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SHORT NOTES

Superposed normal faults in the Ely Springs Range, Nevada: estimates of extension

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Abstract—Paleozoic rocks of the Ely Springs Range were cut by down-to-the-east domino-style normal faults, which resulted in W-dipping strata and gently E-dipping faults. Oligocene volcanic rocks were deposited across these structures, before the entire assemblage was rotated to the east on a down-to-the-west listric normal fault. This rotation returned the domino-style faults to steeper dips and the Paleozoic rocks to gentle dips. Step-wise palinspastic restoration to the pre-fault geometry indicates 70–210% horizontal extension. If the sub-Tertiary unconformity were not recognized, a non-rotational reconstruction of the currently steep normal faults in the Paleozoic strata would yield an erroneously small estimate of extension. Geologists working in extended terrains should consider the possibility that unrecognized extensional rotations occurred. If that possibility is high, estimates of horizontal extension should be considered as minima.

INTRODUCTION

IN THE Basin and Range province of North America, extensional tectonism has been long-lived and has caused overprinting of extensional structures of different ages. Two basic types of normal faults cause rotations (Wernicke & Burchfiel 1982): listric faults rotate hanging-wall strata, and domino-style fault sets cause rotation of both beds and faults. In many areas subsequent rotations have had the same sense, leading to a geometry consisting of steep bedding dips with or without gentle fault dips (e.g. Proffett 1977, Davis *et al.* 1980, Miller *et al.* 1983). In general, this type of geometry is taken to indicate large amounts of extension. The alternative geometry of steep normal faults and gently dipping beds is usually associated with smaller amounts of extension. This geometry can, however, result if multiple rotations caused by normal faults were in opposite directions, and cancelled each other out. The extension would then be much greater than indicated by the geometry. A field example of this misleading geometry is documented below.

GEOLOGY OF THE ELY SPRINGS RANGE

The Ely Springs Range (Figs. 1 and 2) consists of normal-faulted Paleozoic rocks overlain unconformably by Tertiary volcanic and sedimentary strata (Westgate & Knopf 1932, Byrd 1970). The Paleozoic rocks are gently E- or W-dipping and the normal faults dip moderately to steeply E. Striae and corrugations on the fault surfaces indicate dip-slip. The volcanic rocks are composed largely of ash-flow tuffs of the Oligocene Needles Range Group and Pahroc Sequence, which preserve excellent paleohorizontal markers (flattened pumice lapilli). These rocks dip 20–40° E (Figs. 2 and 3a), into a W-dipping listric normal fault, the Ely Springs fault (Figs. 1 and 2). East of the listric fault are brecciated Upper Cambrian rocks that lie above the Highland 'thrust' (Tschanz & Pampeyan 1970), a probable low-angle normal fault hereafter referred to as the Highland detachment (Figs. 1 and 4).

The Ely Springs fault is interpreted as a listric fault for the following reasons. (1) The geometry of hangingwall rocks indicates the presence of a reverse drag fold (Fig. 2). (2) The youngest mud/debris flow overlapped the fault (Tm2, Fig. 2) and is deposited on older rocks in the footwall than in the hangingwall, which suggests syn-sedimentary faulting. The basal contact of Tm2 is nearly horizontal in the footwall, but is tilted eastward in the hangingwall. This differential rotation requires a listric fault geometry. (3) The fault at outcrop is too steep for it to have caused the 40° dips in the hangingwall by domino-style rotation of a planar fault. Even if the fault had been initially vertical, its final dip would be 60° after just 30° of rotation. In fact, the fault dips about 80° at the present level of exposure.

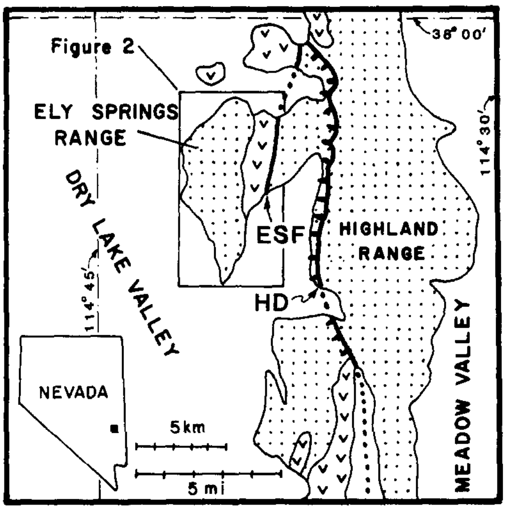

Fig. 1. Location maps for the Ely Springs Range. Dots, Paleozoic rocks; V's, Tertiary rocks; HD, Highland detachment fault (barbs on upper plate); ESF, Ely Springs fault.

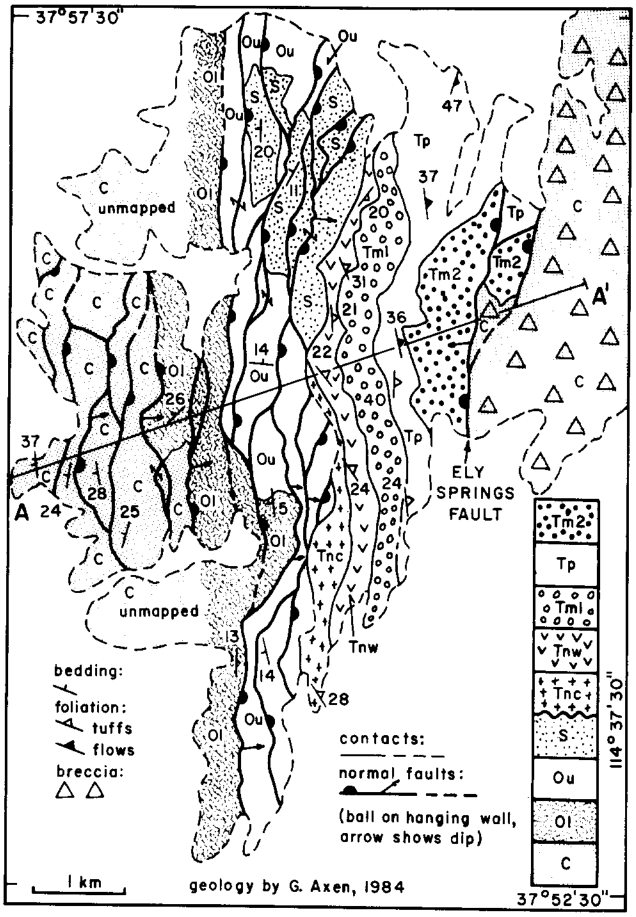

Fig. 2. Simplified geologic map of the Ely Springs Range. C, Upper Cambrian strata; Ol, Ordovician Pogonip Group; Ou, Ordovician Eureka Quartzite and Ely Springs Dolomite; S, Silurian Laketown Dolomite; Tnc, Tnw, Middle Oligocene Cottonwood Wash Tuff and Wah Wah Tuff, respectively, of the Needles Range Group (Tnc includes other unidentified tuffs); Tml, mud/debris flow; Tp, Late Oligocene Pahroc Sequence; Tm2, mud/debris flow.

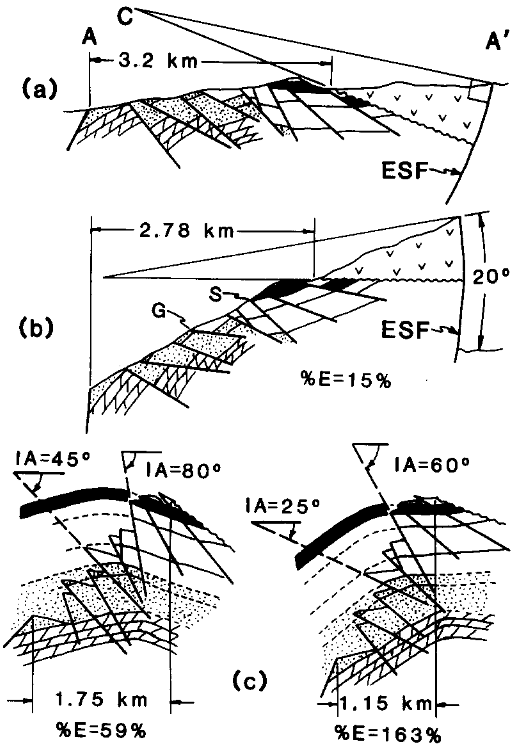

Fig. 3. Graphical reconstruction of cross-section AA′ (Fig. 2). (a) The center of rotation, C, for the listric fault is obtained from the intersection of projections perpendicular to the fault at the surface, and along the sub-Tertiary unconformity. (b) 20° of rotation on the Ely Springs fault (ESF) brings the sub-Tertiary unconformity to horizontal. (c) Two reasonable end-member reconstructions of the domino-style fault set. Arrows in (c) point to blocks which underwent minor distortion. Oblique line ornament, Middle Cambrian strata; stipple, Upper Cambrian; no ornament, Pogonip Group; black, Eureka Quartzite; V ornament, Tertiary strata.

In order to evaluate the amount of extension, stepwise palinspastic reconstruction of cross-section AA′ (Figs. 2 and 3) has been done. The section was constructed in such a way as to minimize the amount of extension required for restoration. For example, reverse drag due to the listric fault was excluded, so a minimum amount of rotation (20°) was used to restore that fault. The true rotation may have been as much as 40°.

When 20° of rotation is restored on the listric fault, only 0.42 km of horizontal offset is required. This is equivalent to 15% horizontal extension for an arbitrary l_0 measured from that fault to the western range-bounding fault (Figs. 3a & b). This rotation brings the gentlest-dipping tuffs back to horizontal, and discloses the pre-tuff geometry of the Paleozoic rocks. The faults in the Paleozoic section are apparently of the 'domino' type, in which beds and faults both rotated during faulting (Fig. 3b). Although some of these older faults may have been antithetic to the Ely Springs fault, and therefore younger than the other E-dipping faults, no evidence was seen for two ages of down-to-the-east faults in the Paleozoic rocks, and this possibility was discounted.

Dips of Paleozoic strata vary across the range and across individual faults of the older set. Therefore, two possibilities exist for reconstruction of the Early Oligocene faults. The first is that older compressional structures existed prior to normal faulting, which is consistent with the regional history of folding and thrust faulting in this area during the Mesozoic Sevier Orogeny. Alternatively, the faults may curve at depth in order to juxtapose rocks with different dips. Where the faults cross deep canyons, they are planar over that amount of relief (>100 m). Nevertheless, several reconstructions were attempted using the curved-fault hypothesis; all led to insurmountable space and balancing problems. However, when the faults were projected as planar, a simple cut-and-paste reconstruction was possible with minor distortion of only two adjacent fault blocks (Fig. 3c).

For these reasons, I prefer to explain the variation of dips across the range by dismemberment of an older fold in the Paleozoic rocks. Therefore, the attitudes of Paleozoic strata could not be used to indicate paleohorizontal or the initial attitudes of faults, and two initial geometries were chosen as feasible end members (Fig. 3c). In one, the steepest normal fault has an initial dip of 80°, which corresponds to 59% horizontal extension. In the other the gentlest fault has an initial dip of 25°, which corresponds to 163% horizontal extension (Fig. 3c). The true amount of extension probably lies between these values. If this is compounded by the

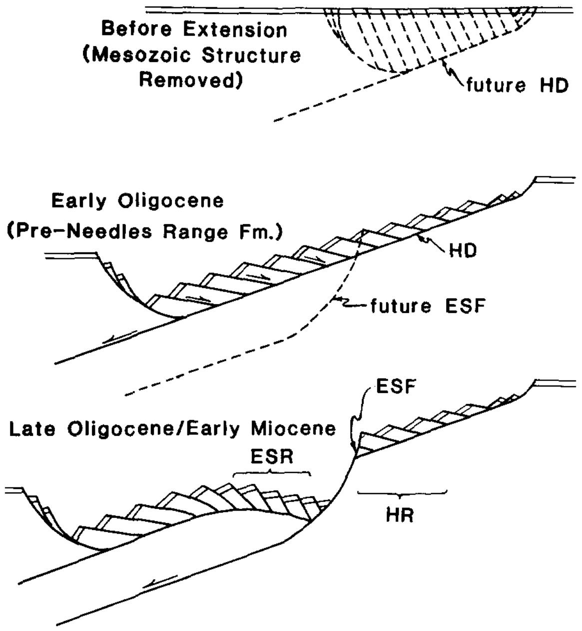

Fig. 4. Schematic structural evolution of the Ely Springs Range (ESR) area. HD, Highland detachment; ESF, Ely Springs fault; HR, Highland Range.

minimum of 15% horizontal extension due to the Ely Springs fault, then a reasonable minimum of 68% is obtained. If 30% horizontal extension occurred on the Ely Springs fault, then as much as 210% is permissible based on palinspastic reconstruction.

Figure 4 shows a possible scheme for evolution of the Ely Springs Range. It is worth noting that a currently unknown amount of non-rotational extension must also be accounted for on the Highland detachment. This must significantly increase estimates of extension in the area.

DISCUSSION

Without the critical exposures of tilted Tertiary rocks in unquestionable depositional contact above previously faulted Paleozoic strata, the rather complex history and reconstruction shown in Fig. 3 would not be possible. If the Tertiary rocks were buried in a basin, then a simple high-angle normal fault reconstruction would have led to a grossly underestimated amount of extension. Many ranges in the Great Basin contain steep normal faults which cut gently tilted beds. It may be that they have similar histories. Workers in extended terrains should consider the possibility that unrecognized rotations have left a misleading geometry. If this possibility exists, estimates of horizontal extension should be considered as minima.

Perhaps the most important application of this knowledge is in interpretation of reflection seismic profiles shot in extensional orogens. Care must be taken to differentiate between a single faulting event, with synthetic and antithetic faults, and the situation described here of two faulting events of different ages. In the single event case, contemporaneous sediment fans shed from a master fault and antithetic faults will have opposite provenance directions. However, in the case of two faulting events which cause opposite rotations (Fig. 5), the provenance direction of sedimentary wedges reverses through time. Note also that in Fig. 5, or an analogous situation involving two opposing listric faults, a geometry results which could easily be interpreted as being caused by a single horst-and-graben-forming event.

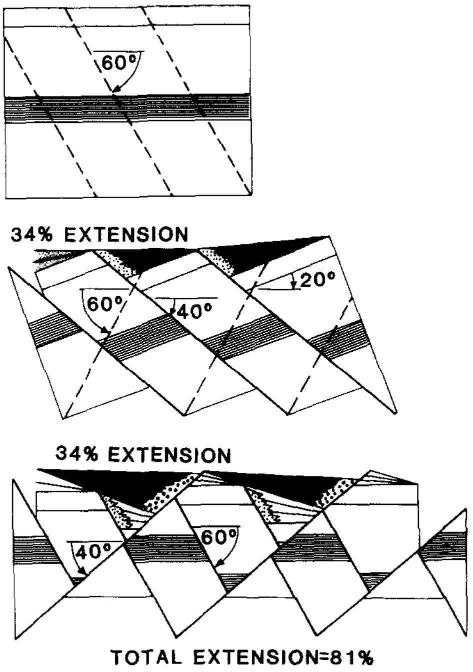

Fig. 5. Idealized structural and sedimentary evolution of two sets of opposing domino-style faults. Both sets of faults initiate with 60° dips and cause 20° of rotation. Note that facing of sedimentary wedges (dark shading with stippled fault-scarp facies) changes through time.

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