Observations from the Basin and Range Province (western United States) pertinent to the interpretation of regional detachment faults

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Abstract: This paper summarizes the results of completed and ongoing research in three areas of the Basin and Range Province of the western United States that casts doubt on the interpretation of specific regional detachment faults and the large extensional strains with which such faults are commonly associated. Given that these examples were influential in the development of ideas about low-angle normal faults, and particularly in making the case for frictional slip at dips of appreciably less than the 30° lock-up angle for $\mu \approx 0.6$ (where μ is the coefficient of friction), we advocate a critical re-examination of interpreted detachments elsewhere in the Basin and Range Province and in other extensional and passive margin settings.

The Sevier Desert 'detachment' of west-central Utah is reinterpreted as a Palaeogene unconformity that has been traced to depth west of the northern Sevier Desert basin along an unrelated seismic reflection (most probably a splay of the Cretaceous-age Pavant thrust). The absence of evidence in well cuttings and cores for either brittle deformation (above) or ductile deformation (below) is inconsistent with the existence of a fault with as much as 40 km of displacement. The Pavant thrust and the structurally higher Canyon Range thrust are erosionally truncated at the western margin of the southern Sevier Desert basin, and are not offset by the 'detachment' in the manner assumed by those inferring large extension across the basin.

The Mormon Peak detachment of SE Nevada is reinterpreted as a series of slide blocks on the basis of detachment characteristics and spatially variable kinematic indicators that are more closely aligned with the modern dip direction than the inferred regional extension direction. A particularly distinctive feature of the detachment is a basal layer of up to several tens of centimetres of polymictic conglomerate that was demonstrably involved in the deformation, with clastic dykes of the same material extending for several metres into overlying rocks in a manner remarkably similar to that observed at rapidly emplaced slide blocks. The Castle Cliff detachment in the nearby Beaver Dam Mountains of SW Utah is similarly regarded as a surficial feature, as originally interpreted, and consistent with its conspicuous absence in seismic reflection profiles from the adjacent sedimentary basin.

The middle Miocene Eagle Mountain Formation of eastern California, interpreted on the basis of facies evidence and distinctive clast provenance to have been moved tectonically more than 80 km ESE from a location close to the Jurassic-age Hunter Mountain batholith of the Cottonwood Mountains, is reinterpreted as having accumulated in a fluvial–lacustrine rather than alluvial fan–lacustrine setting, with no bearing on either the amount or direction of tectonic transport. The conglomeratic rocks upon which the provenance argument was based are pervasively channelized, with erosional relief of less than 1 m to as much as 15 m, fining-upwards successions at the same scale and abundant trough cross-stratification – all characteristic features of fluvial sedimentation and not of alluvial fans. The interpretation of the Eagle Mountain Formation as having been deposited within a few kilometres of the Hunter Mountain batholith, which depends strongly on assumptions about the dimensions of alluvial fans, is therefore not required. The result is important because the Eagle Mountain offset has been viewed as representing the strongest evidence for extreme extension in this part of California, and for the existence of detachment faults of regional dimensions.

'Even one compelling example of a primary LANF [low-angle normal fault] or of LANF slip is sufficient to prove that they may form and slip at low dip, respectively.' – Axen (2004, 50).

The Basin and Range Province of the western United States has been highly influential in the development of ideas about crustal extension, particularly the role of low-angle normal faults or

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detachments of regional scale (e.g. Armstrong 1972; Crittenden *et al.* 1980; Wernicke 1981, 1985, 1992; Allmendinger *et al.* 1983; Davis 1983; Miller *et al.* 1983; Spencer 1984; Wernicke & Axen 1988; Wernicke *et al.* 1988; Lister & Davis 1989; Spencer & Chase 1989; Axen *et al.* 1990, 1993; John & Foster 1993; Livaccari *et al.* 1993; Axen & Bartley 1997; Brady *et al.* 2000*a*; Snow & Wernicke 2000; Livaccari & Geissman 2001; Axen 2004; Carney & Janecke 2005). The detachment concept is now widely applied in extensional and passive margin settings (e.g. Froitzheim & Eberli 1990; Lister *et al.* 1991; Reston *et al.* 1996; Driscoll & Karner 1998; Hodges *et al.* 1998; Osmundsen *et al.* 1998; Taylor *et al.* 1999; Boncio *et al.* 2000; Manatschal *et al.* 2001; Canales *et al.* 2004). However, the apparent conflict between generally accepted geological interpretations and rock mechanical and seismological considerations has yet to be resolved satisfactorily (Sibson 1985; Jackson 1987; Jackson & White 1989; Collettini & Sibson 2001; Scholz & Hanks 2004; cf. Axen 1992, 1999, 2004; Scott & Lister 1992; Axen & Selverstone 1994; Wernicke 1995; Rietbrock *et al.* 1996; Abers *et al.* 1997; Westaway 1999; Sorel 2000; Collettini & Barchi 2002; Hayman *et al.* 2003).

Beginning in the early 1990s, we became interested in Basin and Range examples for which evidence was regarded by the structural geological community to be the most compelling for slip at dips of appreciably less than 30° – the lowest plausible frictional lock-up angle for crustally rooted normal faults in the absence of unusual materials ($\mu < 0.6$, where μ is the coefficient of friction) (Sibson 1985; Collettini & Sibson 2001) – and for the very large extensional strains with which low-angle normal faults are commonly associated (Wernicke *et al.* 1988; Levy & Christie-Blick 1989; Wernicke 1992; Snow & Wernicke 2000). We reasoned that if progress was to be made in developing a better theoretical understanding, it would be useful to focus on geological examples providing the firmest constraints.

This paper summarizes research from three case studies of historical significance and that individually account for many tens of kilometres of current estimates of upper crustal extension in the Basin and Range Province (Fig. 1). While each example has become closely associated with the work of specific investigators over several years, in offering new interpretations of available data we emphasize that our interest is solely in resolving a long-standing paradox. It is not our intent to cast aspersions on colleagues who have struggled hard with the same issues, and contributed much to the present state of knowledge.

A re-evaluation of the Sevier Desert detachment of west-central Utah (S in Fig. 1; see also Figs 2 & 3) (McDonald 1976; Allmendinger *et al.* 1983; Smith & Bruhn 1984; Von Tish *et al.* 1985; Mitchell & McDonald 1986, 1987; Planke & Smith 1991; Otton 1995; Coogan & DeCelles 1996; Stockli *et al.* 2001) is now largely published

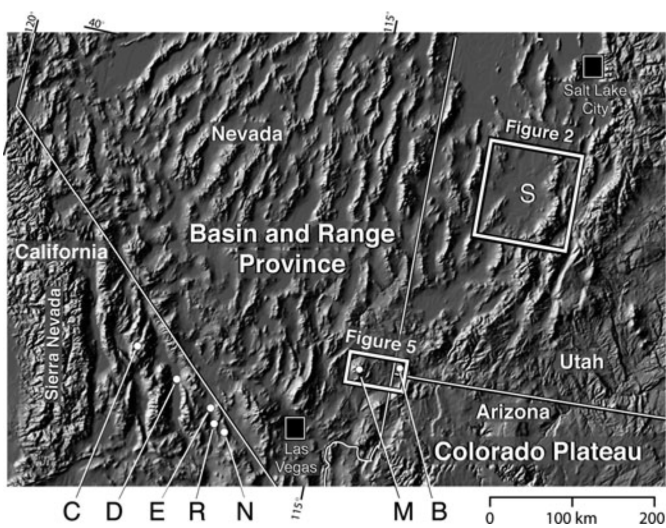

Fig. 1. Location of three study areas in Basin and Range Province: Sevier Desert (S), west-central Utah (see Fig. 2); Mormon Mountains (M), SE Nevada and Beaver Dam Mountains (B), SW Utah (see Fig. 5); and Eagle Mountain (E), eastern California. Other localities mentioned in text: Cottonwood Mountains (C), Death Valley (D), Resting Spring Range (R) and Nopah Range (N). Physiographical base for the map was modified from Thelin & Pike (1991).

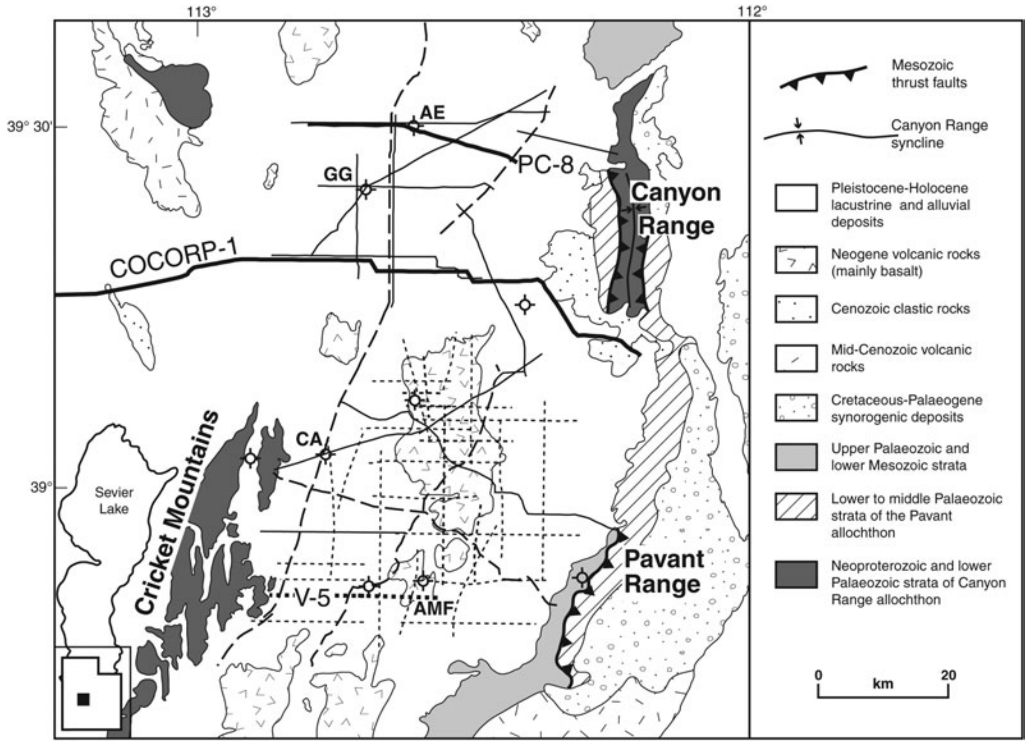

Fig. 2. Generalized map of Sevier Desert basin, Utah (modified from Wills *et al.* 2005; see Fig. 1 for location), showing locations of seismic profiles and wells mentioned in text. Seismic profiles (bold lines): COCORP Utah Line 1 (see Fig. 3); PC-8 and V-5 (see Fig. 4). Wells: AE, Argonaut Energy Federal; AMF, ARCO Meadow Federal; CA, Cominco American Federal; GG, Gulf Gronning. The locations of other seismic profiles and wells used by Wills *et al.* (2005) are included for context, but without labels. Solid, dashed and dotted lines correspond with different seismic datasets. Thrust faults are the Canyon Range thrust in the Canyon Range and the structurally lower Pavant thrust in the Pavant Range (teeth on upper plate). A drafting error in the Wills *et al.* (2005) original (Pavant thrust) has been corrected.

(Anders & Christie-Blick 1994; Wills & Anders 1999; Anders *et al.* 2001; Wills *et al.* 2005; for a discussion of contrasting views, see Allmendinger & Royse 1995; Anders *et al.* 1995, 1998*a*; Wills & Anders 1996; Otton 1996; Coogan & DeCelles 1998; Hintze & Davis 2003; DeCelles & Coogan 2006). Here, we summarize the evidence for an alternative interpretation: that the purported detachment is instead a regional unconformity of Palaeogene age (Gradstein *et al.* 2004) fortuitously aligned down dip in some seismic reflection profiles with a Mesozoic thrust fault.

Our research on detachment faults in the Mormon Mountains and Beaver Dam Mountains of SE Nevada and SW Utah (M and B in Fig. 1), and at known slide blocks elsewhere (Anders *et al.* 2000, 2006; Walker *et al.* 2007), has dealt mainly with the characteristics of fault zones and with the discrimination of crustally rooted structures from features that are surficial (or rootless). Data in hand are not consistent with the long accepted interpretation of the Mormon Peak and associated detachments as rooted faults (Wernicke 1981, 1982, 1995; Wernicke *et al.* 1985, 1988, 1989; Wernicke & Axen 1988; Axen *et al.* 1990; Axen 1993, 2004), and suggest instead that these structures relate to block-sliding with crustal extension accommodated entirely by high-angle normal faults (Anders *et al.* 2006; Walker *et al.* 2007; see also Cook 1960; Tschanz & Pampeyan 1970; Hintze 1986; Carpenter *et al.* 1989; Carpenter & Carpenter 1994; and Axen & Wernicke 1989 and Axen 2004 for a markedly different opinion).

The third example to which we draw attention in this paper relates to the generally accepted geological evidence for more than 400% extension in the Death Valley area of eastern California, between the Cottonwood Mountains and Nopah Range (C and N in Fig. 1) (Stewart 1983; Wernicke *et al.* 1988, 1993; Snow & Wernicke 1989, 2000; Holm *et al.* 1992; Snow 1992*a*; Topping 1993; Brady *et al.* 2000*b*; Niemi *et al.* 2001; for contrasting

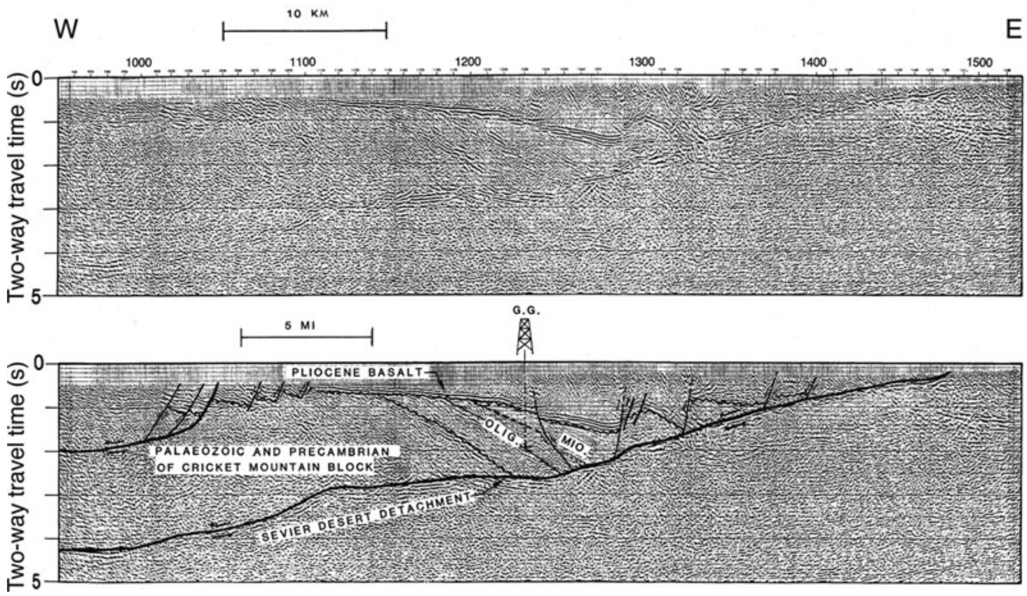

Fig. 3. Part of seismic reflection profile COCORP Utah Line 1, with interpretation of Sevier Desert detachment from Von Tish *et al.* (1985). See Figure 2 for location. The eastward-dipping panel labeled Olig. (Oligocene) by Von Tish *et al.* is reinterpreted as Palaeozoic and Neoproterozoic (Canyon Range allochthon), based on a velocity (3.2 km s^{-1}) for the basin fill at the Gulf Gronning well (G.G.) that is higher than originally assumed. The east-dipping fault beneath G.G. is inferred in Wills *et al.* (2005) and in this paper to offset the purported detachment, misaligning an updip portion of the reflection (interpreted as an unconformity) and a downdip portion (interpreted as a Mesozoic thrust fault, most probably a splay of the Pavant thrust).

interpretations of available data, see Stewart 1967, 1986; Wright & Troxel 1967, 1970; Stewart *et al.* 1968, 1970; Prave & Wright 1986*a*, *b*; Corbett 1990; Wernicke *et al.* 1990; Stevens *et al.* 1991, 1992; Snow 1992*b*; Snow & Wernicke 1993; Stone & Stevens 1993; Serpa & Pavlis 1996). Re-examination of the most important individual piece of evidence, a middle Miocene succession of breccia, conglomerate, sandstone, siltstone, limestone and tephra (Eagle Mountain Formation; E in Fig. 1) interpreted by Niemi *et al.* (2001) to have been deposited in an alluvial fan and lacustrine setting, and to have been transported tectonically more than 80 km from its Cottonwood Mountains source, suggests that the sediments accumulated in a fluvial–lacustrine environment (Renik & Christie-Blick 2004). If this alternative interpretation is correct, these deposits provide no constraint on either the magnitude or direction of extension, and they have no bearing on the interpretation of regional detachment faults.

Sevier Desert detachment

Interpretations of the Sevier Desert detachment of west-central Utah (Figs 2 and 3; see also Appendix 1) are based primarily on 1970s vintage petroleum industry seismic reflection and well data (McDonald 1976; Mitchell & McDonald 1987) and seismic profiles acquired by the Consortium for Continental Reflection Profiling (COCORP; Allmendinger *et al.* 1983; Von Tish *et al.* 1985). The low westward dip (11°) of the hypothesized detachment, its lateral continuity over 7000 km^2, the purported offset of Mesozoic structures by as much as 47 km, the downward termination of high-angle normal faults within the Sevier Desert basin (SDB) and the involvement of sediments as young as Holocene provide seemingly unassailable evidence for large normal offset on a fault that could never have been appreciably more steeply inclined than it is today, and might still be active (Wernicke 1995; Niemi *et al.* 2004).

Difficulties with the detachment hypothesis relate primarily to the absence of anticipated deformation in borehole cuttings and cores, in spite of an extensive study of such materials (Anders & Christie-Blick 1994; Anders *et al.* 2001), and to details of the subsurface stratigraphic and structural interpretation that are at odds with key elements of published palinspastic reconstructions (Wills *et al.* 2005). Cuttings from directly above the Palaeozoic–Palaeogene contact where the maximum depth never exceeded 1.8 km exhibit no sign of deformation expected of a brittle fault at that depth (Anders & Christie-Blick 1994). Fossil trilobite fragments, recovered in core from 12.8 m below the same contact and in cuttings from as close as 3 m, are undeformed (Anders *et al.* 2001). A palinspastic reconstruction assuming 47 km of normal slip on the hypothesized detachment places the trilobite-bearing Palaeozoic carbonate rocks at a depth of at least 14 km at the time faulting is inferred to have begun (after the late Oligocene). Given that the region had been volcanically active for at least 10–20 million years (beginning in the Eocene), any reasonable estimate of the geothermal gradient puts the rocks at a temperature (as high as 425 °C) at which mylonites should have developed in carbonate rocks (Anders *et al.* 2001). No evidence for mylonitization has been observed.

The apparent continuity of the Sevier Desert reflection (SDR) from the Palaeozoic–Palaeogene contact beneath the basin to within deformed Neoproterozoic and Palaeozoic rocks of the Cricket Mountains block to the west is restricted to the northern SDB (Figs 2, 3 & 4a) (Wills *et al.* 2005). In the south, the SDR terminates abruptly at or only a short distance beneath the Cricket Mountains (Fig. 4b). Although seismic attenuation and the absence of a sufficiently large contrast in acoustic impedance offer plausible explanations for this observation, a comprehensive re-analysis of seismic reflection and borehole data, including nearly 600 km of previously unavailable profiles, leads to a different conclusion. The feature with which the SDR is approximately aligned in COCORP Utah Line 1, and in virtually all industry and academic dip-oriented profiles from the northern part of the basin, is a Mesozoic thrust fault, most probably a splay of the Cretaceous-age Pavant thrust. That fault, which places Lower Cambrian quartzite atop Upper Cambrian carbonate rocks in the Cominco American Federal well (CA in Fig. 2), rises southwards approximately 2–3 km with respect to a westward projection of the SDR. Even in COCORP Line 1 (Fig. 3) the two features are misaligned by about 0.3 s two-way travel time at a high-angle normal fault system that has been mapped for approximately 80 km along the western side of the basin (cf. Fig. 4a).

Our re-evaluation of the subsurface data is inconsistent with a related second pillar of the detachment hypothesis: that as much as 47 km of normal slip is needed to account for the offset of Mesozoic thrust sheets across the SDB (Von Tish *et al.* 1985; Allmendinger & Royse 1995; DeCelles

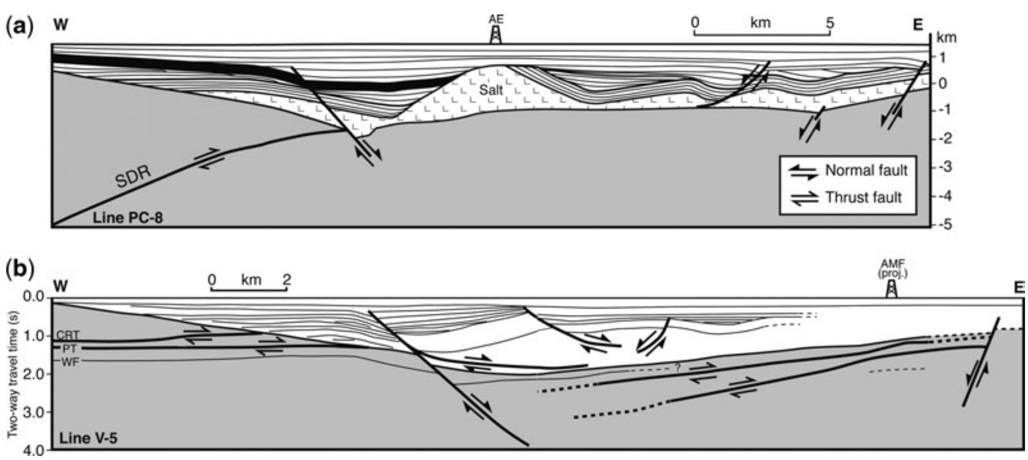

Fig. 4. Interpretive line drawings of seismic reflection profiles from northern and southern Sevier Desert basin (modified from figs 6A and 7D of Wills *et al.* 2005; see Fig. 2 for the location). Grey indicates pre-Cenozoic rocks; white represents Cenozoic basin fill, with stratal geometry shown by fine lines. Both profiles illustrate a persistent pattern of stratal onlap against sub-Cenozoic unconformity of Cricket Mountains block (west) and the existence of basin-bounding high-angle normal faults of relatively small offset. (**a**) PC-8 (McDonald 1976). Black indicates interstratified basalt and clastic sediments penetrated by Gulf Gronning well 10 km south of section. Domal structures flanked by growth stratigraphy are inferred to be salt-cored. SDR is downdip portion of the Sevier Desert reflection, interpreted as a splay of Pavant thrust. AE is Argonaut Energy Federal well. Vertical scale in kilometres. (**b**) V-5 (Wills *et al.* 2005). Listric faults displace panels of subparallel reflections, with stratal growth preferentially at higher stratigraphic levels. Faults interpreted as the Canyon Range thrust (CRT) and Pavant thrust (PT) are erosionally truncated (left). Neither aligns with base of basin to east. WF is Whirlwind Formation (Cambrian). AMF is ARCO Meadow Federal well. Vertical scale in seconds, two-way travel time.

et al. 1995; Coogan & DeCelles 1996, 1998; Stockli *et al.* 2001; DeCelles & Coogan 2006). Both the Pavant thrust and the structurally higher Canyon Range thrust are erosionally truncated at the western margin of the southern SDB (Fig. 4b). The SDB is therefore underlain primarily by sub-Pavant rocks, and by the Pavant and Canyon Range allochthons in the north and west as a result of the regional dip of those structures. That a thick succession of Neoproterozoic strata composing the Canyon Range allochthon in the Cricket Mountains projects approximately 60 km NE across the SDB to a tightly folded klippe of the same thrust sheet at the crest of the Canyon Range (Fig. 2) is a measure of the dimensions of the now dissected Mesozoic allochthon rather than of its offset by a Cenozoic detachment fault.

Taken together, these observations and others summarized in Appendix 1 lead to a very different interpretation of the SDR: that it is a regional unconformity of Palaeogene age, aligned particularly west of the northern SDB with a Mesozoic thrust fault. The downward termination of high-angle normal faults and localized stratigraphic growth, also cited as evidence for the existence of a detachment, are attributed to syndepositional deformation of Oligocene salt that today forms residual masses more than 1500 m thick (Argonaut Energy Federal well; AE in Fig. 4a).

Mormon Peak and associated detachments

The Mormon Peak, Tule Springs and Castle Cliff detachments (MPD, TSD and CCD, respectively) of SE Nevada and adjacent Utah have been interpreted on the basis of geological mapping to be crustally rooted and of regional extent, and to accommodate 54 ± 10 km of Miocene extension (Figs 5 and 6; Appendix 2) (Wernicke 1981, 1982, 1995; Wernicke *et al.* 1985, 1988, 1989; Wernicke & Axen 1988; Axen *et al.* 1990; Axen 1993, 2004). Research on these detachments, beginning in the late 1970s, was instrumental in arguing for the importance of low-angle normal faults and for

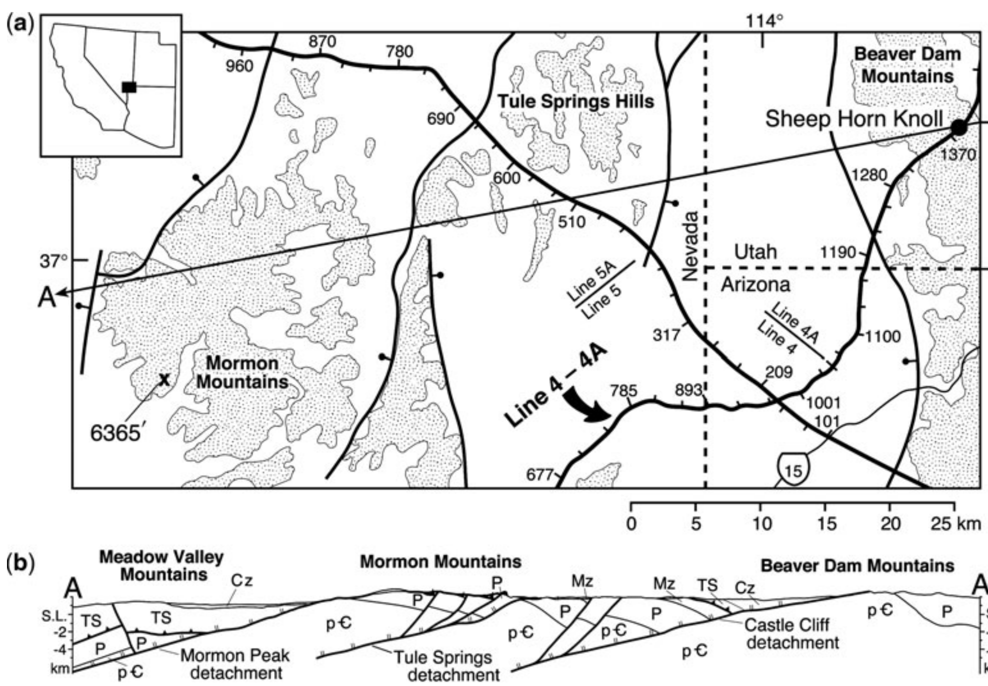

Fig. 5. (**a**) Physiographical map of the Mormon Mountains, Tule Springs Hills and Beaver Dam Mountains of SE Nevada and adjacent Utah, with location of range-bounding normal faults (ball on downthrown side), seismic reflection profiles (with shot points) and the eastern portion of the regional geological cross-section A–A′ (modified from Anderson & Barnhard 1993*a* and Carpenter & Carpenter 1994; see Fig. 1 for the location and Fig. 9 for profile 4-4A). (**b**) Cross-section A–A′ (simplified from fig. 17a of Axen *et al.* 1990 and plate 2 of Anderson & Barnhard 1993*a*; see Fig. 6 for the restored section). Abbreviations: pЄ, Precambrian crystalline rocks; P and Mz, Palaeozoic and Mesozoic strata in footwall of Mormon–Tule Springs thrust fault; TS, Precambrian and Palaeozoic rocks in the hanging wall of Tule Springs thrust fault; Cz, Cenozoic strata.

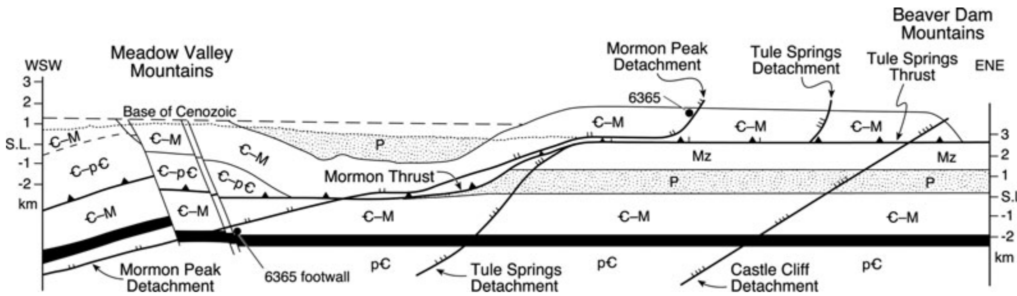

Fig. 6. Published pre-extension restoration of the regional geological cross section A–A′ from Meadow Valley Mountains to Beaver Dam Mountains (modified from fig. 17c of Axen *et al.* 1990; see fig. 5b for the present-day section). Vertical and horizontal scales are the same, with elevations corresponding approximately to those of today at the WSW and ENE ends of the section. The dotted line on the left is present topography. The original line length of 49 km is inferred by Axen *et al.* to have been increased by 54 km in a section oriented 258° (255° ± 10° is extension direction inferred by Wernicke *et al.* 1988). The Mormon Peak, Tule Springs and Castle Cliff detachments (indicated by two, three and four ticks, respectively) are notable for their markedly different restored geometry. The portion of the Tule Springs (Mormon) thrust inferred by Axen *et al.* (1990) to have been reactivated as the Tule Springs detachment is indicated by both thrust (teeth) and detachment (single tick) symbols. Abbreviations: p€ Precambrian crystalline rocks; black, Cambrian clastic rocks; €-M, Cambrian–Mississippian carbonate rocks; P, Pennsylvanian–Permian strata; Mz, Mesozoic strata. Palinspastic location of block 6365 is compared with that of its footwall at western flank of Mormon Mountains (see Fig. 5a).

high extensional strain in regions not associated with metamorphic core complexes. Initial dips inferred from palinspastic reconstruction are 32° for the CCD to a depth of at least 7 km; 20°–28° for the MPD to a depth of at least 6 km; and 3°–15° for the Tule Springs detachment to a depth of 2–5 km, corresponding with a flat in the Mesozoic-age Tule Springs thrust (Fig. 6) (Wernicke & Axen 1988; Axen *et al.* 1990; Axen 1993, 2004). Present dips are 11°W for the CCD; <20°E and <20°W, and with a considerable range of azimuth for the MPD; and near horizontal for the TSD in available outcrop.

Following earlier work by Carpenter & Carpenter (1994), a challenge to the generally accepted rooted interpretation of these detachment faults has emerged recently from studies of the character and kinematics of deformation associated with the MPD (Appendix 2) (Anders *et al.* 2006; Walker *et al.* 2007). As recognized long ago by Wernicke (1982), the MPD is in many places characterized by a 0.1–1m-thick layer of polymictic conglomerate (Fig. 7) that he interpreted as synorogenic gravel overridden by a Mesozoic thrust fault before being carried down in the fault zone of the detachment. More recently, Wernicke re-interpreted the conglomerate as sediments ‘deposited after or near the end of detachment activity in cavern systems that followed the crushed carbonates adjacent to the detachment’ (pers. comm. 2002 to G. J. Axen; p. 61 in Axen 2004).

Neither explanation matches available observations. The conglomerate is compositionally distinct from known Cretaceous synorogenic deposits in this part of Nevada (Carpenter & Carpenter 1994), deposits that are in any case unlikely to have remained unlithified for approximately 50 million years at a depth of up to several kilometres. Although karst is present in these rocks, the grading, flow banding and internal erosional features that characterize the conglomerate are not normally associated with karst infill (James & Choquette 1988). Most important, the conglomerate was demonstrably involved in the deformation, with a lower faulted contact characterized by a thin gouge or cataclastic layer (Fig. 7). As is typical of large gravity slides, a network of clastic dykes is extensively developed above the detachment, but absent below. With one possible exception, no evidence has been found for more than a single emplacement event at any individual locality.

A second difficulty for the concept of an extensional allochthon of regional scale is that kinematic indicators for the MPD (slickenlines and minor faults in the basal conglomerate) are of varied orientation, diverge markedly from the published regional extension direction (Fig. 8; 255° ± 10°) (Wernicke *et al.* 1988), and at many locations correspond approximately with the modern downdip direction of the detachment surface (Anders *et al.* 2006; Walker *et al.* 2007; cf. Axen 2004, p. 60).

Available evidence is consistent with the rapid surficial sliding of blocks downhill, away from the crest of the Mormon Mountains, as it existed in Miocene time (see Appendix 2) (Anders *et al.* 2006; Walker *et al.* 2007). Polymictic conglomerate, similar to that observed at the MPD and recognized as basal layers and dykes within a wide range

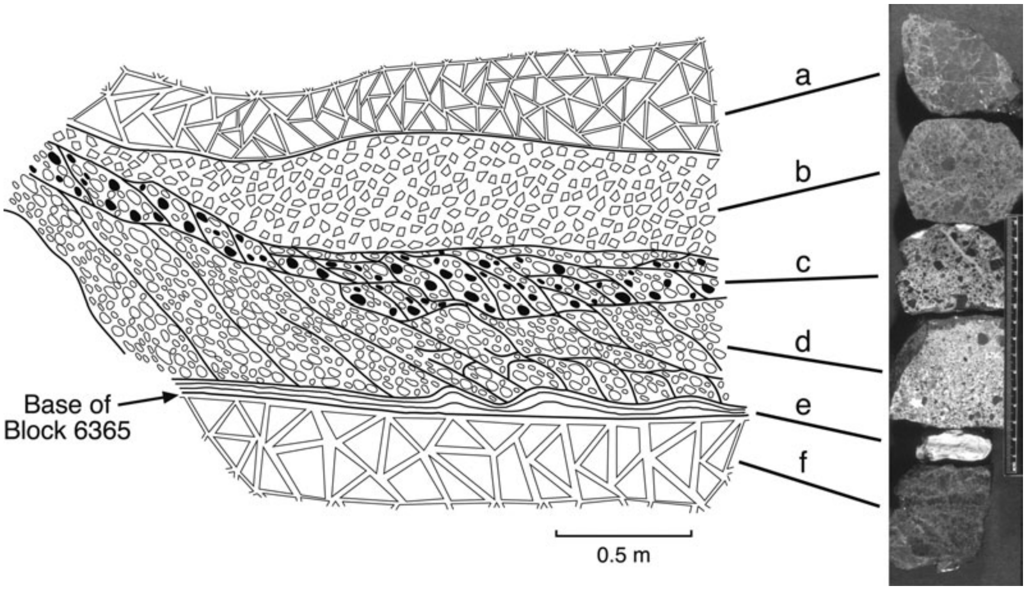

Fig. 7. Cross-section of trench through Mormon Peak detachment beneath block 6365, Mormon Mountains (see Figs 5 and 6 for the location; and Anders *et al.* 2006 for additional information about this contact). Arrow points to detachment surface. Representative hand specimens on right: a, crackle breccia of Devonian dolomite (Sultan Formation); b, matrix-supported auto-breccia of Devonian dolomite; c, mixture of dolomite and conglomerate; d, polymictic conglomerate with well-rounded particles; e, basal gouge layer; f, brecciated Cambrian dolomite (Bonanza King Formation). The conglomerate illustrated by specimen d is commonly characterized by grading, flow banding and internal erosional features.

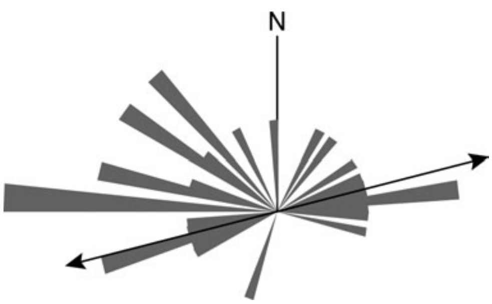

Fig. 8. Rose diagram showing the trend of 31 kinematic indicators (mostly slickenlines and grooves) at localities along Mormon Peak detachment in Mormon Mountains, Nevada (data from C. D. Walker). The indicators, which provide no independent measure of sense of displacement, are plotted according to local direction of plunge and in increments of 5°. Double-headed arrow indicates inferred extension direction of $255^\circ \pm 10^\circ$ from Wernicke *et al.* (1988). Azimuths are remarkably dispersed, 29% of them more than 40° from 255° or 075°. Only two readings (6%) are oriented at more than 40° from the local dip direction of the detachment.

of slides (e.g. Yarnold & Lombard 1989; Shaller 1991; Beutner & Craven 1996; Anders *et al.* 2000), is thought to be associated with fluidization, which serves to explain the long runouts of such features (Shaller 1991; Anders *et al.* 2000; Beutner & Gerbi 2005).

The Castle Cliff detachment on the western flank of the Beaver Dam Mountains is one of the structures used by Wernicke & Axen (1988) to exemplify their rolling hinge model for extensional unroofing, but its significance is challenged by seismic reflection data and geological mapping that were available in the 1980s (Fig. 9) (Hintze 1986; Carpenter *et al.* 1989). As interpreted by Wernicke & Axen (1988), the detachment passes beneath now isolated exposures of Cambrian–Mississippian rocks at Castle Cliff and Sheep Horn Knoll (Fig. 5a), as well as a series of smaller blocks and their substrate of Neogene (Gradstein *et al.* 2004) gravel at the range front, and projects to depth with a dip of 11° (Fig. 5b) (Wernicke *et al.* 1989; Axen *et al.* 1990; Axen 2004; cf. Anderson & Barnhard 1993*a*, *b*). Surprisingly, no detachment can be discerned in a seismic reflection profile that intersects the range front only 5 km south of the geological cross-section (Figs 5a & 9) (section 4A of Carpenter & Carpenter 1994) or in seismic reflection data from anywhere else in the Virgin River depression immediately south and east of the Mormon Mountains and Tule Springs Hills (Bohannon *et al.* 1993). Instead, profile 4A reveals the presence of a range-bounding normal fault that, after depth conversion and a correction for its oblique orientation, dips at 60° (Fig. 9b). In the absence of any evidence for a transfer fault between section A–A′ and line 4-4A (Fig. 5) (cf. Axen 2004, p. 60), the apparent inconsistency can perhaps be resolved by hypothesizing that the detachment is offset to a depth of at least 4 s (>5.5 km) by the high-angle fault (G. J. Axen pers. comm. 1998). However, that interpretation is at odds with the published cross-section (Fig. 5b) as well as with the rolling hinge model for the detachment (Wernicke & Axen 1988; see Axen & Bartley 1997).

A more plausible interpretation is that the Castle Cliff detachment is an expression of landsliding, as previously suggested by Cook (1960), Hintze (1986), Carpenter *et al.* (1989) and Anders *et al.* (1998*b*), and has nothing to do with crustal extension. According to that view, the isolated blocks of Palaeozoic rocks have a common origin (they are all rootless), independent of whether their substrate is Precambrian or Neogene; and the sub-Neogene contact at the flank of the Beaver Dam Mountains is in part depositional and in part faulted, but not an expression of the Castle Cliff detachment.

The slide block interpretation has been dismissed by Axen & Wernicke (1989) and by Axen (2004) for a host of reasons, none of them definitive or accounting for the specifics outlined here. A key argument relates to the near concordance (<5°–10°; Hintze 1986) between Oligocene–Miocene sedimentary and volcanic rocks and Cretaceous–Palaeogene (?) strata in the northern Beaver Dam Mountains (Axen & Wernicke 1989). It is reasoned

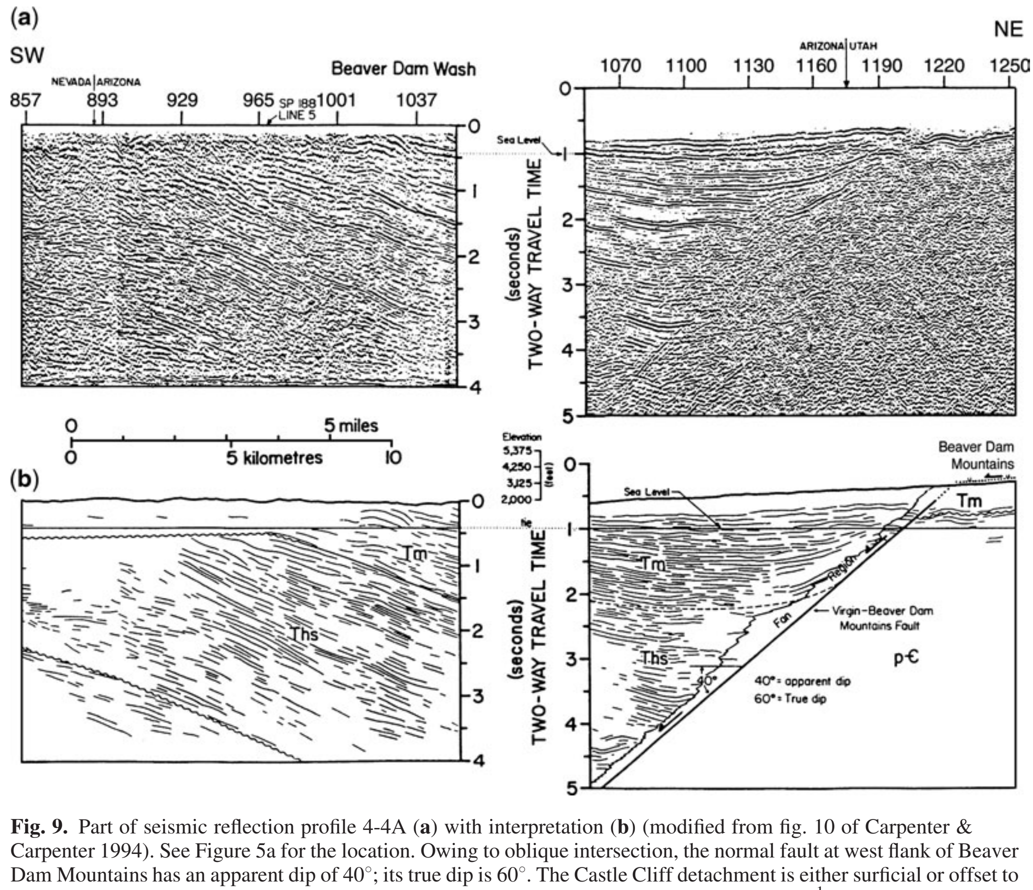

Fig. 9. Part of seismic reflection profile 4-4A (**a**) with interpretation (**b**) (modified from fig. 10 of Carpenter & Carpenter 1994). See Figure 5a for the location. Owing to oblique intersection, the normal fault at west flank of Beaver Dam Mountains has an apparent dip of 40°; its true dip is 60°. The Castle Cliff detachment is either surficial or offset to a depth of at least 4 seconds two-way travel time (>5.5 km for seismic velocity of 2.74 km s^{-1} assumed by Carpenter & Carpenter 1994). Neither interpretation is consistent with that shown in Figure 5b (simplified from Axen *et al.* 1990). Abbreviations: Ths, Horse Spring Formation (Miocene); Tm, Muddy Creek Formation and younger strata.

on this basis that an anticline cored by crystalline rocks at the west flank of the range (Wernicke & Axen 1988) must have developed as a result of uplift and exhumation of the footwall of the Neogene extensional system. At issue is: (1) whether the perceived footwall uplift relates to the Castle Cliff detachment or (more likely) to high-angle normal faults along the front of the range (compare sections A–A′ and B–B′ in fig. 2 of Wernicke & Axen 1988); and (2) whether the fold itself is an expression of footwall deformation, or is perhaps older. Two observations cast doubt on the purported Neogene age of the fold (plate 2 of Hintze 1986). First, the structure is oblique to and truncated by the range-bounding fault system, not aligned along it. Second, the existence of a panel of strongly overturned Pennsylvanian–Permian strata between the range-front crystalline rocks and the outcrops of Oligocene–Miocene strata is inconsistent with the supposed structural simplicity upon which the argument of Axen & Wernicke (1989) critically depends. For these reasons, we do not think that the fold necessarily has any bearing on the interpretation of the CCD.

Eagle Mountain Formation

Upper crustal extension across the Death Valley region of eastern California (D in fig. 1) has long accounted for as much as two-thirds of the approximately 250–300 km estimate of WNW motion of the Sierra Nevada away from the Colorado Plateau, and for the fraction of the total that, on the face of it, is best constrained from restorations of Neoproterozoic and Palaeozoic isopachs and facies transitions, Mesozoic thrust faults and folds, and palaeoisothermal surfaces (Stewart 1983; Wernicke *et al.* 1988, 1993; Snow & Wernicke 1989, 2000; Wernicke 1992). The very large inferred strain has also served to explain as much as 10–15 km of middle and late Miocene exhumation of the Black Mountains on the east side of Death Valley, placing Neogene volcanic and sedimentary rocks in low-angle normal fault contact with rocks as old as 1.7 Ga as a result of tectonic removal of more than 10 km of Neoproterozoic and Palaeozoic strata that is still preserved in surrounding ranges (Holm *et al.* 1992; Topping 1993). The preferred mechanism for the inferred deformation is westward migration of a rolling hinge (Holm *et al.* 1992; Wernicke 1992; Axen & Bartley 1997).

In spite of the apparent convergence of disparate structural, stratigraphic, geochronological and thermochronological constraints (e.g. Snow & Wernicke 1989), such reconstructions are subject to significant uncertainties: in structural correlation (of late Palaeozoic–Mesozoic thrust faults and folds), in the spatial variability of stratigraphic thickness that limits confidence in reconstructing both the location and orientation of isopachs, and in matching imprecisely defined facies transitions (e.g. Stewart 1983, 1986; Prave & Wright 1986*a*, *b*; Wernicke *et al.* 1988, 1990; Corbett 1990; Stevens *et al.* 1991, 1992; Snow 1992*a*, *b*; Snow & Wernicke 1993; Stone & Stevens 1993). It is also necessary to assume some simple pre-extensional configuration for whatever markers are selected (e.g. fig. 3 of Snow & Wernicke 2000). To the extent that there is no way independently to verify what the configuration was, particularly for crustal blocks no more than a few kilometres across, the problem becomes intractable in the absence of an independent constraint.

Research by Niemi *et al.* (2001) on the middle Miocene Eagle Mountain Formation provides a series of piercing points that appear to circumvent these inherent difficulties, at least for the structural elements in which these sediments are preserved (Fig. 1; Appendix 3). The presence in conglomerate at Eagle Mountain and in the central Resting Spring Range (E and R in Fig. 1) of a distinctive clast assemblage, including approximately 180 Ma leucomonzogabbro boulders (<1 m) indistinguishable from rocks found in the Hunter Mountain batholith of the Cottonwood Mountains (C in fig. 1) more than 80 km to the WNW, and sedimentological evidence for deposition at an alluvial fan together suggested an original location no more than 20 km from the source (taking that figure as a reasonable upper bound on fan dimensions). Although Niemi *et al.* (2001) asserted that the 'lack of dilution of this detritus by other sources' at least locally and at some stratigraphic levels by itself implies proximity to the Hunter Mountain batholith, other explanations can be considered (Appendix 3). The critical issue that we set out to test is whether the fan interpretation can be sustained. If deposition took place in a fluvial–lacustrine rather than alluvial fan–lacustrine setting, for example, the distribution of the Eagle Mountain Formation may instead reflect the configuration of the mid-Miocene drainage, with no significance for either the magnitude or direction of crustal extension.

Sedimentological studies, to be reported in detail elsewhere, do not support the fan interpretation (Appendix 3; Renik & Christie-Blick 2004). Disorganized to diffusely stratified gravel is found in both alluvial fans and bedload rivers of sufficient gradient and discharge (Blair & McPherson 1994). The key to the distinction of these depositional settings in the Eagle Mountain Formation is stratigraphic architecture. Three features in particular point to deposition in a fluvial environment. The leucomonzogabbro-bearing deposits are characterized by pervasive channelization with erosional relief from less than 1 m to as much as 15 m (conglomerate-filled incised valleys), by fining-upwards successions at the same scale within an overall upwards-coarsening succession 90 m thick, and by abundant trough cross-stratification (Fig. 10).

- *Channels* Rivers are fundamentally channelized (e.g. Campbell 1976; Miall 1992; Best & Bristow 1993; Marzo & Puigdefábregas 1993; Willis 1993*a*; Collinson 1996). Alluvial fans are constructed primarily by sheet-flooding or sediment gravity flows, and composed of relatively tabular sedimentary bodies (Blair & McPherson 1994). Channels exist at alluvial fans only insofar as the fan surface is modified locally or from time to time as a result of changes in sediment flux, gradient or base level, for example, and ultimately through some combination of climate change, variations in sea or lake level and crustal deformation. The best-developed channels, other than the feeder channel at the fan apex, are commonly associated with headward erosion from fault scarps. At steady state, and in the absence of active faults, fan surfaces beyond the intersection point at the feeder channel terminus are relatively smooth, with only superficial gullies related to surface run-off between times of active accumulation.
- *Fining-upwards successions* A tendency for upwards fining in bedload-dominated braided systems results from changing conditions during individual flood events and from the filling and abandonment of one channel in favour of another (e.g. Campbell 1976; Willis 1993*b*). An increase in discharge tends to be associated with renewed cutting of existing channels or the development of new channels. In contrast, the lateral building of alluvial fans results preferentially in the opposite motif at the same scale (metres to tens of metres): upwards coarsening punctuated by stratigraphic discontinuities (sequence boundaries or flooding surfaces; e.g. Steel *et al.* 1977; Gawthorpe *et al.* 1990; Blair & McPherson 1994; López-Blanco *et al.* 2000).
- *Cross-stratification* Bedforms are not well developed in all fluvial systems, particularly those transporting gravel. However, cross-stratification is observed in most fluvial deposits because bedforms are common in fluvial channels. Cross-stratification is not an important feature in alluvial fans because the processes of sheet-flooding and sediment gravity flow do not involve large bedforms.**:** None of this bears

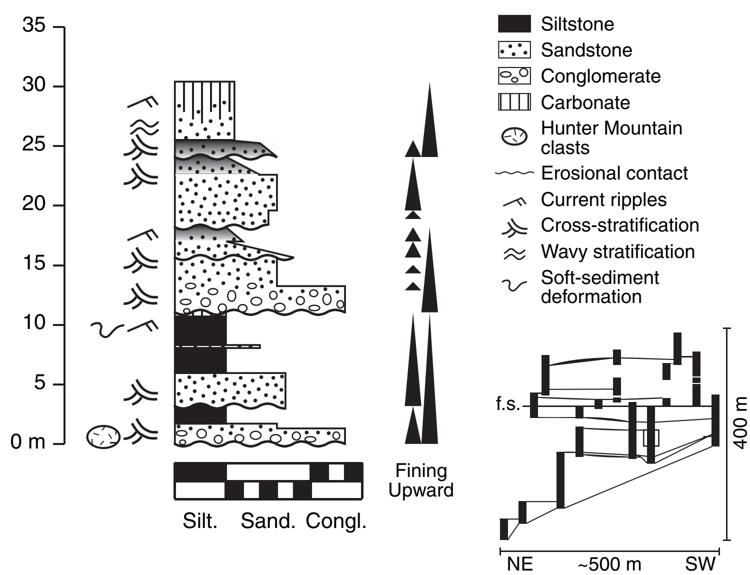

Fig. 10. Detail of inferred fluvial stratigraphy from middle Miocene Eagle Mountain Formation at Eagle Mountain (data from B. Renik). The column corresponds to the boxed portion of one of a series of 13 closely spaced measured sections depicted in the lower right area, within the lower part of unit Te2 of Niemi *et al.* (2001). The Eagle Mountain Formation unconformably overlies Cambrian Bonanza King Formation. Facies are mostly fluvial below prominent flooding surface (f.s., top of unit 17 in fig. 2 of Niemi *et al.* 2001), with valley-filling breccia and minor lacustrine sediment at the base; and mostly lacustrine deposits above that flooding surface. The grain size shown is the overall mean for sandstones and siltstones, and mean of granules and larger clasts for conglomerates (Wentworth scale).

on other arguments for large-scale crustal extension across the Death Valley region. At issue, however, is precisely how much extension, and the mechanisms by which it was achieved. If the Eagle Mountain Formation has been misinterpreted, for the reasons indicated, we are forced to retreat to the somewhat unsatisfactory palinspastic uncertainty that existed prior to 2001.

Discussion

A critical re-evaluation of three Basin and Range examples, widely regarded prior to our work as providing a firm observational basis for frictional normal-sense slip along gently inclined faults of regional scale, leads us to interpretations that in each case and in quite different ways resolve the mechanical paradox with which such features are associated. (1) The Sevier Desert 'detachment' is reinterpreted as a Palaeogene unconformity that has been traced to depth along an unrelated seismic reflection (most probably a splay of the Pavant thrust). (2) The Mormon Peak detachment, the structure that was surely among the most influential in moving the low-angle normal fault concept away from metamorphic core complexes, is reinterpreted as a series of rootless slide blocks on the basis of detachment characteristics and spatially variable kinematic indicators. The nearby Castle Cliff detachment, a defining example for the rolling hinge model (but see Axen & Bartley 1997), is similarly regarded here as a surficial feature on the basis of its conspicuous absence in seismic reflection profiles west of the Beaver Dam Mountains – returning to a view that was generally accepted prior to 1988. (3) Conglomerates and sandstones of the middle Miocene Eagle Mountain Formation, only recently claimed to provide definitive piercing points for the reconstruction of extreme extension across the Death Valley region, turn out to be fluvial rather than alluvial fan deposits – with no bearing on either the amount or direction of tectonic transport, in spite of their unique provenance.

We do not imply that the low-angle normal fault paradigm is falsified on the strength of these examples alone. Nor do we deny the reality of extreme crustal extension. Obviously, in the vicinity of the continent–ocean transition at passive continental margins, continental crust thins to zero. The results summarized here are significant primarily because they are unexpected, and because they suggest that a critical re-examination of other generally accepted evidence is now in order.

At stake is not the existence of gently dipping normal faults (and other geological discontinuities). It is how such readily observable field relations developed as a function of time, particularly in regions such as the Basin and Range Province where deformation and magmatism have been protracted, where crustal faults are in some cases distinguished with difficulty from the effects of surficial sliding, and where sediments have accumulated locally on exhumed fault surfaces. The interpretation of detachment faults from geological data depends critically on palinspastic restoration, and on the assumptions and uncertainties that are inherent in such reconstructions.

We single out metamorphic core complexes of eastern California and adjacent Arizona for renewed attention, along with less easily studied locations along modern and ancient continental margins at which subcontinental mantle appears to have been dragged tectonically to the sea floor (e.g. Manatschal *et al.* 2001, 2007). Also of interest are the megamullions at mid-ocean ridges (Canales *et al.* 2004), a setting in which the rolling hinge model might be expected to apply owing to the inherent weakness of hot young lithosphere (e.g. Garcés & Gee), and may not (Expedition Scientific Party 2005). In each case, and in contrast to the Sevier Desert and Mormon Mountains, crustally rooted faults are an important part of the story – and, for that reason, these examples are undoubtedly among the most important not included in this paper.

Among issues to be resolved are: the manner in which brittle deformation relates to mylonitization (or not); the degree to which faults are folded or tilted to lower dip, as a result of progressive or unrelated deformation; the role of unusual materials such as talc in reducing frictional coefficients (e.g. Moresby seamount, Woodlark Basin; Floyd *et al.* 2001); and the significance of fluids in fault zones and more generally in crustal rheology (Axen 1992; Manatschal 1999; Collettini & Barchi 2002; Hayman *et al.* 2003; Collettini & Holdsworth 2004; Evans *et al.* 2004; Scholz & Hanks 2004). Wills & Buck (1997) examined the possible role of stress-field rotation in the development of rooted detachment faults, and concluded that applied stresses are not in general sufficient to create low-angle normal faults that would propagate to the Earth's surface (cf. Westaway 1999). There will be no one-size-fits-all solution. Our problem as a community may be, at least in part, one of attempting to shoehorn unrelated phenomena into an overly simplified conceptual model.

Experience over the past decade indicates that no matter how important an example is or was regarded, once questions are raised about its significance, other allegedly better examples come to the fore, along with all manner of secondary hypotheses for preserving the original interpretation. It remains to be determined whether the now-reinterpreted examples upon which we have worked will prove to be of general significance or (as some critics have asserted) peripheral to an understanding of detachment fault mechanics. The paradox of low-angle normal faulting is after all a frictional issue even in areas in which mylonitic rocks are also present, and most troublesome at the shallowest crustal levels. As a practical matter, hypotheses can be tested only with reference to specific examples, and if evidence is to be regarded as compelling in the manner implied by the quote with which this paper begins, it ought to withstand scrutiny, not simply lead to conclusions that are known in advance to be correct.

Appendix 1: Arguments for contrasting interpretations of Sevier Desert reflection (SDR)

References

[1]McDonald (1976); [2]Allmendinger *et al.* (1983); [3]Smith & Bruhn (1984); [4]Von Tish *et al.* (1985); [5]Mitchell & McDonald (1986); [6]Mitchell & McDonald (1987); [7]Planke & Smith (1991); [8]Anders & Christie-Blick (1994); [9]Hamilton 1994; [10]Allmendinger & Royse (1995); [11]Anders *et al.* (1995); [12]DeCelles *et al.* (1995); [13]Otton (1995); [14]Coogan & DeCelles (1996); [15]Otton (1996); [16]Wills & Anders (1996); [17]Anders *et al.* (1998*a*); [18]Coogan & DeCelles (1998); [19]Wills & Anders (1999); [20]Anders *et al.* (2001); [21]Stockli *et al.* (2001); [22]Hintze & Davis (2003); Davis (2003); [23]Niemi *et al.* (2004); [24]Wills *et al.* (2005); [25]DeCelles & Coogan (2006).

Detachment interpretation

[1–4,7]Lateral continuity of SDR inclined at 11° over 7000 km^2 beneath Sevier Desert basin (SDB) and (down dip) within deformed Neoproterozoic and Palaeozoic rocks of Mesozoic orogen (Fig. 3).

[1–4,7]Accounts for downward termination of high-angle normal faults at the SDR (Fig. 3).

[1–7,10,12,14,18,21]Provides explanation for the SDB and for normal sense offset of Mesozoic structures by <47 km (detachment may in part reactivate a Mesozoic thrust fault[1,5]).

[2,10]Explains gravity high and culmination in crystalline basement rocks beneath the SDB.

[1,2,4,14,18,21,23]Stratigraphic growth consistent with displacement on detachment after 28–26 Ma; youngest sediments involved in deformation are Holocene.

[10,21]Fission track ages from footwall rocks of Canyon Range (19–15 Ma; apatite) and ARCO Meadow Federal well (13.0 ± 1.0 Ma to 10.8 ± 0.9 Ma; zircon), and from hanging-wall rocks in Cominco American Federal well (8.5 ± 2.2 Ma; apatite) are attributed to mid- to late Miocene displacement and tectonic exhumation along the hypothesized detachment.

[13,15]Brittle deformation in Canyon Range on eastern margin of the SDB interpreted as outcrop expression of hypothesized detachment.

Unconformity interpretation

Absence of anticipated deformation problematical

[8]No increase in abundance of microcracks in borehole cuttings of Cenozoic clastic sediments no more than 3 m above hypothesized detachment.

[8,20]No evidence for ductile deformation in borehole core of Palaeozoic carbonate rock 12.8 m below same contact or in cuttings from as close as 3 m, in spite of a restored depth of at least 14 km and temperatures as high as 425 °C (initial conditions based upon an offset of <47 km).

[16,19]Deformation in Canyon Range at eastern margin of the SDB relates to mapped Mesozoic fold hinges and faults, and to slide blocks that are demonstrably surficial (the SDR projects above the level of outcrop[9]).

Difficulties with palinspastic reconstruction and reflection geometry

[8,24]Re-evaluation of subsurface data indicates that the SDR is fortuitously aligned down dip with a Mesozoic thrust fault west of the northern SDB (Fig. 4a), and not present/imaged west of the southern SDB (Fig. 4b)[6,7].

[24]Published estimates of extension across the northern SDB (<47 km[4,14,25]) and southern SDB (6 km[7]) are markedly different in cross-sections only 20 km apart.

[23]Mesozoic thrust faults are truncated by sub-Cenozoic unconformity at western margin of the southern SDB (Fig. 4b; no evidence for termination against the SDR, as required by published palinspastic reconstructions).

[17,24]Widespread onlap without growth at the western margin of the SDB (Fig. 4) contrasts with previous interpretations of stratigraphic growth in seismic data (see below) and with expected stratal geometry for a supradetachment basin.

[24]SDR offset by high-angle normal faults with up to 500 m of stratigraphic separation at the eastern margin of the SDB, and up to 750 m at the western margin (precluding a throughgoing detachment or placing constraints on its most recent movement; see below).

[24]As much as 1.3 km of relief on the SDR in a north–south direction (50 km wavelength) contrasts with apparently planar geometry of more familiar east–west profiles, and lacks an adequate structural explanation (other than an assertion that they are primary corrugations).

Timing constraints and difficulties

[6,17,20,23,24]The SDB is relatively long-lived: pre-Oligocene (oldest strata) to Holocene.

[11,17,23]Dipping reflections at the western margin of the SDB, interpreted as Oligocene (28–26 Ma) and used to infer time of onset of displacement along detachment[1,2,4,14,18,21], are likely within Neoproterozoic–Palaeozoic rocks of the Mesozoic orogen if a more plausible (higher) velocity of 3.2 km s^{-1} is assumed for SDB fill at Gulf Gronning well.

[24]A high-angle normal fault cutting the SDR is overlapped by strata as old as ?Miocene (providing an approximate younger bound on timing of hypothesized detachment).

[11,19,20,24]Fission track ages of 19–8.5 Ma are subject to multiple interpretations (see below), with no direct bearing on basin formation that began prior to the Oligocene.

[20]No evidence for any lateral progression in ages of volcanic rocks above hypothesized detachment (Eocene–Oligocene, mid-Miocene and Pliocene–Holocene volcanism).

Alternative explanations

[8,11,20,22,24]SDR is a regional unconformity of Palaeogene age (consistent with kilometre-scale relief) and, where present west of the SDB, a Mesozoic thrust fault.

[8,17,24]Downward termination of high-angle normal faults and localized stratigraphic growth are due to syndepositional deformation of intrabasinal Oligocene salt (Fig. 4a).

[11]Culmination in crystalline rocks beneath the SDB attributed to a ramp in a hypothesized intrabasement thrust fault (such faults are known in outcrop within Mesozoic orogen).

[11,19,24]Fission track ages from Canyon Range (19–15 Ma) are attributed to exhumation of range as a result of displacement along high-angle normal faults; ages as young as 13.0–10.8 Ma in ARCO Meadow Federal No. 1 well and 8.5 Ma in Cominco American Federal well may reflect contemporaneous magmatism.

[24]Origin of SDB: an erosional piggy-back basin within orogen, tilted westward by out of sequence thrusting, augmented by extension- or slab-related regional subsidence, sediment loading and minor high-angle normal faulting.

Appendix 2: Arguments for contrasting interpretations of Mormon Peak and associated detachments

References

[1]Cook (1960); [2]Tschanz & Pampeyan (1970); [3]Wernicke (1981); [4]Wernicke (1982); [5]Novak (1984); [6]Wernicke *et al.* (1985); [7]Hintze (1986); [8]Wernicke & Axen (1988); [9]Wernicke *et al.* (1988); [10]Axen & Wernicke (1989); [11]Carpenter *et al.* (1989); [12]Wernicke *et al.* (1989); [13]Axen *et al.* (1990); [14]Wernicke *et al.* (1990); [15]Anderson & Barnhard (1993*a*); [16]Anderson & Barnhard (1993*b*); [17]Axen (1993); [18]Carpenter & Carpenter (1994); [19]O'Sullivan *et al.* (1994); [20]Wernicke (1995); [21]Axen & Bartley (1997); [22]Stockli (1999); [23]Axen (2004); [24]Anders *et al.* (2006); Walker *et al.* (2007).

Rooted detachments of regional scale

[3,4,6,8–10,12–14,17,20,21,23]Mormon Peak, Tule Springs and Castle Cliff detachments (MPD, TSD and CCD) are interpreted to accommodate 54 ± 10 km of crustal extension, with displacements of approximately 25 km, up to 7 km and approximately 24 km, respectively.

[13,17,23]TSD follows portion of Tule Springs thrust (a Mesozoic thrust décollement) for more than 10 km in direction of detachment transport.

[4,6,8,13,17,23]Palinspastic restoration implies initial dips of 20°–28° to a depth of at least 6 km (MPD); 3°–15° to a depth of 2–5 km, steepening down dip at greater depths (TSD); and 32° to a depth of at least 7 km (CCD); present dips are up to 20°E and 20°W, and with a range of azimuths (MPD), approximately 0° (TSD) and 11° (CCD).

[4,6,8,10,13,15,16,21,23]Isostatic rebound of footwall results in uplift, tilting, folding ('rolling hinge') and in tendency for detachment to become more gently dipping (or dipping both eastward and westward in case of MPD); near concordance of steeply inclined Oligocene–Miocene strata with Cretaceous–Palaeogene (?) beneath the CCD taken to demonstrate a post-Laramide origin (i.e. not related to crustal shortening).

[17,23]Normal faults with up to 3 km of stratigraphic separation in the hanging wall of the TSD do not offset footwall stratigraphic contacts.

[6,13,17]Relative ages of detachments (MPD > TSD > CCD) are interpreted on the basis of offset of the MPD and TSD by high-angle normal faults that are assumed (with some observational support in Tule Springs Hills) to have been coeval with displacement on structurally lower detachments.

[13]MPD post-dates rhyolitic tuff correlated with Kane Springs Wash volcanic suite (*c.* 15–12 Ma).

[19,22]Apatite fission track ages in crystalline rocks from Beaver Dam Mountains (16 Ma) are attributed to tectonic exhumation by the [22,23]CCD (on the face of it, inconsistent with an age younger than the MPD based upon inferred fault geometry).

Rootless localized slide blocks

Geometrical difficulties with rooted detachment interpretation

[24]Each detachment crops out in a series of isolated exposures (original detachment contiguity is a matter of hypothesis rather than observation).

[11,18,24]Seismic reflection profile 4-4A, which obliquely intersects western flank of Beaver Dam Mountains, shows that the range is bounded by a high-angle normal fault (Figs 5a & 9); the CCD is either surficial or offset to a depth of at least 4 seconds two-way travel time (>5.5 km); neither interpretation is consistent with regional detachment illustrated in Figure 5b; the CCD also not imaged in section 5-5A (fig. 11 of Carpenter & Carpenter 1994; see Fig. 5 for the location).

The MPD cuts high-angle normal faults in both the hanging wall and footwall, challenging an assumption used to infer relative ages of detachments.

The TSD is especially problematic owing to an interpreted initial dip of $3^\circ-15^\circ$ and a present-day dip of approximately 0° (inclinations that are appreciably less than the frictional lock-up angle).

Folding attributed to footwall deformation in the Beaver Dam Mountains is discordant with the range-bounding fault system; Mesozoic origin cannot be excluded.

Unclear why MPD was domed, the TSD was folded by a rolling hinge and the CCD was tilted to a lower dip but remained essentially planar (Fig. 5b).

Difficulties related to character and kinematics of deformation

[18,24]Polymictic conglomerate is present widely at the MPD as a 0.1–1 m-thick layer intimately involved in deformation, filling a network of clastic dykes above detachment, with grading, flow banding and internal erosional features, and, with one possible exception, no evidence for more than one generation of conglomerate or dyke intrusion; the conglomerate is compositionally distinct from Cretaceous synorogenic deposits, and not likely to have remained unlithified for about 50 million years at a depth of several kilometres; the geometry, textures and structure of conglomerate bodies are not consistent with karst infill.

[24]Asymmetrical deformation: rocks above MPD are pervasively brecciated; those below are virtually undeformed.

[24]Microfracture density in isolated quartz grains in conglomerate is lower than typically the case in fault zones; microfractures are abundant in quartz grains of Cambrian Tapeats Sandstone beneath MPD, but with no significant variation with distance from detachment (which would be expected if the two were related).

[24]Footwall carbonate rocks are brecciated in thin zone (<1 m), with no evidence for other deformation typically observed along faults of large displacement (mylonites, cross-cutting veins, reduced grain size, preferred orientation of calcite twinning).

[24,25]Kinematic indicators (slickenlines at detachment surface, and minor faults involving the conglomerate) diverge from published regional extension direction ($255^\circ \pm 10^\circ$; Fig. 8), and correspond approximately with modern dip direction of the MPD.

Alternative explanations

[1,2,7,11,18,24,25]The MPD and CCD are basal contacts of several rootless slide blocks; rootedness of the TSD, also regarded as a gravity slide in early mapping[2], is in doubt by association.

[24]All of the characteristics of conglomerate layer and dykes at the MPD are duplicated at known slide blocks, and are consistent with fluidization during block emplacement in a single catastrophic event (for each example).

[24]Asymmetrical pattern of brecciation at the MPD, a knife-sharp detachment surface, and up to several centimetres of gouge are typical of known slide blocks.

[24]Expected ‘toes’[4,6] are absent because structures mapped as the MPD and TSD are as old as middle Miocene, and toe regions of interpreted slide blocks are inferred to have been offset by high-angle normal faults, eroded away or buried by younger gravels.

[24,25]Varied orientation of kinematic indicators is consistent with existence of more discrete blocks than implied by current detachment terminology in Mormon Mountains.

[24]Age of MPD is not well constrained: youngest west-tilted volcanic unit at the NW flank of Mormon Mountains yields $^{40}Ar/^{39}Ar$ age of 13.61 ± 0.06 Ma, and overlies a sequence of volcanic rocks as old as 23.27 ± 0.04 Ma, with dips increasing with age; near-horizontal to east-tilted ash-flow tuffs in Meadow Valley Wash, west of Mormon Mountains are 14.49 ± 0.02 Ma (M. H. Anders unpubl.), consistent with ash-flow tuff ages of <14 Ma[5] from Kane Springs Wash caldera; our interpretation is that tilting of volcanic rocks along west flank of Mormon Mountains relates to high-angle normal faulting documented from mapping and seismic reflection profiles (C. D. Walker unpublished data).

[19]Fission track ages from Beaver Dam Mountains (16 Ma) are also attributed to exhumation of range as a result of displacement along high-angle normal fault.

Appendix 3: Arguments for and significance of contrasting interpretations of the depositional setting of the Eagle Mountain Formation (middle Miocene)

References

[1]Stewart (1967); [2]Wright & Troxel (1967); [3]Stewart *et al.* (1968); [4]Stewart *et al.* (1970); [5]Wright & Troxel (1970); [6]Stewart (1983); [7]Prave & Wright (1986*a*); [8]Prave & Wright (1986*b*); [9]Stewart (1986); [10]Wernicke *et al.* (1988); [11]Snow & Wernicke (1989); [12]Corbett (1990); [13]Wernicke *et al.* (1990); [14]Stevens *et al.* (1991); [15]Holm *et al.* (1992); [16]Snow (1992*a*); [17]Snow (1992*b*); [18]Stevens *et al.* (1992); [19]Wernicke (1992); [20]Snow & Wernicke (1993); [21]Stone & Stevens (1993); [22]Topping (1993); [23]Wernicke *et al.* (1993); [24]Brady *et al.* (2000*b*); [25]Snow & Wernicke (2000); [26]Niemi *et al.* (2001).

Alluvial fan and lacustrine

[26]Conglomerate at Eagle Mountain and central Resting Spring Range contains a distinctive clast assemblage, including approximately 180 Ma leucomonzogabbro (<1 m) indistinguishable from rocks found in the Hunter Mountain batholith of Cottonwood Mountains more than 80 km to WNW; abundance of these clasts at some locations and as much as 50% modal plagioclase in some sandstone beds implies proximity to Cottonwood Mountains source at time of deposition (*c.* 15–11 Ma).

[24,26]Sedimentary characteristics of succession at Eagle Mountain indicate deposition at an alluvial fan less than 20 km from source (assuming upper limit on fan dimensions): *rock avalanche deposits* (conglomerate and breccia, characterized by angular clasts, local provenance, lack of bedding, and lack of matrix); *non-cohesive debris flows* (massive, clast-supported conglomerate, characterized by lateral continuity of individual units, poor sorting, angular clasts, and lack of clay-rich matrix); *sheetflood couplets* (granular sandstone and conglomerate, characterized by lithologic alternation, parallel bedding, upper flow regime structures and unimodal palaeocurrents); *sheetflood sandskirt* and *tabular fluvial braidplain* (sandstone and pebby sandstone, characterized by lateral continuity of bedding, lithological alternation, and planar and trough cross-stratification); *lacustrine* (siltstone and fine sandstone, characterized by lack of mudcracks or evaporitic horizons and lack of current-related structures; and micritic limestone, characterized by algal laminae and lenses of rippled fine sandstone). 'Upward progression from rockfall and/or rockslide to debris flow, sheetflood, and sandskirt facies is consistent with a depositional system that evolved from a relatively small drainage area to a larger one, and... with upward change in clast derivation from local bedrock to a more distal source.'

[26]Tectonic transport of Cottonwood Mountains source more than 80 km towards 293° and away from Eagle Mountain implies more than 400% extension of the upper crust since 11–12 Ma.

[1,3,4,6,9–11,13,15–17,19,20,22–25]Interpretation consistent with other estimates of extension based upon restoration of Neoproterozoic and Palaeozoic isopachs and facies transitions, Mesozoic thrust faults and folds, palaeoisothermal surfaces, and Miocene rock-avalanche deposits.

Fluvial and lacustrine

Overall characteristics of succession revealed by 13 measured sections and mapping of physical surfaces at Eagle Mountain: (1) basal erosion surface with metres to tens of metres of local erosional relief; (2) locally derived monolithological carbonate breccia and sandstone (140 m), onlapping basal unconformity; (3) lacustrine siltstone and diamictite (*c.* 10 m); (4) braided fluvial conglomerate, sandstone, siltstone and minor limestone, pervasively channelized, with abundant trough cross-stratification, fining-upwards successions up to 1 m to more than 10 m thick, and overall upwards coarsening over 90 m; (5) disorganized to diffusely stratified, heterolithic conglomerate, with least well-stratified facies filling incised valleys up to 14 m deep; and (6) mostly lacustrine sandstone, siltstone and minor limestone up to 140 m thick, characterized by relatively tabular bedding, parallel stratification to low-angle cross-stratification, current and wave ripples, soft-sediment deformation and rare tufa.

'Rock avalanche deposits' of Niemi *et al.* (2001) are reinterpreted as valley fill; 'noncohesive debris flows', 'sheetflood couplets' and 'sheetflood sandskirt' are fluvial; 'tabular fluvial braidplain deposits' are lacustrine event layers (delta front). Rounded clasts of leucomonzogabbro are found exclusively within interpreted fluvial deposits.

If deposition took place in a fluvial–lacustrine rather than alluvial fan–lacustrine setting, distribution of Eagle Mountain Formation is hypothesized to reflect mid-Miocene drainage, with no significance for either magnitude or direction of crustal extension.

Local abundance of Hunter Mountain detritus may be due to: (1) preferential erosion owing to local topography or climate-related factors; (2) episodic reaming out of valley/channel system; or (3) relative resistance to breakage during transport.

Difficulties with other evidence for extreme extension between Cottonwood Mountains and Nopah Range

[2,5,7,8,12,14,18,21]Apparent convergence of disparate structural, stratigraphic, geochronological and thermochronological constraints is subject to circular reasoning. Difficulties include: uncertainty in structural correlation (thrust faults and folds); spatial variability of stratigraphic thickness that limits confidence in both location and orientation of isopachs; imprecisely defined facies transitions; and assumptions needed about the pre-extensional configuration of all markers. Inferences based on restoration of Miocene rock-avalanche deposits[22] hinge on whether provenance can be tied uniquely to specific source areas.

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