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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: Discussion

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Cartwright et al. (1995) have published an interesting and valuable study of fault growth by segment linkage based on field studies in the Needles District of Canyonlands National Park, southeastern Utah, where there is an unusually well exposed suite of grabens and associated valley anticlines (Harrison, 1927; Prommel and Crum, 1927; Baker, 1933; Lewis and Campbell, 1965; Potter and McGill, 1978; McGill and Stromquist, 1979; Huntoon, 1982; Trudgill and Cartwright, 1994; Cartwright et al., 1995, 1996; Schultz and Moore, 1996; Cartwright and Mansfield, 1998; Moore and Schultz, 1999). However, we disagree with the cross-sectional geometry assumed by Cartwright et al. The Canyonlands grabens have received much attention in recent years for at least three reasons: 1) they represent accessible analogues for simple graben structures exposed on the Moon and Mars; 2) they provide valuable field tests of theoretical fault propagation models; and 3) they are excellent on-land analogues for offshore oil-producing graben complexes. It is our opinion that it is important to understand the geometry of these grabens in order to infer kinematics and mechanics with confidence.

As originally suggested by Baker (1933), the grabens can be explained as due to downdip creep of a ~460-m-thick section of brittle Pennsylvanian and Permian limestones and sandstones on underlying Paradox evaporites (Fig. 1). Conditions favorable for this creep include the existence of a ~4° northwest regional dip towards the Colorado River (Elston and Shoemaker, 1961), coupled with rapid downcutting by the Colorado River (Hunt, 1969). Estimated rates of erosion (Hunt, 1969; Biggar et al., 1981; Huntoon, 1988) result in downcutting through the entire brittle plate to expose a free face in the wall of Cataract Canyon in only a few million years. Once a free face existed, the brittle plate was free to creep towards the river. Rapid erosion implies that the structures must be relatively young, which is consistent with the excellent preservation of the grabens and valley anticlines. The existence of anticlines following and evidently controlled by pre-existing valleys was first noted during the Powell expedition of 1871–72 (Bishop, 1947). That these structures are probably related to the same mechanism responsible for the grabens was suggested by Potter and McGill (1978). A more detailed description of the graben system and of individual grabens and valley anticlines may be found in Potter and McGill (1978), McGill and Stromquist (1979), Trudgill and Cartwright (1994) and Moore and Schultz (1999).

McGill and Stromquist (1979) proposed a model for the kinematics and mechanics of graben formation and evolution based on elementary rock-mechanics principles and a mechanical analogy with valley glaciers. A symmetrical graben geometry was inferred, including bounding faults with approximately equal slip and graben floors with negligible transverse tilt. More recent work (Trudgill and Cartwright, 1994; Schultz and Moore, 1996; Moore and Schultz, 1999) clearly indicates that these assumptions are too simple, and that at least some of the grabens are not symmetrical. In

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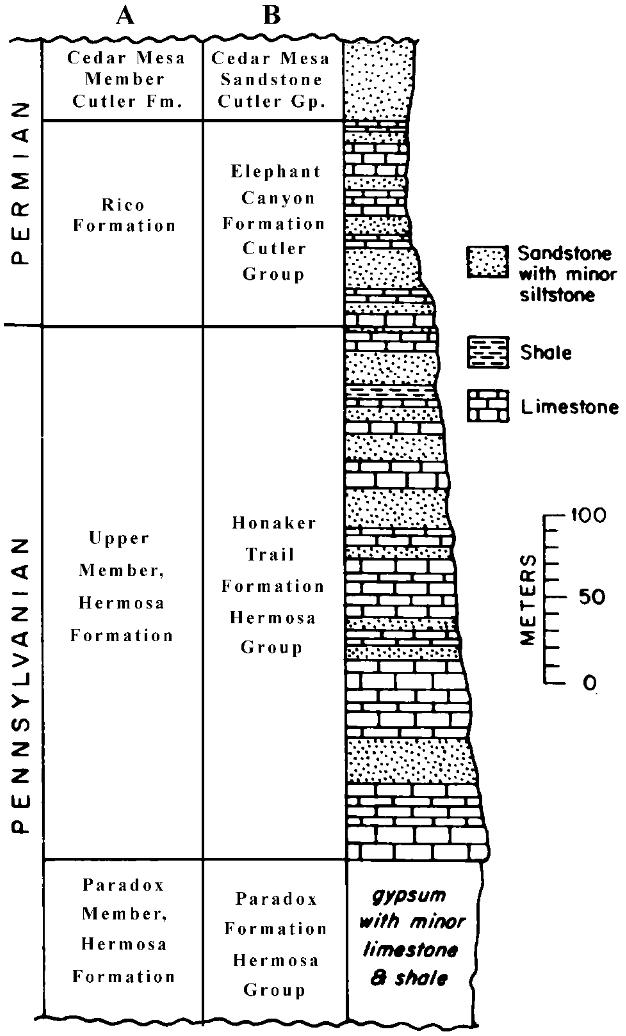

Fig. 1. Representative columnar section of rocks exposed in the Needles District, Canyonlands National Park. A is stratigraphic terminology of Lewis and Campbell (1965); B that of Huntoon et al. (1982). Both terminologies have been used in this region, but the differences are not relevant to structural geology issues. Thicknesses and lithologies of some formations change significantly within this region.

cross-section, the grabens were described by McGill and Stromquist (1979) as being bounded by joint-controlled vertical faults to a depth of about 100 m, and then by converging faults with average dips of about 75° from 100 m to ~460 m depth, which is the depth of the contact between the brittle plate and the underlying Paradox evaporites. However, in contrast with all earlier descriptions, including that of Trudgill and Cartwright (1994), Cartwright et al. (1995, 1996) have proposed that the faults bounding the grabens are nearly vertical entirely through the brittle plate, and thus that the grabens are basically plugs dropped into the underlying Paradox evaporites. We do not agree that the grabens exhibit this geometry, and it is the purpose of this comment to clarify what can be observed or inferred from outcrop about the cross-sections of the grabens.

The cross-sectional geometry originally proposed by McGill and Stromquist (1979) was based on exposures in deeply incised canyons oriented about normal to the grabens, and included detailed mapping in Lower Red Lake Canyon (Stromquist, 1976), a reconnaissance foot traverse in Y and Cross Canyons in 1976, and aerial reconnaissance. Y and Lower Red Lake Canyons were re-examined in the field in 1997. Aerial reconnaissance by small plane over Lower Red Lake, Y, and Cross Canyons, and also over the unnamed canyon south of Cross Canyon (Fig. 2), was repeated in 1997 and 1998. These four canyons provide the only exposures of the deep structures of the grabens; that is, exposures below the depth to which their bounding faults are controlled by older joints and thus are approximately vertical. Cartwright et al. (1995, 1996) state that they have seen grabens exposed in these cross canyons with bounding faults that extend with dips of ~90° entirely through the brittle plate to the top of the Paradox evaporites, although they do not provide specific localities. This postulated geometry is puzzling, however, because erosion has not reached the evaporites below any of the grabens exposed in cross-section in these canyons, and the bounding faults clearly converge downward in most instances and can be seen or inferred to meet at or above the top of the Paradox evaporites. The geological map by Huntoon et al. (1982), which is based on detailed field work, also clearly shows that faults bounding the grabens converge downward across these canyons, an elementary 'rule of Vs' indication that the bounding faults dip inward at angles significantly less than 90°. These relationships are consistent with recent work in several other grabens, such as Devils Lane and Devils Pocket, where demonstrable master and antithetic faults require nonvertical dips at depth (Moore and Schultz, 1999).

Cross and Y Canyons provide the best exposures of deep graben structures (Fig. 3) because three major grabens are transected by both of these canyons, and both canyons are eroded to sufficient depth to show the geometry of the grabens clearly. Figs. 4 and 5 are photographs taken from the air or on the ground showing more detailed strike-parallel views of grabens exposed in Cross and Y Canyons. The figures demonstrate that the grabens narrow with depth, as expected if the bounding faults dip towards each other. For two of these (grabens 2 and 3; Figs. 3 and 5), projection of this narrowing trend suggests that the faults meet at or a short distance above the top of the Paradox evaporites. Graben 1 (Figs. 3 and 4) and the small graben east of graben 3 (Fig. 3) are bounded by faults that meet above stream level in these canyons; that is, well above the top of the Paradox evaporites. This also can

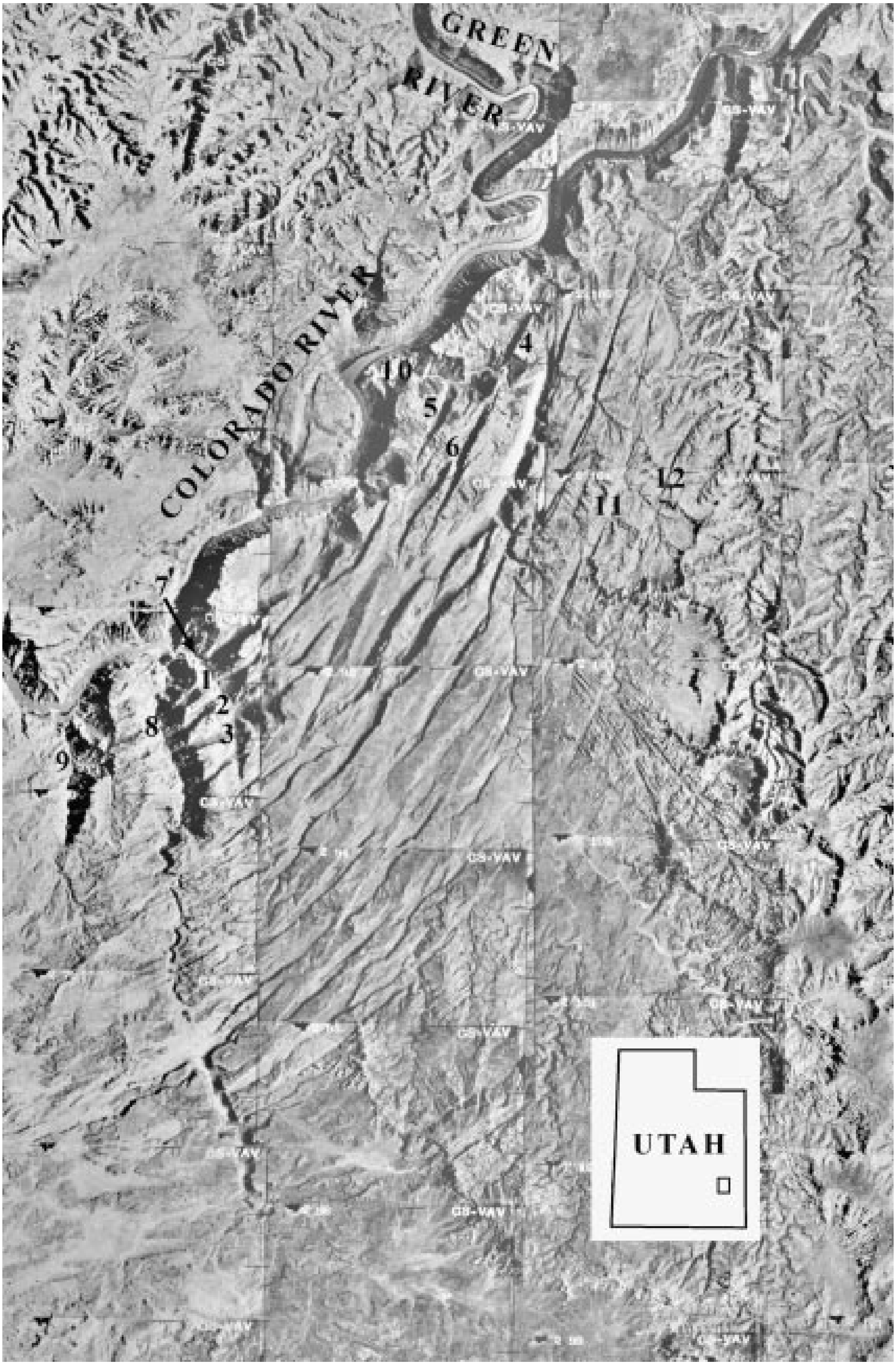

Fig. 2. Index map showing the location of the Canyonlands graben system and of the four deep canyons that transect these grabens: Lower Red Lake Canyon, Y Canyon, Cross Canyon, and an unnamed canyon south of Cross Canyon. 1–3 are grabens illustrated in Fig. 3; 4 is Lens Canyon; 5 is unnamed small graben west of Twin Canyon; 6 is Twin Canyon; 7 is Y Canyon; 8 is Cross Canyon; 9 is unnamed canyon south of Cross Canyon; 10 is Lower Red Lake Canyon; 11 is Devils Lane; 12 is Devils Pocket.

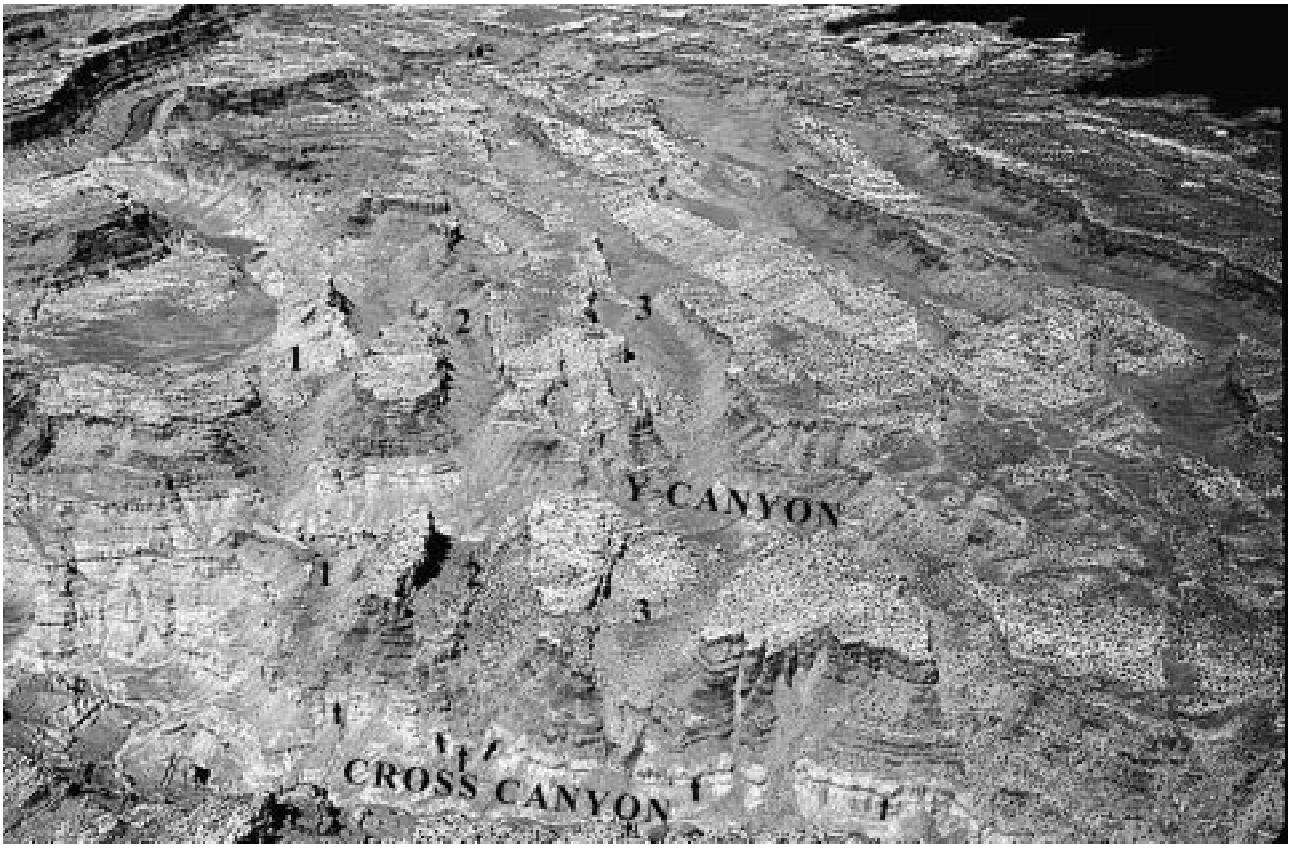

Fig. 3. Oblique view, looking north, of grabens crossing Cross Canyon (foreground) and Y Canyon. Grabens are numbered 1–3 for reference. Downward convergence of graben faults is implied by the prominent dark cliff (arrows) within a thick light-gray interval. Only one graben fault cuts this cliff beneath graben 1 (Fig. 4), the widths of grabens 2 (Fig. 5) and 3 across this cliff are much less than their widths at plateau level, and the faults bounding the small graben east of graben 3 converge above this cliff. The light gray interval containing the cliff is about in the middle of the Honaker Trail Formation. Photograph taken from about 2000 m above the upland land surface. Width of view in vicinity of Y Canyon is about 5 km; exposed relief is about 375 m.

be inferred from the geologic map of Huntoon et al. (1982), which shows faults bounding some of the grabens meeting above stream level.

Two grabens are exposed in cross-section in Lower Red Lake Canyon. One, Lens Canyon (4 on Fig. 2), has an eastern bounding fault that retains a near-vertical dip through the entire exposed section. However, the base of exposed rock at stream level is well above the top of the Paradox evaporites and, furthermore, the western fault bounding this graben clearly converges with the anomalously steep eastern bounding fault well above stream level (Stromquist, 1976). Whether the eastern bounding fault retains its steep dip into the underlying evaporites is indeterminate, but the exposed structure indicates that only the eastern fault can penetrate to the evaporites and thus that the overall graben structure is not best envisaged as a plug.

The second graben exposed in cross-section by Lower Red Lake Canyon is a relatively small structure west of Twin Canyon. This graben (5 on Fig. 2) is extensively choked with rock debris, and thus it is difficult to observe directly the traces of the bounding faults in cross-section. However, exposures of beds within the Honaker Trail Formation a short distance up slope from stream level and the foot trail in the canyon indicate that these faults cannot be more than about 75 m apart at this level, whereas the width of the graben within Cedar Mesa Sandstone at the top of the canyon wall is on the order of 200 m. Thus even though not as well exposed as the other examples cited here, this graben also is constrained to have bounding faults that dip inward at angles significantly less than 90°.

1. Summary

The geometry and kinematics of the Canyonlands grabens are more complex (and more interesting) than implied by the simple model of McGill and Stromquist (1979). However, our photographs, in conjunction with the results of detailed mapping by Stromquist (1976), Huntoon et al. (1982), and Moore and Schultz

Fig. 4. Graben 1 (Fig. 3) on the north wall of Y Canyon. View looking north from about 500 m above the upland surface. The bounding faults converge above the prominent dark cliff (arrows), with slip only on the left (west) fault continuing through this part of the section.

(1999), demonstrate that there is no outcrop evidence that the Canyonlands grabens are bounded by faults that maintain ~90° dips at depth. Thus we suggest that the available evidence indicates that the grabens are downward-pointed wedges rather than plugs with near-vertical bounding faults. Differences in interpretation of observed structures, as is the case for the Canyonlands grabens, are to be expected; indeed, such differences are a sign of a healthy science. However, the geometry of the grabens is a critically important parameter for any effort to infer kinematics and mechanics, and we hope that this discussion will contribute to closer agreement concerning the general cross-sectional geometry of the Canyonlands grabens.

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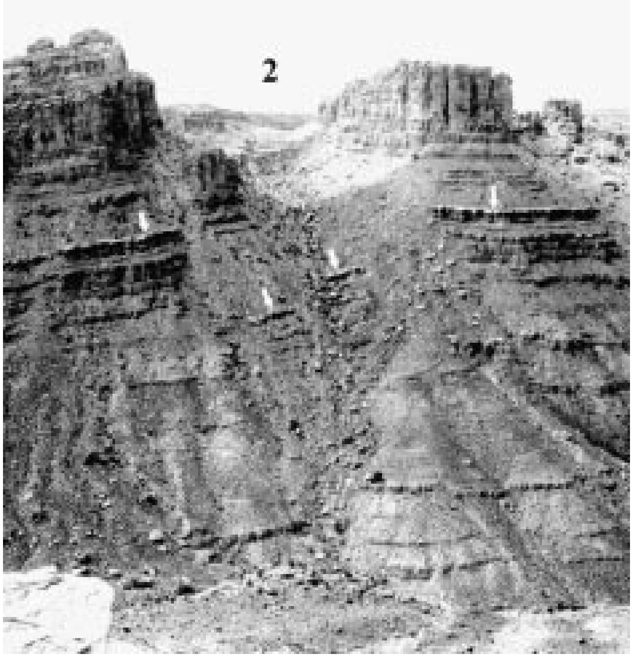

Fig. 5. Graben 2 (Fig. 3) on the south wall of Y Canyon. View looking south taken from the north wall of the canyon. The main bounding faults clearly converge downward and can be projected to meet at a shallow depth below stream level where they would still be within the Honaker Trail Formation. The white-topped cliff (arrows) is within an interval mapped as Halgaito Shale/Elephant Canyon Formation transition by Huntoon et al. (1982).

References

Baker, A.A. 1933. Geology and oil possibilities of the Moab district, Grand and San Juan counties, Utah. U.S. Geological Survey Bulletin 841.

Biggar, N.E., Harden, D.R., Gillam, M.L., 1981. Quaternary deposits in the Paradox basin. In: 1981 Field Conference Guidebook. Rocky Mountain Association of Geologists, pp. 129–145.

Bishop, F.M., 1947. Bishop's journal. In: Kelley, C. (Ed.), Biographical sketches and original documents of the second Powell expedition of 1871–72, Utah Historical Quarterly, vol. 15, pp. 159–238.

Cartwright, J.A., Trudgill, B.D., Mansfield, C.S., 1995. Fault growth by segment linkage — an explanation for scatter in maximum displacement and trace length data from the Canyonlands grabens of SE Utah. Journal of Structural Geology 17, 1319–1326.

Cartwright, J.A., Mansfield, C., Trudgill, B., 1996. The growth of normal faults by segment linkage. In: Buchanan, P.G., Nieuwland, D.A. (Eds.), Modern developments in structural interpretation, validation and modelling, vol. 99. Geological Society Special Publication, pp. 163–177.

Cartwright, J.A., Mansfield, C.S., 1998. Lateral displacement variation and lateral tip geometry of normal faults in the

Canyonlands National Park, Utah. Journal of Structural Geology 20, 3–19.

Elston, D.P., Shoemaker, E.M. 1961. Preliminary structure contour map on top of salt in the Paradox Member of the Hermosa Formation in the salt anticline region, Colorado and Utah. U.S. Geological Survey Oil and Gas Investigations Map OM-209, scale 1:250,000.

Harrison, T.E., 1927. Colorado–Utah salt domes. American Association of Petroleum Geologists Bulletin 11, 111–133.

Huntoon, P.W., 1982. The Meander anticline, Canyonlands, Utah: An unloading structure resulting from horizontal gliding on salt. Geological Society of America Bulletin 93, 941–950.

Huntoon, P.W., 1988. Late Cenozoic gravity tectonic deformation related to the Paradox salts in the Canyonlands area of Utah. Utah Geological and Mineral Survey Bulletin 122, 81–93.

Huntoon, P.W., Billingsley, G.H., Breed, W.J. 1982. Geologic map of Canyonlands National Park and vicinity. The Canyonlands Natural History Association, Moab, Utah, scale 1:62,500.

Hunt, C.B. 1969. Geologic history of the Colorado River. U.S. Geolological Survey Professional Paper 669-C.

Lewis, R.Q. Sr, Campbell, R.H. 1965. Geology and uranium deposits of Elk Ridge and vicinity, San Juan county, Utah. U.S. Geolological Survey Professional Paper 474-B.

McGill, G.E., Stromquist, A.W., 1979. The grabens of Canyonlands National Park, Utah: Geometry, mechanics, and kinematics. Journal of Geophysical Research 84, 4547–4563.

Moore, J.M., Schultz, R.A., 1999. Processes of faulting in jointed rocks of Canyonlands National Park, Utah. Geological Society of America Bulletin 111, 808–822.

Potter Jr, D.B., McGill, G.E., 1978. Valley anticlines of the Needles District, Canyonlands National Park, Utah. Geological Society of America Bulletin 89, 952–960.

Prommel, H.W.C., Crum, H.E., 1927. Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation. American Association of Petroleum Geologists Bulletin 11, 373–391.

Schultz, R.A., Moore, J.M., 1996. New observations of grabens from the Needles District, Canyonlands National Park, Utah. In: Huffman Jr, A.C., Lund, W.R., Goodwin, L.H. (Eds.), Geology and resources of the Paradox basin. Utah Geological Association Guidebook, vol. 25, pp. 295–302.

Stromquist, A.W. 1976. Geometry and growth of grabens, Lower Red Lake Canyon area, Canyonlands National Park, Utah. Department of Geosciences, University of Massachusetts, Amherst, Contribution 28.

Trudgill, B., Cartwright, J., 1994. Relay-ramp forms and normal-fault linkages, Canyonlands National Park, Utah. Geological Society of America Bulletin 106, 1143–1157.