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Discussion on mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia

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Nicholas Christie-Blick writes: Kilometre-deep buried canyons in the upper Neoproterozoic successions of South Australia are unusual by any standard, and any viable explanation for their origin will probably involve an unusual set of circumstances. Williams & Gostin (2000) review published geological constraints and competing hypotheses, and suggest a role for uplift and crustal deformation associated with the passage of a mantle plume. On the basis of available evidence, I continue to favour an alternative explanation—that they are due to the short-lived evaporative drawdown of sea level in a marine embayment that became temporarily isolated from the global ocean (von der Borch *et al.* 1989; Christie-Blick *et al.* 1990; Christie-Blick 1998).

Spatial and temporal distribution of erosion. Canyons more than 1 km deep in the Wonoka Formation of the Adelaide fold belt and up to 700 m deep in the subsurface of the eastern Officer basin are reasonably interpreted as coeval and of common origin, with a length scale of order 1000 km. Comparable erosional features are found nowhere else in Australia, even in the Kimberley region and western Officer basin (Coats & Preiss 1980; Walter *et al.* 1994, 1995), where flood basalts of possible plume origin are widespread (Bultitude 1976; Jackson & van de Graaff 1981). Bender (2000) independently noted the distribution of late Neoproterozoic to early Palaeozoic magmatism in Western Australia, and analyzed the possible role of plume-related uplift and erosional thinning of the crust in early Palaeozoic subsidence of the Canning basin. However, that basin is some 2000 km to the northwest of the Adelaide fold belt, where the canyons are best known.

A rather thornier problem is that in the Adelaide fold belt prominent erosion surfaces are present at three other horizons above the level of Marinoan glaciation and below Cambrian strata. These are in the upper part of the Wonoka Formation (<200 m of relief; DiBona 1989; Christie-Blick *et al.* 1990), in the Rawnsley Quartzite (<250 m deep; Gehling 1982, 2000) and at the base of the Uratanna Formation (<150 m deep; Daily 1973; McDonald 1992; see Williams & Gostin 2000, fig. 2). While less impressive than the Wonoka canyons, these features are also of unusually large relief. For spans of geological time lacking evidence for significant glaciation, incised valleys in sedimentary basins are typically no more than a few tens of metres deep, even in tectonically active settings such as foreland basins (e.g., Dalrymple *et al.* 1994; Van Wagoner 1995; Plint 2000). This suggests that whatever hypothesis is proposed for the Wonoka canyons, it may need to work four times. An interpretation that calls for repeated large-scale uplift and renewed subsidence of a basin over a span of no more than a few tens of millions of years (and perhaps appreciably less than that), with little associated faulting, folding or even tilting of the stratigraphy, is implausible.

Fluvial erosion versus marine mass wasting. The mechanism of canyon incision is extremely important because it influences our perception of the magnitude of vertical crustal motion or sea-level change that may be required. As Williams & Gostin (2000) recognize, there has been considerable debate about whether the canyons were initially cut by rivers or whether they are due entirely to marine mass wasting. The best arguments for subaerial erosion are not the ones they state. At the deepest levels of the Wonoka canyon system, at a palaeogeographically distal site (Umberatana syncline), an upward-coarsening and -thickening motif at a scale of a few metres and abrupt fining and thinning of beds in the direction of sediment transport suggest that the rocks are fluvial-deltaic, and not related to sediment gravity flow in deep water (Christie-Blick 1998). At the same locality, the basal 275 m of the canyon fill is divisible into nine high-order unconformity-bounded sequences. These are laterally persistent for many kilometres and of remarkably uniform thickness (28 m). Such architecture and evident stratigraphic periodicity contrasts with what might be expected from the cutting and filling of random thalweg channels in a deep submarine canyon (e.g., Morris & Busby-Spera 1988; Goodwin & Prior 1989; Bruhn & Walker 1997).

Other evidence summarized by Williams & Gostin (2000) is mostly pertinent. However, re-evaluation of carbonate rocks that veneer the canyon walls indicates that they are reciprocal to sequence boundaries and represent times of flooding, not subaerial exposure (Christie-Blick *et al.* 1995; cf. Eickhoff *et al.* 1988; von der Borch *et al.* 1989)! Carbon and oxygen isotopic values that are uniformly highly depleted through much of the Wonoka canyon fill (M.J. Kennedy pers. comm. 2000), and indeed through much of the sub-canyon Wonoka Formation, as well as in spar-filled veins, are best interpreted as pervasively homogenized by orogenic fluids, with no primary stratigraphic significance retained. (See Calver 2000 for a very different interpretation involving salinity stratification of the water column, a view that also departs radically from the non-marine tufa interpretation of canyon-wall carbonates.)

Timescale of canyon erosion and filling. In the absence of geochronology, only indirect argments can be made about the timescale of canyon erosion and filling. A potentially important constraint is that where the canyon-cutting unconformity passes into concordant stratigraphy, no evidence has yet been found for subaerial exposure, even though the surface must have been more than 1 km above sea level when the canyons were being cut (Christie-Blick *et al.* 1995). Williams & Gostin (2000) reiterate several possible explanations. Of these, extremely short-lived exposure in an arid climate may be most important. A second constraint on the timescale of canyon filling relates to the cyclic stratigraphy documented at the Umberatana syncline example. Williams & Gostin (2000) correctly point out that even if the cyclicity is due to orbitally driven climate change, we cannot confidently determine which period corresponds with the 28 m thick sequences, and we suspect that most of the familiar frequencies were somewhat different in the geological past (e.g., Berger & Loutre 1994*a*). However, for a site at low latitude (see Sohl *et al.* 1999 for a recent review), precession frequencies are likely to have been important (Berger & Loutre 1994*b*), consistent with a timescale for canyon filling in the order of several hundred thousand years. That is the same timescale as the Messinian drawdown in the Mediterranean (Clauzon *et al.* 1996), a possible modern analogue. Even if a more conservative timescale of 'no more than a few million years' (Williams & Gostin 2000) is adopted, that is problematic for the plume hypothesis because, if the canyons are fluvially incised, a subsidence rate comparable to or greater than that of young oceanic crust is implied by any timescale shorter than about 10 million years (e.g., Marty & Cazenave 1989; Kane & Hayes 1994).

Uniqueness of features ascribed to passage of plume. Williams & Gostin (2000) draw attention to a variety of other geological observations that they view as consistent with the plume hypothesis: unconformity development as evidence for regional uplift; and sediment gravity flow and the development of extensional faults as indicators of tectonic instability. None of these features is especially diagnostic. One of the most remarkable characteristics of the younger Proterozoic geology of the Adelaide fold belt is the paucity of evidence in well exposed stratigraphy for syn-depositional deformation, other than that readily ascribed to local salt motion at depth. The Officer basin appears to have been a foreland basin during the interval of interest (Preiss 1993), but there too, the distribution and scale of canyons suggests that deformation was subordinate to and not the primary cause of canyon development (cf. Lindsay & Leven 1996; Calver & Lindsay 1998). Other than the presence of the canyons, evidence for the existence of a plume in the right place at the right time is slight. Large-scale canyons within sedimentary basins are also not an obvious signature of regional plume-driven uplift in other examples where the existence of a plume is well established.

Summary. Messinian-style evaporative drawdown of sea level in temporarily isolated marine embayment remains the best explanation for the available observations. The restricted distribution of deep canyons in a much broader region that may have been affected by a mantle plume, and stratigraphic evidence in the Adelaide fold belt for repeated large-scale oscillations of base level at a comparatively short timescale together argue against a role for plume-related uplift and deformation in canyon development. None of the stratigraphic features ascribed by Williams & Gostin (2000) to the passage of a plume is uniquely so interpreted, and evidence supplied in opposition to the drawdown hypothesis is not definitive. The Afiq Canyon, an eastern Mediterranean analogue to which they refer (Druckman *et al.* 1995), was cut in the early Oligocene, not during the Messinian desiccation. The apparent absence of evaporites at an appropriate stratigraphic level in the Neoproterozoic of Australia may simply reflect the inaccessibility in outcrop and the subsurface of the deep basin in which evaporites would have preferentially accumulated. Carbon- and oxygen-isotopic values are either reset and not pertinent to the origin of the canyons, or not inconsistent with the drawdown hypothesis (Calver 2000).

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G. E. Williams & V. A. Gostin reply: Our hypothesis that regional uplift related to a rising mantle plume caused canyon incision within late Neoproterozoic successions in the Adelaide fold belt and eastern Officer Basin also offers a unifying explanation for diverse events in these widely separated successions, including the development of regional unconformities, the onset of turbidity current activity and gravity slides, syn-depositional normal faulting, and flood basalt volcanism (Williams & Gostin 2000). Our hypothesis also is consistent with evidence for substantial erosion of the central Gawler Craton since the Neoproterozoic and for widespread mantle plume activity in adjoining regions of Australia and Antarctica during the late Neoproterozoic–early Palaeozoic. By comparison, the alternative hypothesis of evaporitive drawdown of sea level for canyon origin favoured by Christie-Blick to us appears wanting and ad hoc because of the lack of evidence for evaporite deposition or extreme evaporitive conditions at the appropriate stratigraphic level in either succession and because it cannot be related to other late Neoproterozoic events in Australia.

Lack of evidence for evaporite deposits or extreme evaporitive conditions. Evaporite deposits are unknown at the appropriate stratigraphic level in the Adelaide fold belt and Officer Basin, casting grave doubt on the hypothesis of extreme desiccation and sea-level drawdown. Because of the excellent exposure of strata in the Adelaide fold belt and the abundance of diapirs that originate from evaporitic sediments at other stratigraphic levels in deep parts of the sedimentary basin (Preiss 1987), one would expect any evaporite deposit at the level of the Wonoka Formation to be evident either in outcrop or through diapirism. However, no such evaporite deposit or diapir is known. Moreover, the 49 petroleum and deep stratigraphic/mineral exploration holes drilled to date in the South Australian part of the Officer Basin, including the deepest portions of the basin, and the accompanying 6800 km of 2D seismic lines (Harvey & Hibburt 1999), have provided no evidence of an evaporite deposit at, or associated diapirism originating from, the stratigraphic level of the canyons.

Wonoka units 4 and 5 include distal turbidites and are of relatively deep water origin (Haines 1990). However, those units also contain rare gypsum crystals usually <1 mm long dispersed in mudstone, suggesting to Calver (2000) either a regime of salinity stratification in a silled basin where evaporation exceeded total freshwater inflow or that diapirs rising from much deeper levels that are known to have breached the sea floor in Wonoka times contributed to gypsum saturation of bottom waters. Such situations are of course a far cry from Messinian-style desiccation and drawdown, and Calver (2000, p. 136) concluded from stable isotope studies that 'there is no overall evolution to more extreme evaporitive conditions in the Wonoka Formation'. As first shown by Ayliffe (1992), Urlwin *et al.* (1993) and Pell *et al.* (1993) and subsequently confirmed by Calver (2000), various independent textural and geochemical criteria point to the depleted $\delta^{13}C_{carb}$ values for Wonoka units 3–7 being the primary signature. We would expect that the stable isotope signature of the unmetamorphosed Wonoka Formation would reflect extreme desiccation if indeed such an event had taken place.

Spatial and temporal distribution of erosion. The idea of evaporitive drawdown of sea level in an isolated marine embayment was perhaps easier to envisage when only the canyons in the Adelaide fold belt were known. This idea looked much less plausible with the subsequent discovery of a coeval canyon system in the eastern Officer Basin up to 900 km distant and on the opposite side of the Gawler Craton. These discrete canyon systems originate from near the onlapped eastern and western margins of the Gawler Craton, suggesting that vertical movements of the craton influenced canyon incision and filling. The tectonic setting may have been particularly favourable for the development and also the preservation of such erosional features.

We did not imply that the shallower palaeovalleys at other stratigraphic levels in the late Neoproterozoic succession of the Adelaide fold belt are related to the proposed canyon-forming regional uplift. There is no evidence that the palaeovalleys and canyons have a common cause and the relative influences of eustacy and flexural warping on stratigraphic patterns and basin development in general remain unclear (see Dennison 1994). The stratigraphic positions of the palaeovalleys in the Adelaide fold belt rule out glacial eustacy related to the preceding widespread Marinoan glaciation as a possible cause of palaeovalley incision. However, evidence for an Ediacarian glaciation in Western Australia that may correlate with the upper Wonoka Formation (Grey & Corkeron 1998) suggests glacial eustacy may have been an influence in the erosion of the palaeovalley at the top of the Wonoka Formation.

Time scale of canyon erosion and filling. It is difficult to assess the significance of cycles in the Wonoka canyon fill because of the limited information available. The palaeomagnetic data of Sohl *et al.* (1999) for the Adelaide fold belt are not relevant to the origin of the cycles because the formations they studied lie stratigraphically well below the Wonoka and because the timing of the magnetizations they identified is not well constrained. However, accordant palaeomagnetic data for the Acraman impact structure on the Gawler Craton and the coeval ejecta-bearing Bunyeroo Formation, which is conformably overlain by the Wonoka Formation, imply a palaeolatitude of *c.* 15° in Wonoka times (Schmidt & Williams 1996). Early Palaeozoic cyclic deposits in Western Australia, which are among the oldest sediments to provide spectral evidence of Milankovitch orbital periods, formed at a comparable palaeolatitude and record a strong 100 000 year eccentricity cycle (Williams 1991). Eccentricity cycles have periods also of *c.* 400 000 years and possibly longer and have remained fairly stable with time (Fischer & Bottjer 1991; Berger & Loutre 1994*a*). As the nine cycles that Christie-Blick (1993, 1998) has identified in the Wonoka canyon fill constitute only *c.* 20% of the fill, a million-year time-scale for canyon filling is possible. Such estimates of time-scale based on the stratigraphy of canyon fill will remain uncertain, however, until the nature of the fill is better understood.

Theoretical and experimental studies of the interaction of mantle plumes with the Earth's surface show that surface uplift occurs at an accelerating rate above a plume head, with most uplift taking place over the final 3–5 million years, to be followed by rapid subsidence over the next 5 million years (Griffiths & Campbell 1991; Hill *et al.* 1992). Estimates of uplift and subsidence rates depend on the value assumed for the viscosity of the upper mantle, and Griffiths & Campbell (1991) noted that the above time-scale for uplift could be three times smaller if lower values are assumed for upper mantle viscosity. These findings are consistent with our hypothesis that the late Neoproterozoic canyons in South Australia were incised and filled during rapid uplift and subsidence taking no more than a few million years.

Uniqueness of features ascribed to passage of plume. We agree that most of the events we described are not by themselves diagnostic of mantle plume uplift. However, their distribution and sequence in discrete successions on opposite sides of the Gawler Craton together provide a strong case for regional uplift of the craton and bordering areas during the late Neoproterozoic. The occurrence of penecontemporaneous flood basalt volcanism in the region further suggests that the uplift was caused by a rising mantle plume.

Canyons like those of late Neoproterozoic age in South Australia may prove to be more common in the geological record than Christie-Blick supposes. Despite their excellent exposure in the Adelaide fold belt, the Wonoka canyons were recognized as such and described in detail for the first time only in the 1980s. The canyons in the eastern Officer Basin were not recognized until a decade later. The forthcoming volume on the identification and location of pre-Mesozoic mantle plumes (Ernst & Buchan 2001), which includes a review of evidence for mantle plume uplift in the sedimentary record (Rainbird & Ernst 2001), should generate much interest in the geological signature of mantle plumes and may stimulate a search for further examples of Wonoka-type canyons that can be related to regional uplift above plume heads.

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