| Ber. Inst. Erdwiss. K.-F.-Univ. Graz | ISSN 1608-8166 | Band 9 | Graz 2004 |
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# UNCONSTRAINED LISTRIC FAULTS

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The concept of a listric (based on the Greek word *listron* or shovel), concave-up normal fault was introduced by Suess (1909) as part of his description of curved faults in the coal mines of Saint-Eloi and Léon (northern France). They are now recognized in many places around the world (e.g. Shelton, 1984). Three features have been considered as characteristic of listric normal faults: a flat detachment surface, a rigid footwall, and hanging wall strata with a dip that increases toward a normal fault (i.e. rollover anticline or reverse drag). Balanced cross section analyses of listric faults are widely applied to investigate these features, to quantify regional extension, and in the exploration for hydrocarbons. Rollover anticlines, for example, are one of the most important hydrocarbon traps (Tearpock and Bischke, 2003 and references cited therein). Since these methods also are used to assess the geometry of normal faults, which can seal subsurface fluid flow, they are important in defining the volume of a hydrocarbon reservoir. The impact and widespread use of listric fault models prompt us to re-examine two of the commonly held perceptions about these faults.

We start with the assumption that a hanging wall rollover implies a listric fault geometry. This assumption seems highly precarious to us. Firstly, although listric faults appear common, not all normal faults have listric geometries. For example, seismic reflection data commonly indicate normal fault traces that are not concave up in cross sections (e.g. Jackson, 1987). Additionally, earthquake data provide little evidence for the notion that large scale normal faults invariably flatten with depth. Secondly, reverse drag and rollover-like geometries occur at all scales and within a broad range of different homogeneous and heterogeneous rheologies, including faults which have non-listric geometries (Passchier, 2001, Grasemann et al. 2003). Thirdly, many mechanical models of planar faults (e.g. Gibson et al. 1989; Ma and Kusznir, 1993; Reches and Eidelman, 1995; Grasemann et al. 2003) show reverse drag. So listric fault geometries are not a prerequisite for reverse drag to develop.

The second perception that appears suspect to us is that the footwall of a normal fault is rigid. This assumption has no mechanical basis, and it certainly does not make sense in cases where rocks of similar lithology (or rheology) are juxtaposed by faulting. Indeed, geodetic measurements for single slip events, high-resolution three-dimensional seismic data sets, and detailed investigations of faults in outcrops commonly reveal reverse drag profiles in both the hanging and footwall (e.g. Kasahara, 1981; McConnel and Kattenhorn, 1997; Mansfield and Cartwright, 2000). Two reasons might contribute to the perception that footwalls are rigid:

The first is that displacements (and drag effects) in the footwall can be much less than those in the hanging wall. Such an association would be strong evidence for a stiffness difference for faults that are substantially deeper than their down-dip extent (i.e., faults that behave as though they were in an infinite body). Mechanical analyses of normal faults that intersect or interact with the earth's surface, however, reveal decidedly different slip profiles from faults far from the surface. Surface-breaching faults or near-surface faults tend to have a slip maximum at or near the surface rather than near the fault center. Perhaps more significantly though, unlike faults in an infinite elastic body with no free surface, normal faults in an elastic half-space generate an asymmetric displacement field, with greater displacement (and more pronounced drag) in the hanging wall than in the footwall (Ma and Kusznir, 1993). The contrast in displacement could be mistaken for an increase in rigidity in the footwall, when it actually reflects a difference in the "effective thickness" of the units on the opposing sides of the fault. For a fault near the surface, the hanging wall is thin relative to the "infinitely thick" footwall. Rigidity (i.e., the shear modulus) is an intrinsic property of a rock and does not depend on the geometry of a rock body. It should not be confused with “flexural rigidity”, the resistance to bending, which is highly dependent on the geometry of a body.

A second reason regards the ease of preparing physical models with rigid footwalls (e.g. McClay et al., 1991) that yield hanging wall deformation akin to that in outcrops or inferred in seismic cross sections. The similarity in results does not mean that the footwalls of faults in the earth are rigid though.

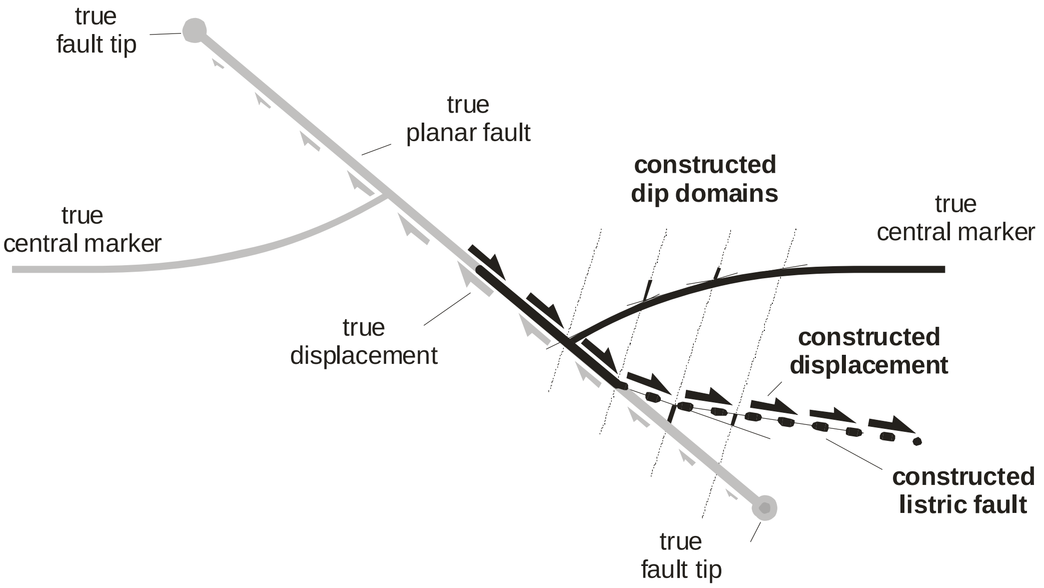


Figure 1: Listric fault (bold lines) balanced from a mechanically modelled planar “true” normal fault with reverse drag: Using the reverse drag of the central marker in the hanging wall and the dip of the fault at the intersection with the marker as input parameters, the graphical dip domain technique can be applied by incorrectly assuming that the reverse drag has been generated by slip along a listric fault. The dip of the domains has been obtained by determining the Coloumb collapse angle (72°) from the reverse drag shape. The technique will necessarily result in a listric geometry, although the result is obviously wrong.

Listric fault models and the associated hanging wall rollover have been extensively applied by many workers in order to quantify regional extension, probably due to the ease with which hanging wall collapse may be restored using the vertical shear construction or one of its many derivatives (Yamada and McClay, 2003). However, because these techniques commonly are predicated on the assumption of a listric fault geometry, they will necessarily predict a listric geometry even for faults that are planar (Figure 1).

Therefore we conclude that the concept of roll-over anticlines forming above extensional faults may be alternatively explained by reverse fault drag caused by the displacement field associated with slip. The reverse drag model may be a superior explanation for roll-over anticlines, especially for a normal fault that does not flatten into a subhorizontal detachment or are not listric at all.

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