive systems tract). Sandstone beds characterized by well-developed flute casts, parting lineation, and climbing ripples represent episodic turbulent underflows. It is not clear whether these underflows were induced during times of high sediment input (floods), by slumping or by storms. Nor is it yet clear whether beds displaying combined-flow ripples represent single events or are composite. Siltstone is thought to have accumulated in part from bottom flows and in part as background sediment from suspension.

Timing of Canyon Incision

The sequence boundary corresponding to the Wonoka canyons is located on a regional scale between the top of unit 2 of the Wonoka Formation and the base of unit 4, subdivisions defined on the basis of lithic criteria and not necessarily having time-stratigraphic significance. Owing to the depth of incision and the fact that the canyons cut across at least two other sequence boundaries, it is difficult to eliminate the possibility that the erosion took place during two or more discrete events. However, the presence low in the canyon fill at the Fortress Hill and Patsy Springs localities (fig. 2, loc. 1 and 5) of distinctive clasts of siltstone and dolomite from the Bunyeroo Formation suggests that if they existed, the canyons were virtually empty at the end of Bunyeroo deposition.

Von der Borch and others (1989) suggested that erosion may have taken place mainly during the development of the boundary at the top of the Bunyeroo sequence, a boundary that according to the interpretation presented was subsequently modified by lateral and headward erosion of the canyon walls. This view stems primarily from the existence of an abrupt regional facies discontinuity at the base of unit 2 of the Wonoka Formation, but it poses difficulties with respect to the time of deposition of unit 2. If unit 2 accumulated after partial filling of the canyons, its absence within the canyon fill at those localities where it is also present in the canyon walls (fig. 2, loc. 6, 7, 9 and 10) is puzzling. If unit 2 was deposited before appreciable amounts of sediment had accumulated in the canyons, either the canyons were cut by mass-wasting below sealevel (not the preferred interpretation) or sealevel needs to have fallen twice, first to cut the canyons subaerially and then to permit shallow marine sedimentation after the deposition of unit 2.

For these reasons, we now favor the idea that canyon cutting was associated primarily with the development of the uppermost sequence boundary (within unit 3 of the Wonoka Formation). At localities away from the canyons, the sequence boundary is subtle or cryptic and not associated with prominent upward-shoaling in underlying strata of unit 3. This may indicate a relatively rapid lowering of depositional base level, although this possibility is difficult to evaluate quantitatively.

Origin of Canyon Sinuosity

The sinuosity of the Fortress Hill canyon complex (fig. 2, loc. 1) is best explained as inherited from a fluvial system that developed during formation of the sequence boundary (Eickhoff, von der Borch and Grady, 1988). The rivers would at least initially have been of low gradient (ramp setting), and the fine grain size of much of the Wonoka Formation and underlying stratigraphic units suggests that the sediment load would have been relatively fine-grained. Indeed, the existence of pronounced sinuosity constitutes supportive evidence for subaerial erosion because where submarine canyons intersect modern continental shelves they tend to be both relatively straight and rather shallow in comparison with the Wonoka canyons (Farre and others, 1983).

Localization of the Wonoka Canyons in Synclines

Several of the canyon exposures in the northern Flinders Ranges are in the axial regions of synclines (loc. 1, 5, and 8 in fig. 2). Only one, Beltana canyon (fig. 2, loc. 10), crops out within an anticline. This may be a function of the present level of exposure, but an idea worth pursuing is that fold geometry may have been influenced by the distribution of evaporites at depth. We know that deposition of the Wonoka Formation was accompanied by diapirism, and it is therefore possible that canyons were localized in areas of salt withdrawal. Drainage patterns during development of the sequence boundary would have been influenced even by subtle topography. For this reason, among others detailed below, the idea that canyon incision was localized preferentially in areas of salt-induced uplift seems unlikely (compare Eickhoff, von der Borch, and Grady, 1988, von der Borch and others, 1989).

INCISED VALLEYS AT THE BASE OF WONOKA SEQUENCE 3

In the vicinity of the Fortress Hill canyon complex (fig. 2, loc. 1, 5, and 8), the base of Wonoka sequence 3 (equivalent to unit 8 of Haines, ms) is characterized by a series of incised valleys with more than 200 m of erosional relief (fig. 4; DiBona, ms). Mapping by P.A. DiBona over a distance of approx 30 km indicates that along the southern limb of the Umberatana syncline the sequence boundary locally cuts downward through Wonoka sequence 2 and the main canyon-cutting surface into the Bunyeroo Formation. The valleys are filled by a succession of medium- to very fine-grained sandstone and siltstone, in part channelized, and arranged into a broadly thinning- and fining-upward succession. Sedimentary structures include current and combined-flow ripples, parallel laminae, and rare hummocky cross-stratification, together with evidence for soft sediment deformation, slumping, and dewatering, especially in the lower part. Beneath the valleys, the Wonoka Formation consists of more than 200 m of thinly bedded limestone and siltstone, passing upward into a coarsening-upward succession of siltstone and fine-grained sandstone also about 200 m thick (broadly equivalent to units 4 to 7 of Haines, ms). Sedimentary structures in these rocks include parallel laminae and current and combined-flow ripples.

Interpretation.—Strata in the uppermost part of Wonoka sequence 2 are interpreted as a shoaling-upward sequence (highstand systems tract), with sedimentation predominantly above storm wave base at the top. The valleys are inferred to have been cut in part by rivers and to a lesser extent by mass-wasting, and to have been filled by a deepening-upward succession of shallow-marine sediments (transgressive systems tract). A change in depositional base level of more than 200 m is implied by the geometry of the sequence boundary and the distribution of shallow-water facies. Although this is considerably less than that inferred for the main Wonoka canyons, the result is important because it demonstrates that large-scale base-level changes took place at least twice during deposition of the Wonoka Formation.

WORKING HYPOTHESES FOR THE ORIGIN OF THE CANYONS

Working hypotheses for the origin of the Wonoka canyons and an evaluation of available evidence are summarized in table 2. Assuming that existing stratigraphic and sedimentological imterpretations are correct, the following observations need to be accommodated.

1. The canyons developed about 630 to 580 my ago within a thermally subsiding basin influenced by diapirism. The overall paleogeographic context is one of a broad, shallow depositional ramp deepening gradually toward the north and east.
2. The canyons are distributed in two discrete regions over an area nearly 300 km in north-south dimension.
3. The canyons are erosional features, in some cases more than 1 km deep. They cannot be explained in terms of syn-sedimentary detached faulting or loading into unconsolidated sediment, nor by reference to Phanerozoic deformation, although later deformation has in some cases significantly modified canyon geometry (Patsy Springs; fig. 2, loc. 5). The depth of erosion is greatest in the northern part of the outcrop, paleogeographically closest to the depocenter.

4. The presence of shallow marine sedimentary rocks immediately beneath the canyon shoulders and at the lowest levels within the canyon fill requires the lowering of depositional base level by more than 1 km. Erosion was most likely accomplished by a combination of fluvial incision and mass-wasting of the canyon walls in a subaerial environment.
5. The presence of shallow-marine indicators at all stratigraphic levels within the canyons indicates that during deposition of the fill sediment accumulation kept pace with the relative sealevel rise, although the actual rates involved are not known.
6. The basin was connected with the open ocean during deposition of the ABC Range Quartzite. Possible evidence for tidal activity, and hence connection with the global ocean, is also present locally within the canyon fill.
7. The Wonoka Formation is the only unit within the Wilpena Group to contain appreciable amounts of carbonate rock. No layered evaporites are known at this stratigraphic level, but tepee dolomite with evaporitic pseudomorphs is observed locally on the canyon shoulders.
8. A second level of incised-valley development is present at the base of unit 8 of the Wonoka Formation in the vicinity of the Fortress Hill canyon complex (fig. 2, loc. 1), in this case involving lowering of depositional base level on the order of 200 m.

Regional Uplift

The regional distribution of the canyons requires lowering of depositional base level on a regional scale, either through uplift or lowering of sealevel. Although diapirs were clearly active at the time and led to a number of local stratigraphic and sedimentological complexities, diapirism by itself cannot account for the distribution of erosion (table 2). Nor can it account for pronounced uplift even locally in an extensional setting lacking evidence for basin inversion (compare Eickhoff, von der Borch, and Grady, 1988). Any regional uplift would therefore have been of tectonic origin (including epeirogeny).

The Wonoka canyons appear to be restricted for the most part to the Adelaide geosyncline, although they may be present also in the Officer basin about 800 km to the west (B. Thomas, personal commun., 1990). No independent evidence exists in the Adelaide geosyncline for compressional deformation coeval with the development of the canyons. However, the presence in the northern part of the Officer basin of an unusually thick succession broadly correlative with the Wonoka Formation raises the possibility that subsidence (and uplift) there may have been due to crustal shortening (W. V. Preiss, personal commun., 1990), and this is an idea that merits further consideration.

Another way to account for regional uplift would be to consider the effects of continued extension of the lithosphere. As noted above, there is very little evidence in the Wilpena Group for significant extension of the crust (Preiss, 1987), so that any extension would have been distributed inhomogeneously. A possible scenario involves extension of the lower crust and mantle, but little or no extension of the upper crust in the area of outcrop. A regional balance can be obtained in the amount of extension at all levels by supposing that deep extension beneath the Adelaide geosyncline was transferred to the upper crust in the area north and/or east of the present outcrop, perhaps by means of regional detachment faults (for excellent recent discussions concerning the role of detachment faults in continental extension, see Kusznir, Karner, and Egan, 1987; and Lister and Davis, 1989). Depending on the distribution of extension with depth, the flexural rigidity of the lithosphere and the duration of extension, renewed thermal subsidence may be preceded by either syn-extensional subsidence or uplift (Kusznir, Karner, and Egan, 1987).

A possible difficulty with this hypothesis is the requirement that the amount of uplift was relatively uniform over distances of hundreds of kilometers. Stratigraphic units below the Wonoka canyons do not appear to have been appreciably tilted on a regional scale, and any doming must therefore have been very subtle. Another difficulty is the fact that pronounced lowering of depositional base level appears to have taken place at least twice. Although we have no information about the time-scales involved, the close stratigraphic spacing of the two sequence boundaries involved suggests that they may differ in age by no more than a few million years. Large-scale oscillatory vertical motion of this sort over a broad region is not readily explained tectonically.

Messinian-Style Sealevel Change in an Isolated Basin

An alternative to regional uplift is the possibility that sealevel was lowered (fig. 8). Sealevel changes in excess of 1 km are too large to be ascribed to a simple eustatic control, and von der Borch and others (1989) have suggested an evaporitic lowering of sealevel in an isolated basin, analogous to the Messinian event in the Mediterranean (Hsu and others, 1978; Cita, 1982). This mechanism readily accounts for the wide distribution and scale of the canyons (compare Ryan and Cita, 1978), for the absence of evidence for shoaling in unit 3 of the Wonoka Formation below the sequence boundary, for the presence of carbonate rocks and evaporitic pseudomorphs in the Wonoka Formation in general, and for pronounced and repeated lowering of depositional base level.

One possible difficulty with the drawdown hypothesis for the Wonoka canyons is that lowered sealevel in an isolated basin would seem to be inconsistent with tidal activity, although evidence for earlier and later connections between the Adelaide geosyncline and the open ocean can be accommodated readily if the basin was isolated only during times of pronounced drawdown. Sedimentary structures supposedly of tidal origin in the sedimentary fill of the Wonoka canyons therefore need to be re-evaluated.

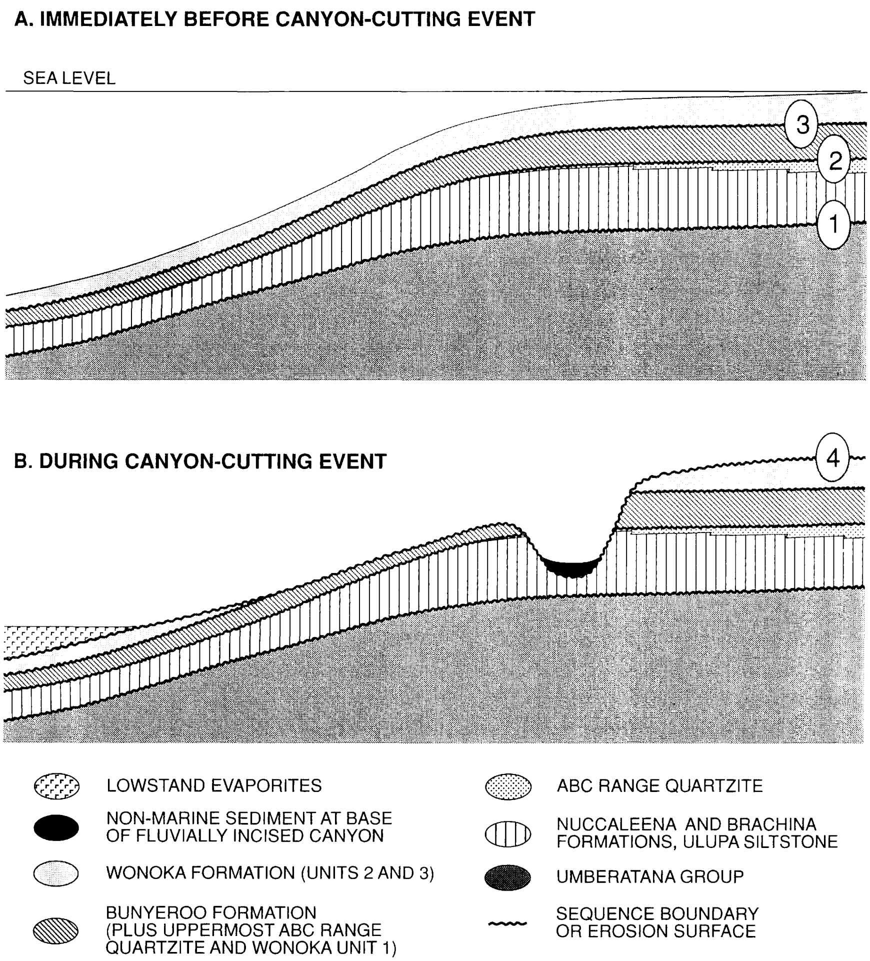


Fig. 8. Interpretive cross sections showing the evolution of the Wonoka canyons assuming a Messinian-style drawdown of sealevel. Stratigraphic units within the lower part of the Wilpena Group are shown thinning northward as a result of reduced sedimentation rates on the hypothetical outer part of the depositional ramp (A) and through erosion during development of the canyons (B). The drawdown hypothesis requires a deep basin to have existed north and east of the Flinders Ranges prior to canyon incision.

One of the main differences between a hypothesized Wonoka drawdown and the Messinian crisis of the Mediterranean is the fact that during filling of the canyons sediment accumulation appears to have kept pace with the rate of sealevel rise. Around the margins of the Mediterranean, fluvial and shallow marine facies are in many cases overlain abruptly by deep marine transgressive deposits (Barber, 1981; Cita, 1982). This implies either that catastrophic flooding did not take place in the Adelaide geosyncline or that the sediment supply was sufficiently large in the area of the present outcrops to maintain a shallow marine environment. A possible paleogeographic analogue in the Mediterranean region is the incised valley of the River Nile (Chumakov, 1973).

Another difference is the apparent absence of evidence for layered evaporites either in outcrop or in seismic reflection profiles that we have examined from the area immediately north of the Flinders Ranges. The absence of evaporites in outcrop is easy to justify. These would have accumulated during the time of canyon cutting. Sedimentary rocks now observed to fill the canyons represent the post-evaporitic transgressive phase. In the Mediterranean, Messinian evaporitic facies similarly tend to be restricted to the deeper parts of the basin (Decima and Wezel, 1973; Montadert and others, 1978). The absence of evidence for salt structures in seismic reflection profiles may be explained by supposing that desiccation was either incomplete, that is, desiccation was sufficient to lower sealevel, but not enough to produce significant thicknesses of evaporites, or that the basin dried up completely. Without replenishment of the evaporated water, the thickness of evaporites would have been negligible. In the case of the Mediterranean, one of the main problems has been to explain the very great thicknesses of salt! It is also possible in the case of the Wonoka canyons that the deepest part of the basin was located beyond the region where Neoproterozoic rocks can be imaged satisfactorily in the subsurface.

A final puzzle for both uplift and drawdown hypotheses has to do with the apparent absence of evidence for meteoric diagenesis within unit 3 of the Wonoka Formation in parts of the central Flinders Ranges far removed from sites of canyon incision. In those areas, the canyon-cutting sequence boundary corresponds to a cryptic surface that must have been exposed 1 km or more above sealevel. Possible explanations are that local rainfall was very small, or that evidence for diagenesis was simply removed during subsequent transgression, but this is another aspect of the story that needs further study.

Further Research

In the course of recent studies it has been possible to narrow down the range of likely working hypotheses for the origin of the Wonoka canyons (table 2). Further studies are needed, however, to corroborate or falsify the shallow-water interpretation of the canyon fill and especially to investigate further the origin of supposed tidal facies; to evaluate the sedimentology within the canyons in a time-stratigraphic context; to investigate the possible diagenetic consequences of large-scale lowering of base level both in the vicinity of the canyons and in areas where no canyons are present; to refine interpretations of sequence stratigraphy and paleogeography on a regional scale; and to compare the history of the Wilpena Group with equivalent stratigraphic units in adjacent basins such as the Officer basin. By these means, it may be possible to gain further insights about the origin of the canyons.

IMPLICATIONS FOR NEOPROTEROZOIC EUSTASY AND ADELAIDEAN TECTONICS

Given the present status of knowledge in the Adelaide geosyncline, what are the implications for the history of eustatic change during Neoproterozoic time? The existence of obvious stratigraphic complexities in the Wilpena Group demands prudence in attempts at global correlation, but it does not necessarily preclude eustasy as an important control. If regional uplift was involved in the development of the Wonoka canyons, its role may have been to enhance an unconformity that would have developed anyway. If a Messinian-style drawdown was involved, the timing of isolation from the global ocean may also have been related to a time of eustatic fall, as appears to have been the case in the Mediterranean during late Miocene time (Cita, 1982; Kastens, 1989). In comparing the sequence stratigraphy of the Adelaidean with that of other basins of the same general age, it is important to focus primarily on the time of formation of sequence boundaries—to the extent that this can be resolved in Proterozoic rocks—not on the geometry of the boundaries or the facies involved, aspects of the stratigraphy that are likely to be controlled locally.

The Wonoka canyons are significant also to the tectonic development of the Adelaide geosyncline, not only because tectonic uplift may have been responsible for the canyons, but because of the possible implications for the depth of the adjacent basin if the drawdown hypothesis is verified. Even allowing for the isostatic response to a drawdown event, base-level changes of more than 1 km require that the adjacent basin was on the order of 1 km or more deep. Such deep water is unusual for extensional basins on continental crust and, as in the case of the Mediterranean, indicates the presence at least locally either of highly attenuated continental crust or of oceanic crust. It is of course possible that the portion of the basin characterized by thin crust, and the most likely site of evaporite accumulation, was removed during Cambrian rifting and continental separation or tectonically depressed during the Delamerian orogeny.

ACKNOWLEDGMENTS

Research on which this paper is based was supported in part by the Donors of the Petroleum Research Fund, administered by the American Chemical Society (PRF 16042-G2 and PRF 19989-AC2), by the Arthur D. Storke Memorial Fund of the Department of Geological Sciences, Columbia University, and by Esso Australia Ltd., the Flinders University Research Budget, and the Australian Research Grants Scheme. We thank J. P. Grotzinger, P. W. Haines, P. F. Hoffman, K. A. Kastens, G. D. Karner, and W. V. Preiss for helpful reviews of the manuscript, and numerous colleagues for discussions that contributed to the ideas presented. Lamont-Doherty Geological Observatory Contribution Number 4643.

References

Allen, P. A., 1985, Hummocky cross-stratification is not produced purely under progressive gravity waves: Nature, v. 313, p. 562–564.

Barber, P. M., 1981, Messinian subaerial erosion of the proto-Nile delta: Marine Geology, v. 44, p. 253–272.

Benus, A. P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point Formation, Avalon Zone, eastern Newfoundland), *in* Landing, E., Narbonne, G. M., and Myrow, P. eds., Trace fossils, small shelly fossils and the Precambrian-Cambrian boundary: University of the State of New York, New York State Museum/ Geological Survey, Bulletin 463, p. 8–9.

Berg, O. R., and Woolverton, D. G., eds., 1985, Seismic stratigraphy II: An integrated approach to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 36, 276 p.

Binks, P. J., 1968, Orroroo, South Australia: Geological Survey of South Australia, geological map, sheet SI 54-1, 1:250,000 scale.

Bond, G. C., Nickeson, P. A., and Kominz, M. A., 1984, Breakup of a supercontinent between 625 and 555 Ma: new evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345.

Christie-Blick, N., 1990, Sequence stratigraphy and sea-level changes in Cretaceous time, *in* Ginsburg, R.N., and Beaudoin, B., eds., Cretaceous Resources, Events and Rhythms: NATO ASI C-Series, v. 304, p. 1–21.

Christie-Blick, N., Grotzinger, J. P., and von der Borch, C. C., 1988, Sequence stratigraphy in Proterozoic successions: Geology, v. 16, p. 100–104.

Christie-Blick, N., and Levy, M., 1985, A new approach to time correlation in Proterozoic rocks: sequence boundaries in the Brigham Group, Utah: Geological Society of America Abstracts with Programs, v. 17, p. 546.

———— 1989, Concepts of sequence stratigraphy, with examples from strata of late Proterozoic and Cambrian age in the western United States, *in* Christie-Blick, N., and Levy, M., eds., Late Proterozoic and Cambrian tectonics, sedimentation, and record of metazoan radiation in the western United States: International Geological Congress, 28th, Washington, D.C., Field trip guidebook T331 (American Geophysical Union), p. 23–37.

Christie-Blick, N., Mountain, G. S., and Miller, K. G., 1988, Sea level history, technical comment: Science, v. 241, p. 596–597.

———— 1990, Seismic stratigraphic record of sea-level change, *in* Sea-level change: National Academy of Sciences, Studies in Geophysics, in press.

Chumakov, I. S., 1973, Pliocene and Pleistocene deposits of the Nile Valley in Nubia and upper Egypt, *in* Ryan, W. B. F., Hsu, K. J. and others, Initial Reports of the Deep Sea Drilling Project, v. 13: Washington, D.C., U.S. Government Printing Office, p. 1242–1243.

Cita, M.B., 1982. The Messinian salinity crisis in the Mediterranean: A review, *in* Berckhemer, H., and Hsu, K., eds., Alpine-Mediterranean geodynamics: American Geophysical Union, Geodynamics Series v. 7, p. 113–140.

Clarke, G. L., and Powell, R., 1989, Basement-cover interaction in the Adelaide foldbelt, South Australia: the development of an arcuate foldbelt: Tectonophysics, v. 158, p. 209–226.

Cloud, P., and Glaessner, M. F., 1982, The Ediacarian Period and System: Metazoa inherit the Earth: Science, v. 218, p. 783–792.

Coats, R. P., 1973, Copley, South Australia: Geological Survey of South Australia, geological map, sheet SH 54-9, 1:250,000 scale.

Cowie, J. W., Ziegler, W., and Remane, J., 1989, Stratigraphic Commission accelerates progress, 1984 to 1989: Episodes, v. 12, p. 79–83.

Cross, T. A., ed., 1989, Quantitative Dynamic Stratigraphy: Englewood Cliffs, New Jersey, Prentice Hall, 625 p.

Dalgarno, C. R., and Johnson, J. E., 1964, Wilpena Group (new name): Quarterly Geological Notes, Geological Survey of South Australia, no. 9, p. 12–16.

———— 1966, Parachilna, South Australia: Geological Survey of South Australia, geological map, sheet H 54-13, 1:250,000 scale.

Decima, A., and Wezel, P. C., 1973, Late Miocene evaporites of the central Sicilian basin, Italy, *in* Ryan, W. B. F., Hsu, K. J., and others, Initial Reports of the Deep Sea Drilling Project, v. 13: Washington, D.C., U.S. Government Printing Office, p. 1234–1240.

de Raaf, J. F. M., Boersma, R. J., and van Gelder, A., 1977, Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland: Sedimentology, v. 24, p. 451–483.

DiBona, P. A., ms, 1989, Geologic history and sequence stratigraphy of the Late Proterozoic Wonoka Formation, northern Flinders Ranges, South Australia: Ph.D. dissertation, Flinders University, Bedford Park, South Australia, 207 p.
DiBona, P. A., von der Borch, C. C., and Christie-Blick, N., in press, Sequence stratigraphy and evolution of a basin-slope succession—the late Proterozoic Wonoka Formation, Flinders Ranges, South Australia: Australian Journal of Earth Sciences.
Dott, R. H., Jr., and Bourgeois, J., 1982, Hummocky stratification: Significance of its variable bedding sequences: Geological Society of America Bulletin, v. 93, p. 663-680.
Duke, W. L., and Leckie, D. A., 1986, Origin of hummocky cross-stratification. Part 2, paleohydraulic analysis indicates formation by orbital ripples within the wave-formed flat-bed field, *in* Knight, R. J., and McLean, J. R., eds., Shelf sands and sandstones: Canadian Society of Petroleum Geologists Memoir 11, p. 339.
Eickhoff, K.-H., von der Borch, C. C., and Grady, A. E., 1988, Proterozoic canyons of the Flinders Ranges (South Australia): submarine canyons or drowned river valleys?: Sedimentary Geology, v. 58, p. 217–235.
Fanning, C. M., Flint, R. B., and Preiss, W. V., 1983, Geochronology of the Pandurra Formation: Quarterly Geological Notes, Geological Survey of South Australia, no. 88, p. 11–16.
Fanning, C. M., Ludwig, K. R., Forbes, B. G., and Preiss, W. V., 1986, Single and multiple grain U-Pb zircon analyses for the early Adelaidean Rook Tuff, Willouran Ranges, South Australia: Geological Society of Australia, Abstracts, no. 15, p. 71–72.
Farre, J. A., McGregor, B. A., Ryan, W. B. F., and Robb, J. M., 1983, Breaching the shelfbreak: passage from youthful to mature phase in submarine canyon evolution, *in* Stanley, D. J., and Moore, G. T., eds., The shelfbreak: critical interface on continental margins: Society of Economic Paleontologists and Mineralogists Special Publication no. 33, p. 25–39.
Forbes, B. G., Coats, R. P., and Daily, B., 1972, Truro Volcanics: Quarterly Geological Notes, Geological Survey of South Australia, no. 44, p. 1–5.
Gatehouse, C. G., 1988, Kanmantoo field symposium excursion guide: South Australia, Department of Mines and Energy, Report 88/35, 89 p.
Gehling, J. G., ms, 1982, The sedimentology and stratigraphy of the Late Precambrian Pound Subgroup, central Flinders Ranges, South Australia: M.Sc. thesis, University of Adelaide, Adelaide, South Australia, 112 p.
Glaessner, M. F., 1984, The Dawn of Animal Life: Cambridge, Cambridge University Press, 244 p.
Gostin, V. A., Haines, P. W., Jenkins, R. J. F., Compston, W., and Williams, I. S., 1986, Impact ejecta horizon within late Precambrian shales, Adelaide Geosyncline, South Australia: Science, v. 233, p. 198–200.
Gostin, V. A., and Jenkins, R. J. F., 1983, Sedimentation of the early Ediacaran, Flinders Ranges, South Australia: Australian Geological Convention, 6th, Geological Society of Australia, Abstracts, no. 9, p. 196–197.
Gradstein, F. M., Agterberg, F. P., Aubry, M.-P., Berggren, W. A., Flynn, J. J., Hewitt, R., Kent, D. V., Klitgord, K. D., Miller, K. G., Obradovitch, J., Ogg, J. G., Prothero, D. R., and Westerman, G. E. G., 1988, Sea level history, technical comment: Science, v. 241, p. 599-601.
Grotzinger, J. P., Adams, R. D., McCormick, D. S., and Myrow, P., 1989, Sequence stratigraphy, correlations between Wopmay orogen and Kilohigok basin, and further investigations of the Bear Creek Group (Goulburn Supergroup), District of Mackenzie, N. W. T.: Geological Survey of Canada, Paper 89-1C, p. 107–119.
Haines, P. W., ms, 1987, Carbonate shelf and basin sedimentation, late Proterozoic Wonoka Formation, South Australia: Ph.D. thesis, University of Adelaide, Adelaide, 152 p.
——— 1988, Storm-dominated mixed cabonate/siliciclastic shelf sequence displaying cycles of hummocky cross-stratification, late Proterozoic Wonoka Formation, South Australia: Sedimentary Geology, v. 58, p. 237–254.
Hambrey, J. J., and Harland, W. B., eds., 1981. Earth's Pre-Pleistocene Glacial Record: Cambridge, England, Cambridge University Press, 1004 p.
——— 1985, The Late Proterozoic glacial era: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 51, p. 255–272.
Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.
——— 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., and van Wagoner, J. C., eds., Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication, no. 42, p. 71–108.

Harris, C. W., and Eriksson, K. A., 1990, Allogenic controls on the evolution of storm to tidal shelf sequences in the Early Proterozoic Uncompahgre Group, southwest Coloradio, USA: Sedimentology, v. 37, p. 189–213.
Hegarty, K. A., Weissel, J. K., and Mutter, J. C., 1988, Subsidence history of Australia's southern margin: Constraints on basin models: American Association of Petroleum Geologists Bulletin, v. 72, p. 615–633.
Hsu, K. J., Montadert, L., Bernoulli, D., Cita, M. B., Erickson, A., Garrison, R. E., Kidd, R. B. Mélières, F., Müller, C., and Wright, R., 1978, History of the Mediterranean salinity crisis, *in* Hsu, K. J., Montadert, L., and others, Initial Reports of the Deep Sea Drilling Project, v. 42; Washington, D.C., U.S. Government Printing Office, p. 1053–1078.
James, D. P., and Leckie, D. A., eds., 1988, Sequences, stratigraphy, sedimentology: surface and subsurface: Canadian Society of Petroleum Geologists, Memoir 15, 586 p.
Jenkins, R. J. F., 1981, The concept of an 'Ediacaran Period' and its stratigraphic significance in Australia: Transactions of Royal Society of South Australia, v. 105, p. 179–194.
Jenkins, R. J. F., Ford, C. H., and Gehling, J. G., 1983, The Ediacara Member of the Rawnsley Quartzite: the context of the Ediacara assemblage (late Precambrian, Flinders Ranges): Journal of Geological Society of Australia, v. 30, p. 101–119.
Jordan, T. E., and Flemings, P. B., in press, Large-scale stratigraphic architecture, eustatic variation, and unsteady tectonism: a theoretical evaluation: Journal of Geophysical Research.
Kastens, K., 1989, Did a glacio-eustatic sealevel drop trigger the Messinian salinity crisis in the Mediterranean? New evidence from ODP Site 654 in the Tyrrhenian Sea: EOS, v. 70, p. 1135.
Kusznir, N. J., Karner, G. D., and Egan, S., 1987, Geometric, thermal and isostatic consequences of detachments in continental lithosphere extension and basin formation, *in* Beaumont, C., and Tankard, A. J., eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists, Memoir 12, p. 185–203.
Larue, D. K., and Provine, K. G., 1988, Vacillatory turbidites, Barbados: Sedimentary Geology, v. 57, p. 211–219.
Larue, D. K., and Speed, R. C., 1983, Quartzose turbidites of the accretionary complex of Barbados, I: Chalky Mount succession: Journal of Sedimentary Petrology, v. 53, p. 1337–1352.
Lemon, N. M., 1985, Physical modeling of sedimentation adjacent to diapirs and comparison with late Precambrian Oratunga breccia body in central Flinders Ranges, South Australia: American Association of Petroleum Geologists Bulletin, v. 69, p. 1327–1338.
Lindsay, J. F., 1987, Sequence stratigraphy and depositional controls in Late Proterozoic-Early Cambrian sediments of the Amadeus basin, central Australia: American Association of Petroleum Geologists Bulletin, v. 71, p. 1387–1403.
——— 1989, Depositional controls on glacial facies associations in a basinal setting, Late Proterozoic, Amadeus basin, central Australia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 73, p. 205–232.
Lindsay, J. F., and Korsch, R. J., 1989, Interplay of tectonics and sea-level changes in basin evolution: an example from the intracratonic Amadeus basin, central Australia: Basin Research, v. 2, p. 3–25.
Lindsay, J. F., Korsch, R. J., and Wilford, J. R., 1987, Timing the breakup of a Proterozoic supercontinent: Evidence from Australian intracratonic basins: Geology, v. 15, p. 1061–1064.
Link, P. K., Jansen, S. T., Halimdihardja, P., Lande, A., and Zahn, P., 1987, Stratigraphy of the Brigham Group (Late Proterozoic-Cambrian), Bannock, Portneuf, and Bear River Ranges, southeastern Idaho, *in* Miller, W. R., ed., The thrust belt revisited: Wyoming Geological Association, 38th Annual Field Conference Guidebook, p. 133–148.
Lister, G. S., and Davis, G. A., 1989, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A.: Journal of Structural Geology, v. 11, p. 65–94.
Matthews, R. K., 1988, Sea level history, technical comment: Science, v. 241, p. 597–599.
Mawson, D., and Sprigg, R. C., 1950, Subdivision of the Adelaide System: Australian Journal of Science, v. 13, p. 69–72.
Miall, A. D., 1986, Eustatic sea level changes interpreted from seismic stratigraphy: A critique of the methodology with particular reference to the North Sea Jurassic record: American Association of Petroleum Geologists Bulletin, v. 70, p. 131–137.

Montadert, L., Letouzey, J., and Mauffret, A., 1978, Messinian event seismic evidence, *in* Hsu, K. J., Montadert L., and others, Initial Reports of the Deep Seas Drilling Project, v. 42: Washington, D.C., U.S. Government Printing Office, p. 1037–1050.
Mount, J. F., 1989, Re-evaluation of unconformities separating the "Ediacaran" and Cambrian Systems, South Australia: Palaios, v. 4, p. 366–373.
Myers, J. S., 1990, Precambrian tectonic evolution of a portion of Gondwana, southwestern Australia: Geology, v. 18, p. 537–540.
Nøttvedt, A., and Kreisa, R. D., 1987, Model for the combined-flow origin of hummocky cross-stratification: Geology, v. 15, p. 357–361.
Parsons, B., and Sclater, J. G., 1977, An analysis of the variation of ocean floor bathymetry and heat flow with age: Journal of Geophysical Research, v. 82, p. 803–827.
Plummer, P. S., 1978a, Stratigraphy of the lower Wilpena Group (late Precambrian), Flinders Ranges, South Australia: Transactions of Royal Society of South Australia, v. 102, p. 25–38.
———— ms, 1978, The upper Brachina Subgroup: A late Precambrian intertidal deltaic and sandflat sequence in the Flinders Ranges, South Australia: Ph.D. dissertation, University of Adelaide, Adelaide, 170 p.
———— 1978b, Note on the palaeoenvironmental significance of the Nuccaleena Formation (upper Precambrian), central Flinders Ranges, South Australia: Journal of Geological Society of Australia, v. 25, p. 395–402.
Posamentier, H. W., Jervey, M. T., and Vail, P. R., 1988, Eustatic controls on clastic deposition I—conceptual framework, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., and van Wagoner, J. C., eds., Sea-level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication, no. 42, p. 109–124.
Prave, A. R., 1985, Can hummocky cross-stratification be formed *below* effective storm wave base?: Geological Society of America Abstracts with Programs, v. 17, p. 693.
Prave, A. R., and Duke, W. L., 1990, Small-scale hummocky cross-stratification in turbidites: a form of anticline stratification?: Sedimentology, v. 37, p. 531–539.
Preiss, W. V., 1983, Depositional and tectonic contrasts between Burra Group and Umberatana Group sedimentation, *in* Adelaide Geosyncline sedimentary environments and tectonic settings, symposium, Adelaide: Geological Society of Australia, Abstracts, no. 10, p. 13–16.
———— compiler, 1986, Adelaide Geosyncline and Stuart Shelf, Precambrian and Paleozoic geology (with special reference to the Adelaidean): Geological Survey of South Australia, map, scale 1:600,000, 2d. ed.
———— compiler, 1987, The Adelaide Geosyncline. Late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics: Geological Survey of South Australia Bulletin 53, 438 p.
Preiss, W. V., and Forbes, B. G., 1981, Stratigraphy, correlation and sedimentary history of Adelaidean (late Proterozoic) basins in Australia: Precambrian Research, v. 15, p. 255–304.
Reineck, H.-E., and Singh, I. B., 1980, Depositional Sedimentary Environments, 2d. ed.: New York, Springer-Verlag, 549 p.
Rutland, R. W. R., Parker, A. J., Pitt, G. M. Preiss, W. V., and Murrell, B., 1981, The Precambrian of South Australia, *in* Hunter, D. R., ed., Precambrian of the Southern Hemisphere: Amsterdam, The Netherlands, Elsevier, p. 309–360.
Ryan, W. B. F., and Cita, M. B., 1978, The nature and distribution of Messinian erosional surfaces—indicators of several-kilometer deep Mediterranean in the Miocene: Marine Geology, v. 27, p. 193–230.
Schlee, J. S., ed., 1984, Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, 184 p.
Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–113.
———— 1988, Forty years of sequence stratigraphy: Geological Society of America Bulletin, v. 100, p. 1661–1665.
Southard, J. B., Lambie, J. M., Federico, D. C., Pile, H. T., and Weidman, C. R., 1990, Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification: Journal of Sedimentary Petrology, v. 60, p. 1–17.
Sprigg, R. C., 1947, Early Cambrian (?) jellyfishes from the Flinders Ranges, South Australia: Transactions of Royal Society of South Australia, v. 71, p. 212–224.

Thomson, B. P., 1969a, Precambrian basement cover, the Adelaide System, *in* Parkin, L. W., ed., Handbook of South Australian geology: Adelaide, South Australia, Geological Survey of South Australia, p. 49–83.

———— 1969b, Paleozoic Era, *in* Parkin, L. W., ed., Handbook of South Australian geology: Adelaide, South Australia, Geological Survey of South Australia, p. 84–132.

———— compiler, 1980, Geological map of South Australia: Geological Survey of South Australia, 1:1,000,000 scale.

Vail, P. R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy. Part I: Seismic stratigraphy interpretation procedure, *in* Bally, A. W., ed., Atlas of seismic stratigraphy: American Association of Petroleum Geologists Studies in Geology no. 27, v. 1, p. 1–10.

Vail, P. R., Hardenbol, J., and Todd, R. G., 1984, Jurassic unconformities, chronostratigraphy, and sea-level changes from seismic stratigraphy and biostratigraphy, *in* Schlee, J. S., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 129–144.

Vail, P. R., Mitchum, R. M., Jr., Todd, R. G., Widmier, J. M., Thompson, S., III, Sangree, J. B., Bubb, J. N., and Hatlelid, W. G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C. E., ed., Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 49–212.

van Wagoner, J. C., Mitchum, R. M., Jr., Posamentier, H. W., and Vail, P. R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy. Part II: Key definitions of sequence stratigraphy, *in* Bally, A. W., ed., Atlas of seismic stratigraphy: American Association of Petroleum Geologists Studies in Geology, no. 27, v. 1, p. 11–14.

van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., and van Wagoner, J. C., eds., Sea-level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication, no. 42, p. 39–45.

von der Borch, C. C., 1980, Evolution of late Proterozoic to early Paleozoic Adelaide foldbelt, Australia: Comparisons with post-Permian rifts and passive margins: Tectonophysics, v. 70, p. 115–134.

von der Borch, C. C., Christie-Blick, N., and Grady, A. E., 1988, Depositional sequence analysis applied to upper Proterozoic Wilpena Group, Adelaide Geosyncline, South Australia: Australian Journal of Earth Sciences, v. 35, p. 59–71.

von der Borch, C. C., Grady, A. E., Aldam, R., Miller, D., Neumann, R., Rovira, A., and Eickhoff, K., 1985, A large-scale meandering submarine canyon: outcrop example from the late Proterozoic Adelaide Geosyncline, South Australia: Sedimentology, v. 32, p. 507–518.

von der Borch, C. C., Grady, A. E., Eickhoff, K. H., DiBona, P., and Christie-Blick, N., 1989, Late Proterozoic Patsy Springs canyon, Adelaide Geosyncline: submarine or subaerial origin?: Sedimentology, v. 36, p. 777–792.

von der Borch, C. C., Smit, R., and Grady, A. E., 1982, Late Proterozoic submarine canyons of Adelaide Geosyncline, South Australia: American Association of Petroleum Geologists Bulletin, v. 66, p. 332–347.

Walker, R. G., Duke, W. L., and Leckie, D. A., 1983, Hummocky stratification: Significance of its variable bedding sequences: Discussion: Geological Society of America Bulletin, v. 94, p. 1245–1249.

Walter, M. R., Elphinstone, R., and Heys, G. R., 1989, Proterozoic and Early Cambrian trace fossils from the Amadeus and Georgina Basins, central Australia: Alcheringa, v. 13, p. 209–256.

Webb, A. W., ms, 1980, Geochronology of stratigraphically significant rocks from South Australia—Amdel progress report 30: South Australian Department of Mines and Energy, open file envelope 1689 (unpublished).

Webb, A. W., ms, 1981, Geochronology of the Stuart shelf—Amdel progress report 3: South Australian Department of Mines and Energy, open file envelope 3859 (unpublished).

Webb, A. W., and Coats, R. P., ms, 1980, A reassessment of the age of the Beda volcanics on the Stuart shelf, South Australia: South Australian Department of Mines and Energy, report 80/6 (unpublished).

Webb, A. W., Coats, R. P., Fanning, C. M., and Flint, R. B., 1983. Geochronological framework of the Adelaide Geosyncline, *in* Adelaide Geosyncline sedimentary environments and tectonic settings, symposium, Adelaide: Geological Society of Australia, Abstracts, 10, p. 7–9.
Williams, G. E., 1979, Sedimentology, stable-isotope geochemistry and palaeoenvironment of dolostones capping late Precambrian glacial sequences in Australia: Journal of Geological Society of Australia, v. 26, p. 377–386.