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Fault growth by segment linkage: an explanation for scatter in maximum displacement and trace length data from the Canyonlands grabens of SE Utah: Reply

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The main aim of the discussion by McGill et al. is to clarify the geometry of the grabens in the Needles District of the Canyonlands National Park, Utah. The motivation for this paper is based on statements in Cartwright et al. (1995, 1996) pertaining to our interpretation of the cross-sectional geometry of the bounding faults of the grabens in this area, and the paper sets out to correct the record with regard to the conflicting views of these and earlier interpretations (by numerous authors). McGill et al. are certainly justified in correcting the impression given by Cartwright et al. (1995, 1996), that no structural intersections between pairs of graben-bounding faults could be observed in this area, although we would not agree that the pendulum of this complex interpretation has swung completely and exclusively back towards intersection at top evaporites or shallower.

Cartwright et al. (1995) originally stated that the "graben-bounding faults are vertical at surface and remain vertical to sub-vertical for the 400–500 m distance to the top of the evaporite sequence ... No evidence was found in these traverses for structural intersection between pairs of graben-bounding faults at depth as previously suggested by McGill and Stromquist (1979) and Trudgill and Cartwright (1994)."

The crucial evidence in question is really restricted to the group of structures referred to by McGill et al. as grabens 1, 2 and 3, intersected in Y and Cross Canyons, since these are the only structures with exposed bases close enough to the top evaporites to allow reasonable downward extrapolation. The comments in the discussion by McGill et al. relating to Lower Red Lake Canyon seem to us to favour neither one interpretation nor the other, although we agree entirely with McGill et al. that the "eastern boundary fault retains a near-vertical dip through the entire exposed section". This 'near-vertical' fault extends over a distance of about 275 m. When we studied this area with the benefit of the excellent 1:12 000 map constructed by Stromquist (1976) whilst remapping this area ourselves, we were not convinced that the western boundary fault did in fact connect with the eastern bounding fault above stream level, and indeed, Stromquist's section drawn 500 m north of the stream shows an intersection 50 m below the level of the top evaporites. Mansfield (1996) argued that the complexities of this area were the result of propagation after a substantial amount of valley cutting had already occurred, and the lack of correlation of structures across the canyon supports this view. This is not a point that McGill et al. or any other authors discuss, but one that Mansfield (1996) argued is critical to the interpretation of the deeper structure exposed in these cross canyons. The deep incisional features represent an important and topologically complex free surface, and we could reasonably expect complex propagation effects close to the tributary canyons, depending on the depth of incision at the time of fault propagation.

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We consider (in our defence!) that the task of assessing the change of fault plane dip with depth is neither simple nor unambiguous in the area of Cross and Y Canyons, owing to the difficulty of accessing suitable vantage points from the ground. Prior to publishing our 1995 and 1996 papers, our two visits to Cross and Y Canyons, convinced us that the deeper structure was as shown in those papers. We were not able to gain access to the stretches of the canyon floors beyond the large waterfalls, and so our views were based on side-on views mainly of the north wall of Cross Canyon. We formed the strong impression that the faults bounding McGill et al.'s graben 2 in particular, could easily pass into the evaporites (estimated to be about 50 m beneath stream level) without intersecting, because they were approximately 70 m apart at the stream level.

Given the uncertainties involved, and with the benefit of hindsight, we should certainly have been much more careful in our phrasing in Cartwright et al. (1995), and not leapt to the general conclusion of a deeper structure based on such equivocal field evidence. In particular, no faults are actually exposed at the contact with the top of the evaporites, and therefore it is incorrect to claim that the geometry is constrained "to the top of the evaporites", although it is quite close in some cases. However, we did acknowledge the inward dipping nature of the graben structure as described by McGill and Stromquist (1979). Our descriptive phrase of "vertical to sub-vertical" is appropriate.

McGill et al. use a selection of oblique aerial photographs of grabens exposed in the canyon walls to make a very convincing case that there is evidence for structural intersection between inward dipping normal faults. Their fig. 5 in particular is definitive, but the other photographic figures are less clear because of perspective. This example (fig. 5) considerably strengthens the case for structural intersection at depth above or at the top of the evaporites *contra* the arguments expressed in our 1995 and 1996 papers. However, without any detailed maps of the key area [Huntoon et al. (1982) mapped at 1:62 500, and this is not sufficiently detailed] it is hard to be certain what the intersection geometry is in a more general sense. Based on evidence collected during the past three field seasons (1995–1997), our current view is that the original geometrical model of McGill and Stromquist (1979) is probably applicable for many of the grabens, but not for all. We disagree entirely, however, with the estimate of extension of 25% across the northern sector of the Needles presented by Schultz and Moore (1996), which seems to us to be based on a fault interpretation consisting of planar faults dipping at approximately 60° from the surface to the top of the Paradox evaporites. As McGill et al. note, there certainly does seem to be a 'scatter' in the interpretation of fault geometry, even in the near surface region.

McGill et al. rightly emphasise in their closing paragraphs the importance of understanding the fault geometry as a prelude to improving our view of the kinematics and mechanics of this classical area. We completely concur with these sentiments and are happy to correct the erroneously definitive impression given by Cartwright et al. (1995, 1996) that graben-bounding faults do not intersect before the top of the evaporites. This correction is obviously important for those preceding authors who argued for such a relationship, and will prevent any future workers in this area from gaining a mistaken view before examining the evidence for themselves. However, there is an obvious need for detailed mapping to completely settle the issue, of the level of detail, for example, achieved by Stromquist (1976) in his excellent map of Lower Red Lake.

In conclusion, the main aim of our 1995 paper was to offer an explanation for scatter in displacement and trace length data that was present in many fault datasets. Our explanation was based on a model of fault growth by linkage of laterally propagating segments. Irrespective of whether the graben-bounding faults intersect at the top of the evaporites, just above the evaporites, within the exaporites, or tip out into ductile structures without direct brittle intersection, there is considerable evidence from the displacement gradient data of the tip regions of many of the graben-bounding faults, that these faults exhibit considerable interaction during their growth (Cartwright and Mansfield, 1998). This mechanical interaction must certainly account for a considerable element of the scatter in displacement and length data, possibly over and above that simply produced through linkage alone. Whilst the deeper geometry is clearly poorly constrained over much of the area, the considerable dissimilarity in displacement profiles between opposing pairs of graben-bounding faults (Cartwright and Mansfield, 1998) argues against a fully coupled growth history exhibited by these pairs of faults. This lessens the probablility, in our view, that graben-bounding pairs nucleated at depth and propagated upwards to intersect the free surface. We think it probable that the majority of the faults in this area nucleated at the surface and propagated downwards (Cartwright and Mansfield, 1998). For this reason, we do not believe that lack of precise constraints on the nature of any intersection relationship near the top of the evaporites lessens the value of the essential point made in our 1995 paper, that segment linkage can produce substantial deviation from idealised scaling behaviour.

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