Reverse drag revisited: Why footwall deformation may be the key to inferring listric fault geometry

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Note to Reader of the Accepted Manuscript:

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The following corrections were recommended during review of the manuscript proofs and will be incorporated in the final publication:

Line 272 replace “80” with “65”
Line 440 replace “8-18 km” with “8 to 18 km”
Lines 441-442 replace “1 - 2.5 m” with “1 to 2.5 m”
Line 516 replace “180 - 220 m” with “180 to 220 m”
Line 543 replace “striking 136 - 144° and dipping 50 - 55° ” with “striking 136 to 144° and dipping 50 to 55° ”
Line 544 replace “0.49 - 0.66 m” with “0.49 to 0.66 m”

Figure Captions:
Figure 6 and 7 should read “b) Best fit antithetic ($\alpha = -20$) and vertical ($\alpha = 0$) …”
Figure 9 should read “… Di Lucio et al. (2010)”
Graphical Abstract

- Planar fault
- Planar fault with detachment
- Listric fault with detachment

Vertical displacement (m)

- Slip imposed
- Free to slip

Distance from fault trace (km)

Depth (km)
Reverse drag revisited: Why footwall deformation may be the key to inferring listric fault geometry.

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KEYWORDS

reverse drag; normal faulting; listric fault; structural modeling

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Abstract

Although reverse drag, the down warping of hanging wall strata toward a normal fault, is widely accepted as an indicator of listric fault geometry, previous studies have shown that similar folding may form in response to slip on faults of finite vertical extent with listric or planar geometry. In this study we therefore seek more general criteria for inferring subsurface fault geometry from observations of near-surface deformation by directly comparing patterns of displacement, stress, and strain around planar and listric faults, as predicted by elastic boundary element models. In agreement with previous work, we find that models with finite planar, planar-detached, and listric-detached faults all develop hanging wall reverse-drag folds. All of these model geometries also predict a region of tension and elevated maximum Coulomb stress in the hanging wall suggesting that the distribution and orientation of near-surface joints and secondary faults may also be of limited utility in predicting subsurface fault geometry. The most notable difference between the three models, however, is the magnitude of footwall uplift. Footwall uplift decreases slightly with introduction of a detachment and more significantly with the addition of a listric fault shape. A parametric investigation of faults with constant slip ranging from nearly planar to strongly listric over depths from 1 to 15 km reveals that footwall fold width is sensitive to fault geometry while hanging wall fold width largely reflects fault depth. Application of a graphical approach based on these results as well as more complete inverse modeling illustrates how patterns of combined hanging wall and footwall deformation may be used to constrain subsurface fault geometry.
1. Introduction

A fundamental unanswered question in continental tectonics is how extension on normal faults exposed at the surface is accommodated in the middle to lower crust. Many geologic cross sections envision listric fault geometries with faults flattening at depth (e.g. Janecke et al., 1998; Brady et al., 2000), while seismological evidence indicates that most, if not all, historic moderate-to-large normal-faulting earthquakes have ruptured relatively high angle faults with nearly constant dip throughout the seismogenic crust (e.g. Stein and Barrientos, 1985; Jackson and White, 1989). We propose that this discrepancy may stem in part from misconceptions, rooted in the assumptions inherent to section balancing methods, regarding the origins of reverse drag.

Reverse drag folds, in which hanging wall strata are warped down toward a normal fault to create a fault-parallel half monocline, are a common structural element of extensional terranes (Schlische, 1995; Janecke et al., 1998). Since Laubscher (1956) and Hamblin (1965) first proposed the relationship, the formation of reverse drag has been widely attributed to slip on faults with listric (concave up) cross-sectional profiles (Shelton, 1984) (Fig. 1a). Others have noted, however, that reverse drag folds form in response to slip on planar faults of finite down dip extent (Barnett et al., 1987) (Fig. 1b). Schlische (1995) proposed reserving the term reverse drag for folds of the latter group while calling the former group rollover folds. In practice, however, the two terms are used nearly synonymously (Jackson, 1997; Peacock et al., 2000) and, in cases where the down
dip fault geometry is not well known, a clear means of differentiating between these two causes of reverse drag has yet to be identified.

2. Previous Modeling of Reverse Drag

Structural modeling provides a means to predict unknown elements of a structural system (e.g. fault geometry, fold geometry, small scale structures) from available observations (e.g. Hilley et al., 2010), as well as to understand tectonic processes responsible for the development of the system. Both physical (e.g. Mandl, 1988; Mcclay, 1990; Withjack et al., 1995) and mathematical (e.g. Crans et al., 1980; Gibbs, 1983; White, 1992; Grasemann et al., 2005; Maerten and Maerten, 2006) models have yielded many insights into processes of structural geology, including the development of reverse drag folds. Mathematical models, however, are generally best suited for parametric studies due to the relative ease with which geometry, boundary conditions, and material behavior may be modified. Mathematical models may be further divided into two subcategories: 1) Kinematic models that use area (Chamberlin, 1910) or line length (Dahlstrom, 1969) balance as a proxy for conservation of mass, assuming that rock volumes are essentially incompressible and exhibit plane strain in modeled 2D cross sections; and 2) Geomechanical models that employ a complete mechanics including conservation of mass, momentum, and energy; kinematic equations; and constitutive relations (Fletcher and Pollard, 1999). Although kinematic models have been most widely applied in past studies of reverse drag, we argue here that mechanical models are most appropriate for a more general exploration into the causes of reverse drag.
Kinematic models of reverse drag generally posit that hanging wall folding occurs due to a “space problem” associated with slip on a listric fault surface and associated detachment (Hamblin, 1965). The hanging wall is down warped or down faulted to fill the space that would be created if a rigid block were translated along the detachment (Fig. 1a). In most models the footwall block is assumed to be rigid. The area “lost” due to down warping is assumed to be balanced by an equal area displaced above the detachment surface. The depth to this detachment may therefore be calculated by measuring the “lost” area and estimating the magnitude of hanging wall extension (e.g. Gibbs, 1983; Groshong, 1994; Poblet and Bulnes, 2005). Kinematic models based on line length or area balance may be used in this way to evaluate the plausibility of cross sections, but don’t provide a direct means to predict fault-fold relationships.

Kinematic models achieve the goal of predicting structural geometry by positing a specific geometric “mechanism” of folding that maintains area balance. Many such mechanisms have been proposed for the development of reverse drag including vertical shear (Verrall, 1981; Gibbs, 1983, 1984), inclined shear (White et al., 1986; White, 1992; Xiao and Suppe, 1992; Withjack and Peterson, 1993), flexural slip (Davison, 1986), slip lines (Williams and Vann, 1987), and rigid block rotation (Moretti et al., 1988). These geometric mechanisms are generally proposed based on an inferred section-scale deformation mechanism, for example antithetic inclined shear as a proxy for distributed antithetic faulting (Rowan and Kligfield, 1989).

Reviews of the efficacy of kinematic models have found, however, that in well-constrained experimental and natural examples antithetic inclined shear provides
the best fit between fault and fold geometry regardless of the geometry and orientation of hanging wall structures (Dula, 1991; Hauge and Gray, 1996).

Kinematic models thus have a number of shortcomings in terms of understanding the processes leading to the development of reverse drag. The geometric mechanism that best fits the observed fault and fold geometry may not directly reflect natural deformation mechanisms (Hauge and Gray, 1996). Furthermore, imposition of a consistent geometric mechanism in these kinematic models precludes heterogeneous deformation that is likely to occur in both physical analog experiments and natural examples (Hauge and Gray, 1996; Withjack and Schlische, 2006). Finally, kinematic models require listric geometry to generate reverse drag and thus preclude one mechanism of reverse drag: folding due to slip on finite planar faults (Barnett et al., 1987; Grasemann et al., 2005).

In contrast to kinematic models, geomechanical models predict hanging wall folding as a natural consequence of heterogeneous displacement fields associated with slip on listric, planar, and even anti-listric faults (Reches and Eidelman, 1995). Reverse drag, rather than forming due to slip over a listric fault surface, may form more generally as a response to the heterogeneous displacement field associated with slip on faults of finite extent (Fig. 1b) (Barnett et al., 1987; Grasemann et al., 2005). Models invoking elastic (King et al., 1988; Reches and Eidelman, 1995; Willemse et al., 1996; Gupta and Scholz, 1998; Grasemann et al., 2005), elastic-plastic (Reches and Eidelman, 1995; Bott, 1997), and viscous (Grasemann et al., 2003) rheologies have all revealed that reverse drag folds may form in response to slip on finite planar faults. Finite fault models have been used to successfully model
structures from outcrop scale (e.g. Gupta and Scholz, 1998; Grasemann et al., 2005) to crustal scale (e.g. Willemse et al., 1996) and over time spans from single earthquakes (e.g. Stein and Barrientos, 1985) to millions of years (e.g. Stein et al., 1988).

Geomechanical models also have been used to investigate the causes and consequences of listric faulting. Models based on soil plasticity theory suggest that listric geometry may form in response to flow of overpressured shales on shallowly dipping delta slopes (Crans and Mandl, 1980; Crans et al., 1980). Elastic and elastic-plastic finite difference models have been used to explore the effects of fault geometry, stratigraphic layering, and inversion on hanging wall deformation above listric faults (Erickson et al., 2001). Sequential restoration based on an elastic finite-element approach has provided insights into the process of secondary faulting associated with hanging wall folding over an experimental listric fault (Maerten and Maerten, 2006). Geomechanical models thus have proven useful in developing our understanding of deformation associated with both finite planar and listric faults and may therefore prove useful in identifying characteristics to distinguish between the two commonly proposed mechanisms of reverse drag.

Although previous studies have evaluated the efficacy of listric vs. planar fault models for specific earthquakes (Stein and Barrientos, 1985) or geologic structures (Willsey et al., 2002) a more general comparison between listric and planar models has yet to be published. In this paper we explore the patterns of displacements and stress resulting from two-dimensional elastic models of planar to listric faults and identify characteristics that may be used to differentiate between these end-
member fault geometries. This parametric study reveals that the absence of
footwall up warping rather than the presence of hanging wall down warping may be
the most distinctive hallmark of listric faulting. Numerous cross sections that infer
listric faulting from hanging wall rotation alone thus warrant a closer look, and
potential revisions may help resolve the apparent disagreement between
interpretations based on earthquake seismology and geologic cross sections.

3. Elastic modeling of deformation around planar and listric faults

To directly compare patterns of displacement, strain, and stress around planar
and listric faults we employ a linear-elastic boundary element method approach.
Linear elastic modeling provides a relatively straightforward mechanically based
approach to model geologic structures. Linear elastic behavior is defined by two
material parameters (e.g. Young’s modulus and Poisson’s ratio) that may be
measured directly in the laboratory for representative rock samples (e.g. Jaeger et
al., 2007). In laboratory experiments, however, rocks exhibit significant departures
from linear elastic behavior, particularly at large strains and over long time periods.
Linear elastic models have thus been used to great success for modeling
deformation due to slip during earthquakes, but their application to geologic
structures has been viewed with greater skepticism. Several studies of well-
constrained outcrop and subsurface examples, however, have shown a remarkable
correlation between modeled and observed patterns of fault related deformation
(Gupta and Scholz, 1998; Healy et al., 2004; Fiore et al., 2007) and elastic models
have provided many insights into the processes of faulting and folding in the upper crust (e.g. Chinnery, 1961; Pollard and Segall, 1987; King et al., 1994).

Mechanical models based on the boundary element methods (BEM) are particularly well suited to problems of faulting, as only the faults must be discretized, rather than the entire rock volume. Models of fault-related deformation may thus be defined by a series of fault elements and the boundary conditions on these elements. In this paper we employ the BEM code TWODD (Crouch and Starfield, 1983), based on the solution of a two-dimensional displacement discontinuity within a linear elastic half space. The original FORTRAN code of Crouch and Starfield (1983) has been rewritten in Matlab (Martel and Langley, 2006) and modified for this study to permit both stress and displacement discontinuity (rather than absolute displacement) boundary conditions. We approximate the elastic behavior of the earth in all of the models using a Young’s modulus of 30 GPa and a Poisson ratio of 0.25 (Pollard and Fletcher, 2005). Two suites of models were developed in order to: 1) explore differences between planar and listric models; and 2) identify characteristics of fold geometry that may be indicative of down dip fault geometry. Finally, we apply these models in an inverse sense to three natural examples to find the best-fit fault geometry associated with deformation due to a single earthquake and deformation accumulated over millions of years.

3.1 Effects of fault geometry on off-fault displacements and stresses
We have constructed a series of three models to explore variations in the displacement and stress fields associated with slip on isolated planar, planar detached, and listric detached fault geometries (Fig. 2a). Each model incorporates a fault with a 60° dip at the surface that extends to 10 km depth, typical of earthquake focal depths in regions of extension (Jackson and McKenzie, 1983), to approximate a fault extending from the surface to the brittle ductile transition. The model results can be normalized by depth so that the absolute choice of this parameter is not critical (see section 3.2). All model surfaces are discretized into linear elements that are ∼100 m in length. A constant slip magnitude of 100 m is imposed across the fault surface using displacement discontinuity boundary conditions. The resulting slip/height ratio is thus ∼10−2 consistent with geologic estimates of slip to length ratios (Cowie and Scholz, 1992; Dawers et al., 1993). Although slip on real faults may vary with changing fault dip, we have chosen constant slip, or a dislocation-like model, as a first order approximation, absent prior knowledge of the slip distribution with depth. The abrupt termination of slip at the lower fault tip leads to a nonphysical condition in models without detachment elements (where slip can transfer onto detachment elements). An appropriate alternative choice of boundary conditions might be a constant stress drop, or crack-like model, (e.g. Willsey et al., 2002) that would lead to tapering slip at the fault tip. The relative difference between the predicted displacements at the earth's surface for crack and dislocation models are relatively minor (Resor, 2008). Stresses associated with the fault tip in dislocation models decay with a 1/r rather than a 1/√r singularity of the crack models (Segall, 2010). Since our focus is on near surface stresses, far from the fault
tip, the stress differences will also be minimized. For the planar detached model a series of horizontal free-slipping elements is added below the hanging wall extending 100 km from the lower fault tip. At the far end of this detachment a vertical traction free boundary is added to permit free motion of the hanging wall block. The listric model is constructed in a similar manner to the planar detached model, but with straight elements approximating a smoothly curving fault surface defined by a third-order Hermite polynomial with a 60-degree dip at the surface and a horizontal dip at the lower tip.

The vertical displacement field (Fig. 2b) for each of these models shows down warping of the hanging wall near the surface trace of the fault leading to the development of a reverse-drag fold (deformed blue surface in Fig. 2a). Hanging wall subsidence, observed at the free-surface 250 meters from the fault, increases from 57 m in the isolated planar fault model to 64 m in the planar detached model to 76 m in the listric detached model. The width of the down warped region, defined by the 10-meter (10% of slip) vertical displacement contour at the surface, increases from 14.75 to 17.25 km with introduction of the detachment. Inclusion of a listric rather than planar fault above the detachment leads to a further increase in the fold width to 18.75 km. Contours of displacement magnitude are approximately vertical in the hanging wall of each model.

The most notable difference between the three models in terms of vertical displacements is the change in footwall uplift. Footwall uplift, observed 250 meters from the fault at the free surface, decreases from 28 m to 21 m with introduction of the detachment and to 9 m with the addition of a listric fault shape. The width of the
uplifted region, again defined by the 10 m contour, also decreases with introduction of the detachment from 11.25 km to 7.25 km. Footwall uplift in the listric model does not exceed 10 m and the fold width is thus undefined or zero. Color-filled contours of footwall displacement magnitude are largely parallel to the fault surface. The presence of a hanging wall reverse drag fold thus appears to be a poor indicator of down dip fault geometry, but the extent and magnitude of down warping relative to footwall up warping are more indicative. The presence of a well-developed footwall fold (up warp) may thus be the best indicator of planar geometry.

Alternatively, it might be possible to estimate subsurface fault geometry from patterns of secondary fracture mode, orientation, and intensity. The magnitude and orientation of stresses associated with discontinuous or irregularly shaped faults has proven useful in predicting the type and orientation of secondary structures around these faults (Segall and Pollard, 1980; Maerten et al., 2002). Specifically, areas of tensile least compressive stress (Fig. 2 c and d) and positive Coulomb stress (Fig. 2 e and f) have been used to predict regions where jointing and faulting, respectively, are likely to occur. The models illustrate the orientation and magnitude of stress due to slip on the fault itself and do not include a remote tectonic stress, such as a most compressive vertical stress and least compressive horizontal stress typical of regions of extension (Anderson, 1951). The models thus illustrate the change in stress associated with fault slip rather than the complete stress state. Adding a homogeneous remote stress field would tend to reduce the variability in principal stress and Coulomb stress orientations with the remote stress field dominating (i.e. vertical most compressive stress and 80 degree dipping maximum
Coulomb shear planes for a coefficient of friction of 0.85) where stress changes are low relative to the remote stress.

We focus the discussion here on patterns of near-surface stress as we are interested in identifying means to differentiate listric and planar faults based on the abundance and orientations of structures observed at or near the earth’s surface during faulting. All models predict a region of increased tension in the hanging wall starting approximately above the lower fault tip and extending further into the hanging wall. This region of tensile stress change reaches 10 MPa at the surface at just under 7 km from the fault trace for the planar models and at just over 7 km for the listric fault. The far limit of this region is located 18 km from the trace for the isolated planar fault model and expands away from the fault with introduction of a detachment (to 26 km) and listric fault geometry (to 30 km). This tensile principal stress is oriented parallel to the earth’s surface. These stress patterns suggest that enhanced vertical jointing should be common in all reverse drag folds irrespective of underlying fault geometry.

Regions of positive maximum Coulomb stress change, calculated for a coefficient of friction 0.85 (Byerlee, 1978), largely follow the patterns of positive least compressive stress due to the normal stress dependency of the Coulomb stress. A second region of positive Coulomb stress greater than 10 MPa develops near the free-surface in the near-fault region of the planar fault models extending from 10 km into the footwall to 3 km into the hanging wall for the isolated planar model and from 5 km into the footwall to 3 km into the hanging wall for the planar detached model. This second region of elevated Coulomb stress is associated with horizontal
compression (Fig. 2d, i and ii) and would likely be counteracted by tectonic tension not included in these models. Synthetic and antithetic normal faults thus are likely to form in the hanging wall of planar and listric normal faults. Overall, the modeled stress fields suggest that the distribution, abundance, and orientation of secondary structures are likely to be of limited use in differentiating between reverse drag associated with planar and listric faults.

3.2 Quantifying the relationship between fault and fold geometries

In order to develop criteria that may be used to distinguish between listric and planar normal faults based on patterns of reverse drag folding we have constructed a second suite of models to explore the combined effects of fault shape and fault depth on the width of hanging wall and footwall folds (Fig. 3). Model fault profiles are constructed using Hermite polynomials so that the surface location and dip as well as lower fault location and dip are the only parameters required to describe fault geometry. All modeled faults are assumed to end at a horizontal detachment surface and thus have a zero degree dip imposed at their lower tip. Fault profiles range from nearly planar when the lower tip is located at the down dip projection from the surface to highly listric when the lower tip is offset horizontally in the hanging wall direction. To quantify the degree of listricity we introduce the term “listric shift” defined as the distance between a planar and listric fault at an equivalent depth (Fig. 3a).

The use of third-order Hermite polynomials to describe all of the fault traces leads to certain geometric limitations. Specifically, the nearly planar faults are not
truly planar as their lower tips still curve smoothly (as approximated by planar elements) to meet the detachment, and the maximum listric shift for faults dipping 60 degrees at the surface is limited to the fault depth as greater shifts lead to faults that extend below the detachment and then rise up to their lower tip. The use of Hermite polynomials to describe all faults, however, has the benefit of allowing the construction of a wide range of fault geometries with the same number of degrees of freedom, making comparison of models relatively straightforward.

Model results are presented as contour plots of hanging wall and footwall fold width in fault depth and listric shift parameter space (Fig. 3 b and c, respectively). We define a fold as initiating at the point where the surface is displaced by 10 m (10% of total fault throw). This criterion significantly exceeds the vertical resolution of field mapping using differential GPS (Maerten et al., 2001; Resor, 2008). Alternatively, fold width could be defined as the point where a certain minimum dip is reached (1-2 degrees for typical field compass measurements).

Using a displacement-based fold definition, however, has the added benefit that fold width is independent of slip magnitude because the model equations (Crouch and Starfield, 1983), or Green’s functions, are linear in slip.

Contours of hanging wall fold width (Fig. 3b) have very gentle positive slopes, indicating a strong sensitivity to fault tip depth and only a weak sensitivity to down dip geometry (listric shift). As discussed in section 3.1, the presence and width of reverse drag folding is thus a poor predictor of listric fault geometry. Contours of footwall fold width (Fig. 3c); however, have a relatively steep negative slope indicating dependence on both fault depth and down dip geometry. Therefore, by
combining observations of footwall and hanging wall folding both the depth and
down dip geometry of faulting can be constrained. Normalizing by one of the
geometric parameters (e.g. hanging wall fold width) reduces the problem to a single
parameterized curve. The ratio of footwall to hanging wall folding is also sensitive
to fault dip (Resor, 2008) so that a suite of curves must be constructed over a range
of surface dips (Fig. 4). Points along a single contour thus represent the ratio
between footwall and hanging wall fold width (intersecting contours of Fig. 3 b and
c). These points are located in hanging wall normalized detachment depth – listric
shift space. This plot can be used in conjunction with observations of footwall and
hanging wall fold width and surface fault dip to uniquely determine the best-fit fault
depth and listric shift. In the following section we apply this graphical approach as
well as a more complete numerical inverse scheme to solve for a best-fit fault depth
and geometry for three examples of normal fault related deformation.

4. Application to studies of earthquake deformation and geologic structures

To illustrate how down dip geometry of normal faults can be inferred from
observations of surface or near surface deformation patterns around these faults we
present brief analyses of three examples: 1) The 1983 Borah Peak earthquake,
Idaho, USA; 2) the Frog fault and Lone Mountain monocline, Arizona, USA; and 3)
the 2009 L’Aquila earthquake, Italy. These examples were chosen to explore
deformation due to a single earthquake (1 and 3) as well as deformation
accumulated over geologic time spans (2) where data were available to constrain
both hanging wall and footwall deformation. The Borah Peak and frog fault
examples have historical significance as they have been used in arguments for planar (Stein and Barrientos, 1985) and listric (Hamblin, 1965) faulting, respectively; while the L'Aquila example is representative of the suite of data available for modeling recent earthquakes. For each example we briefly review the previous work, estimate fault geometry using the mechanics-based graphical approach described in the previous section, then use a more complete mechanically-based inverse approach to solve for the best-fit geometry, and finally compare these results to previous investigations of these structures as well as to kinematic inversions. The mechanically-based inversions use the equations of the elastic boundary element model (TWODD, Crouch and Starfield, 1983) we used for forward modeling deformation in the previous sections to find a set of model parameters that minimize the misfit to the surface displacement data in a least squares sense (see section 3 above for an explanation of the boundary element code TWODD). The problem is non-linear in terms of surface dip, fault depth and listric shift. We therefore explore model parameters using a grid search over a range of fault parameters. The model that results in the lowest squared residual in comparison to the observed displacement data is considered to be the best-fit fault model. For the kinematic inversions we find a best-fit second order polynomial to the observational data from the hanging wall and then construct potential model faults following the approach of White (1992) (Fig. 5). The results are very sensitive to the choice of the shear angle. This angle may be independently estimated when the deformation of two beds is observed (White, 1992) or layer parallel strain is measured within a single bed (Groshong, 1990); however, for the relative displacement of a single
layer, the case we are interested in, the solution is non-unique. We therefore construct two models that are likely to bound the range of reasonable values of shear angle, one with vertical shear planes and the other with shear planes dipping 70° in the opposite direction (antithetic) to the main fault. These analyses serve to illustrate the potential and pitfalls of inferring normal fault geometry using graphical and more complete two-dimensional mechanically-based inverse modeling. In each case the results of the mechanics-based modeling are significantly different from those of the kinematic approach and are generally in better agreement with independent data of down dip geometry.

4.1 1983 Borah Peak earthquake, Idaho

The 1983 Borah Peak earthquake (Mw 6.9) is the largest historical earthquake in Idaho and one of the largest normal faulting events in the Basin and Range tectonic province (Pancha et al., 2006). The event had a hypocentral depth of 13.7 km with a preferred nodal plane striking 138° southeast, dipping 62° southwest, with a nearly pure dip-slip rake of -83° (Dziewonski et al., 1984). The earthquake produced a 36 km long zone of surface ruptures along the Lost River fault dipping 60-80° with a maximum net throw of 2.5-2.7 m (Crone et al., 1987). Surface deformation associated with the earthquake (Fig. 6) was measured with an uncertainty of < 20 mm by combining 1933, 1948, and 1984 leveling surveys that obliquely crossed the zone of surface ruptures (Stein and Barrientos, 1985). These observations reveal a broad region of hanging wall down warping reaching a maximum value of ~1.3 m and a narrower lower-magnitude region of footwall uplift reaching a maximum of
~0.2 m. Barrientos and coauthors (Stein and Barrientos, 1985; Ward and
Barrientos, 1986; Barrientos et al., 1987) used several different inversion methods
to analyze these data and consistently found that planar models provided a better fit
to the data than equivalently framed listric models. Their best-fit model for the
event consisted of two fault segments along strike, with the main fault plane
extending to 14 km depth with a 49° dip and 2.1 m of slip (Barrientos et al, 1987).

The mechanics-based graphical approach outlined in section 3.2 and illustrated
in Fig. 4 may be used to make a preliminary estimate of the down dip geometry of
the Lost River fault from the observed vertical ground displacements (Fig. 6). This
approach requires an estimate of the fault dip at the ground surface (~70° based on
ground rupture observations) and the footwall/hanging wall fold ratio (2.6 km /
13.3 km or 0.20 where folds are defined by the point where ground displacement
exceeds 10% of the 2 m slip magnitude). These parameters yield a depth/ hanging
wall fold width ratio of 0.60 and a listric shift/ hanging wall fold width ratio of 0.27.
The resulting depth (8.0 km) is shallower than the focal depth of 13.7 km. This
error may stem in part from the oblique route the leveling observations take across
the rupture (Fig. 2 of Stein and Barrientos 1985). The geodetic observations
therefore reflect effects of the southeast tip of the rupture as well as the lower fault
tip and would be more appropriately addressed using a three-dimensional (3D)
model. This 3D effect will lead to a narrower fold and thus shallower fault. The
relatively small listric shift of ~3.6 km is fairly consistent with previous analyses
suggesting planar faulting, but is also likely to suffer from the 3D effects discussed
above. These results suggest that the graphical method yields reasonable first order
estimates of fault geometry; however, 3D effects can significantly affect results. More accurate results may be obtained by inverting the entire data set rather than the three parameters used in the graphical approach.

Two-dimensional mechanically-based inverse modeling of the entire geodetic data set for the Borah Peak earthquake (Fig. 6a) results in a best fit dip of 44° (evaluated from 40-65° in 1° increments), a lower tip depth of 13.7 km (evaluated over 8-18 km in 100 m increments), a listric shift of 1.3 km (evaluated from 0 to the fault depth in 100 m increments), and a slip magnitude of 1.3 m (evaluated from 1-2.5 m in 0.1 m increments). Although these results also suffer from the 3D effects described above, they are much closer to previous estimates of the fault parameters and highlight a second limitation of the graphical approach, its extreme sensitivity to the estimate of surface dip. Although surface ruptures of the Borah Peak earthquake had 60-80 degree dips (Crone et al., 1987), the distribution of aftershocks (Richins et al., 1987) and geodetic inversions (Stein and Barrientos, 1985; Barrientos et al., 1987), including this work, suggest that the fault has a significantly shallower dip in the subsurface. The best-fit model has elements that are ~1 km in length and may therefore be unable to resolve any near-surface steepening.

Although the kinematic approach is not typically applied to model earthquake deformation, the observed pattern of hanging wall subsidence might lead one to infer that the causative fault is listric. The best-fit kinematic models (Fig. 6b) yield highly listric fault profiles (necessitated by the near absence of coseismic subsidence at distances greater than ~20 km from the surface rupture) with ~6 km and ~12 km
depth to detachment for antithetic inclined and vertical shear, respectively (Fig. 6b). The inferred detachment depth for the antithetic shear model is well above the depth of the earthquake hypocenter; however, the vertical shear model yields a more reasonable result that is also consistent with the distribution of aftershocks (Fig. 6b). In the case of coseismic deformation, the basic assumption of the kinematic model that volume is conserved (enforced through maintenance of the shear normal component of slip) is inconsistent with observations that horizontal and vertical deformation associated with normal fault earthquakes are of limited spatial extent (e.g. Anzidei et al., 2009; Cheloni et al., 2010).

4.2 The Frog fault and Lone Mountain monocline, Arizona

The Frog fault and associated Lone Mountain monocline were used as an illustration in Hamblin's 1965 paper on the origins of reverse drag and have been mapped and described in detail by Resor (2008). The Frog fault is one of a series of normal faults that accommodate Basin and Range extension across the western Grand Canyon (Hunton and Billingsley, 1981; Billingsley and Wellmeyer, 2003; Huntoon, 2003). The onset of normal faulting is generally inferred to be Miocene or younger (Fenton et al., 2001; Amoroso et al., 2004; Karlstrom et al., 2007) with distributed extension continuing to the present day (Kreemer et al., 2010). Geomorphic, sedimentary, and thermochronologic evidence indicate that the area was eroded to near present-day levels, with the possible exception of the canyons, by this time (Elston and Young, 1991; Dumitru et al., 1994; Pederson et al., 2002; Flowers et al., 2008).
The Frog fault dips ~70° to the southwest at the surface, down dropping Paleozoic strata in the hanging wall up to ~225 meters. Slip on the fault, as evidenced by slickenline orientations, is nearly pure dip-slip. A system of folds parallels the Frog fault, including an upper half-monocline in the hanging wall (the Lone Mountain monocline of Billingsley and Wellmeyer (2003)) and a lower half-monocline in the footwall. GPS surveying of Esplanade Fm. strata has been used to quantify the relative vertical deformation across the structures (Fig. 7) with a precision of ~3.5 m (Resor, 2008). The dip of hanging wall beds increases systematically toward the fault over ~1.5 km generating ~200 m of structural relief near the center of the fault. The dip of footwall beds decreases away from the fault over a distance of ~0.5 km with structural relief typically less than 25 meters. Resor (2008) used elastic dislocation modeling to find parameters for single and multiple planar faults that best fit the GPS survey data. The best-fit single fault had a 52° dip, extending 1300 m down dip (to 1024 m depth) with 188 m of slip. This study did not investigate potential listric geometries.

Once again, the mechanics-based graphical approach may be used to make a preliminary assessment of the down dip geometry of the Frog fault from the observed patterns of bed elevations (Fig. 7). The width of the hanging wall half monocline, defined by the 10% slip criterion, is 1030 m. The footwall fold width is 520 m. The hanging wall to footwall fold ratio is thus 0.5. For a fault dipping 70° at the surface this ratio results (Fig. 4) in a depth/ hanging wall fold width ratio of 0.635 (654 m fault depth) and a listric shift/ hanging wall fold width ratio of 0.05 (listric shift of 52 m). This result suggests that fault-related folding associated with the Frog fault is best fit by slip on a nearly planar fault. The mechanics-based graphical approach, however, again results in
an estimate for the depth to the lower tip of the fault that is shallower than previous estimates. As highlighted in the discussion of the Borah Peak earthquake above, this result may reflect the sensitivity of the graphical method to the estimate of the surface fault dip. Inverse modeling of the entire data set may therefore yield more reasonable estimates of fault parameters.

In the case of the Frog fault, mechanics-based inverse modeling results in best-fit solutions with very low slip (in comparison to field observations) due to the absence of near-fault data (which were removed for this study to reduce the effects of displacement associated with a secondary fault). To overcome this problem we constrained slip to be greater or equal to 180 m for acceptable parameter space. The best-fit fault with this constraint (Fig. 7a) has a dip of 72 degrees (evaluated from 52° to 74° in 2° increments), a depth of 1.1 km (evaluated from 0.6 to 2 km in 100 m increments), a listric shift of 0 km (evaluated from 0 to the fault depth in 100 m increments), and slip of 180 m (evaluated from 180-220 m in 10 m increments). For comparison, the best-fit kinematic model (Fig. 7b) yields a listric fault with a detachment depth of ~800 m for antithetic inclined shear and ~1600 for vertical shear. All models thus yield depth to detachment, or lower fault tip, that is unusually shallow (~1 km). Resor (2008) suggested that this might reflect an effect of the basement/cover contact (Fig. 7) or processes of strain localization that are not captured by either the kinematic or elastic models. Only the kinematic models, however, predict listric fault profiles. Field observations reveal that the fault surface dips steeply (65-85°) to at least 400 m below the Esplanade Fm. footwall cutoff (Resor, 2008). At these depths the antithetic inclined shear model predicts a fault dip of <40° and the
vertical shear model predicts a dip of ~66°. The vertical shear model thus predicts a fault dip that falls at the lower end of the range of observed dips; however, without prior knowledge of the fault dip this choice of shear angle would not be obvious.

4.3 2009 L'Aquila Earthquake, Italy

The April 6, 2009 Mw 6.3 L'Aquila earthquake was the latest of a series of moderate normal faulting events associated with 2-4 mm/year of active extension across the central and southern Apennines (D'Agostino et al., 2001; Hunstad et al., 2003; D'Agostino et al., 2008). The event had a hypocentral depth of 9.5 km (Chiarabba et al., 2009) with a preferred regional centroid moment tensor (RCMT) nodal plane striking 134° and dipping 56° southwest with a rake of -97° (Pondrelli et al., 2010). The coseismic ground deformation field was observed by synthetic aperture radar interferometry (InSAR) (Atzori et al., 2009; Walters et al., 2009; Lanari et al., 2010; Papanikolaou et al., 2010) as well as GPS (Anzidei et al., 2009; Cheloni et al., 2010). These geodetic data have been used in various inversion schemes to find the best-fitting planar fault surface for the event. These models yield results that are largely consistent with seismological results indicating a fault striking 136-144° and dipping 50-55° southwest with a rake of -98 to -105° and 0.49-0.66 m of slip (Anzidei et al., 2009; Walters et al., 2009; Cheloni et al., 2010).

The L'Aquila earthquake, however, produced only minor surface rupturing, extending 2.5 km along the trace of the Paganica fault with a maximum throw of 0.1 m (Emergeo Working Group, 2010). These results suggest that coseismic slip was largely confined to the subsurface and inversions that permit variable slip on the
fault surface have thus shown significant improvement in fitting the data in comparison to similarly framed uniform slip models (Walters et al., 2009; Cheloni et al., 2010).

The largely blind nature of the L’Aquila event precludes use of the mechanics-based graphical approach since the models used to generate the plots assume constant slip on surface breaking faults. Instead we limit our investigation into the down dip geometry of the Paganica fault to a mechanics-based inversion of a two-dimensional profile through the InSAR-derived ground displacement observations of Walters et al. (2009) (Fig. 8). Furthermore, we modify the approach taken in the last two examples to permit variable slip across the fault surface. We iterate over ranges of fault dip at the earth’s surface as well as lower fault tip depth and listric shift as before, however, for each trial model geometry we solve directly for the best-fit variable slip using a damped least squares approach (Harris and Segall, 1987). The best-fit model for the Paganica fault (Fig. 8) has a 50° dip at the surface (evaluated from 46° to 60° in 2° increments) and extends to a 7 km depth (evaluated from 6 to 16 km in 1 km increments) with a listric shift of 3 km (evaluated from 0- the fault depth in 1 km increments). Slip at the surface is 12 cm, decreases to a minimum at ~2 km depth and gradually increases to 139 cm maximum at ~6 km depth where the fault dips 36°. Slip tapers to zero at 7 km depth. The moment-weighted (slip*length) dip of the fault surface is 35°, shallower than the preferred nodal plane from the RCMT.

These results are the first attempt to model the L’Aquila earthquake with a non-planar fault surface and while they suggest that the event may have ruptured a
listric fault, this result requires more thorough investigation including an 
assessments of model resolution, trade-offs, and uncertainties (e.g. Funning et al.,
2005). For example, we have chosen the smoothing parameter to minimize the 
moment after the approach of Funning et al. (2005); however, a slightly smoother 
solution leads to a deeper more-listric fault with a lower maximum slip value. As 
discussed for the Borah Peak earthquake, three-dimensional effects may also 
significantly impact the model results. These effects are even greater for small to 
moderate magnitude earthquakes where the along-strike length of the rupture is 
relatively small. The distribution of relocated aftershocks (Di Luccio et al., 2010) 
from a 10-km-wide swath centered ~ 4.5 km northwest of the profile we selected 
for modeling suggests that the fault extends as a nearly planar surface to ~11 km 
depth inconsistent with our best fit listric model (Fig. 8). Di Luccio et al., however 
also interpret an older thrust fault crossing the Paganica fault at ~7 km depth which 
appears to have been reactivated during the earthquake sequence (Di Luccio et al., 
2010) suggesting that a non-planar geometry should not be dismissed without 
further investigation.

5. Implications for predicting subsurface fault geometry

Since Chamberlin (1910) introduced the concept of area balance to estimate the 
depth to which deformation extends (depth to detachment), section balancing and 
kinematic methods that ensure balanced sections have enjoyed widespread use in 
structural modeling. In regions of extension a variety of methods have been used to 
estimate not only the depth to detachment, but also the geometry of faults in the
subsurface. These methods, however, have several limitations, the most significant for our purposes being the fact that they presume a listric fault geometry in order to generate reverse drag folds when mechanical modeling and field observations have shown that such folds may also form over finite planar faults.

We have constructed a series of two-dimensional elastic models that confirm results of previous studies showing that reverse drag folds are likely to form over faults with a variety of down dip profiles (Reches and Eidelman, 1995). Our modeling results suggest, in fact, that a relative paucity of footwall up warping, rather than the presence of hanging wall down warping, may be the hallmark of listric faulting. Footwall uplift over geologic time scales is generally ascribed to isostatic adjustment associated with unloading of the crust during extension, as it is assumed that uplift due to coseismic fault slip will be largely relaxed during continued extension of the crust (Jackson and McKenzie, 1983). Models of an elastic upper crust over a viscoelastic lower crust and mantle, however, have shown that the relaxation is not likely to be complete (King et al., 1988). The preservation of structures, such as the Lone Mountain monocline with wavelengths and amplitudes that are small in comparison to the crustal thickness appears to corroborate these results. Footwall uplift therefore appears to reflect not only an isostatic effect, but also the process of fault slip itself. The modeling results presented here suggest that the presence of footwall uplift may in fact be an indicator of a planar or nearly-planar fault surface. The width of the hanging wall fold rather than providing direct information about fault geometry as inferred in kinematic models, appears to correlate with the depth of the lower fault tip or detachment for both planar and
listric fault models. Combined observations of hanging wall and footwall deformation may thus be used to constrain fault shape as well as depth.

Based on the results of elastic models we have suggested a simple graphical approach to derive a first-order estimate of fault depth and listric shift using the surface dip of a fault and the ratio of footwall to hanging wall fold widths. Application of this approach to two natural examples suggests that the method's sensitivity to the choice of surface fault dip may potentially lead to inaccurate results. The ratio between footwall uplift and hanging wall down warping may thus provide a quick-check method for estimating down dip fault geometry; however, inverse modeling of data describing the entire fold profile is likely to provide more accurate results. In the Borah Peak earthquake example inversion of the full data set resulted in an estimate of fault depth that was more consistent with seismological estimates.

A second issue in each of the case studies, however, is the impact of three-dimensional effects. In the earthquake examples, the relative proximity of the lateral rupture tips has likely affected the deformation patterns along the modeled profiles, while the two dimensional models assume that the fault is effectively infinite along strike. Similarly, fault slip may be heterogeneously distributed over geologic time scales, particularly along segmented normal faults (e.g. Willemse et al., 1996). We therefore advocate use of fully three-dimensional inverse modeling (e.g. Maerten et al., 2005) in most cases. An additional advantage of applying mechanics-based inversions is that geophysical inverse theory provides tools to estimate model trade-offs and uncertainties (Menke, 1984). Surface deformation data generally
have poor resolving power at depths of 10-15 km depth (e.g. Funning et al., 2005) and the ability to infer down-dip geometry from a set of observations should thus be evaluated before drawing conclusions from modeling.

Interestingly, the patterns of deformation in the mechanical listric models are consistent, to a first approximation, with some common assumptions of kinematic models. For example, kinematic models typically assume a rigid footwall. In the mechanical model of deformation around a listric fault footwall uplift is less than 10% of the slip magnitude (Fig. 2b), which may effectively be treated as non-deforming for some purposes. In a second example, inclined shear models assume that principal strains are consistently oriented (constant shear angle) throughout the hanging wall of a listric fault. In the elastic models stress (and therefore strain) orientations are also relatively consistent in the hanging wall of the listric fault (Fig. 2d), although they diverge significantly from this orientation at the free surface and above the detachment plane. These similarities may explain the ability of kinematic models to reasonably explain deformation above apparently listric faults (Hauge and Gray, 1996). These kinematic methods, however, still fail to explain folding associated with slip on planar faults and their general use for predicting subsurface fault geometry should therefore be avoided.

The models we present here are meant to address basement-involved extension involving relatively stiff rocks above a thermally activated brittle ductile transition. The case of thin-skinned extension over viscous salt or shale layers warrants further investigation using appropriate constitutive laws for these conditions. The main conclusion; however, that reverse drag is insufficient evidence to infer listric
geometry, has been confirmed for a wide range of material behaviors (Reches and Eidelman, 1995; Grasemann et al., 2003; Grasemann et al., 2005).

6. Conclusions

Although a causal link between reverse drag folding and listric faulting is widely accepted in the geologic literature, this relationship is largely based on kinematic models that pre-suppose this relationship. A parametric study of planar and listric geometries using the elastic boundary element method reveals that the absence of footwall up warping rather than the presence of hanging wall down warping may be the most distinctive hallmark of listric faulting. By combining observations of footwall and hanging wall deformation we can thus estimate both the depth to the lower fault tip and the geometry of the fault surface. Application of this approach to three natural examples suggests that normal faults in regions of crustal extension may have both planar and listric geometries. A more thorough investigation of well-constrained geologic and earthquake examples may thus help to resolve the longstanding disagreement over normal fault geometry.

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References


Verrall, P., 1981. Structural interpretations with applications to North Sea problems, Course notes, Joint Association of Petroleum Exploration Courses (JAPEC), London.
Willsey, S., Umhoefer, P., Hilley, G., 2002. Early evolution of an extensional monocline by a propagating normal fault: 3D analysis from combined field


Figure Captions

Figure 1. Two proposed mechanisms for development of reverse drag folds. a) Fault bend folding associated with slip on a listric fault. Folding (iii) is posited to occur in response to a space problem (ii) in association with slip on a listric fault (after Hamblin, 1965). b) Folding due to slip on a finite planar fault. Folding (ii) occurs in response to displacement gradients along the fault and within the surrounding rock volume (after Barnett et al., 1987).

Figure 2. Two-dimensional linear elastic boundary element models of (i) planar, (ii) planar detached and (iii) listric detached faulting. a) Model geometry and boundary conditions. Red solid lines are faults with 100 m constant slip imposed. Red dashed lines are free slipping detachment surfaces. Red dotted lines are free surfaces located 100 km to right of model. Blue line is the free surface of the elastic half space after model displacement (exaggerated 10x). b) Color-filled contours of the vertical displacement field (gray contours at 10 m intervals). ±10 m contours used to define fold width are highlighted in dark gray. c) Color-filled contours (tension positive) of the magnitude of least compressive stress with gray +10 MPa contour. d) Tick marks showing orientation of least compressive stress. e) Color-filled contours of the magnitude of maximum Coulomb stress with gray +10 MPa contour. f) Tick marks showing the orientations of maximum Coulomb shear planes.

Figure 3. Parametric exploration of varying fault geometry from nearly planar to highly listric. a) Model geometry and boundary conditions. See Fig. 2 for general
Listric shift is defined as the horizontal distance between the planar extension of a listric fault's surface dip and the lower tip of the listric fault at the detachment depth. Model results in b and c are for faults with a 60° dip at the surface and 100 m of constant slip imposed on the fault surface. b) Contours of hanging wall fold width for varying depth to detachment and listric shift. Fold width is defined by location where vertical displacement exceeds 10 m. c) Contours of footwall fold width, as defined in b, for varying depth to detachment and listric shift.

Figure 4. Plot of model results normalized by hanging wall fold width for faults with surface dips of 50°, 60°, and 70°. The suite of model results for each value of surface fault dip is reduced to a single parameterized curve with points along the curve corresponding to values of the ratio between footwall and hanging wall fold width. LR and FF are results for the Lost River fault (Borah Peak earthquake) and Frog fault, respectively (discussed in section 4). The jagged nature of the contours is a result of the numerical method by which the plots are generated – exploring a grid of parameter values and then contouring the results. See Fig. 3 for a general explanation of the models.

Figure 5. Inclined shear model after White (1992). a) Undeformed state. The model assumes that deformation occurs by shear on planes inclined at angle α from the vertical. s is the slip vector. The component of slip perpendicular to the shear direction (h') is kept constant. ab and cd are shear-parallel line segments prior to deformation. b) Deformed state. After slip the line segments, a'b' and c'd', have
been translated in the shear perpendicular direction by a distance of $h'$ and in the
shear parallel direction in order to maintain their original length. The inverse
construction is achieved by estimating $ab$ from the deformed state and then using
this length to infer the fault position at $b'$ and then continuing in this manner
incrementally away from the surface trace of the fault.

Figure 6. Example 1 of fault geometry fitting using mechanical and kinematic
inverse modeling approaches. Black dots are observational data. Darker gray line is
best-fit fault geometry, and light gray line is modeled surface displacements. Thin
black line is topographic profile vertically exaggerated 2x. a) Elastic BEM model of
the subsurface geometry of the Lost River fault based on best fit to Borah Peak
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1985, see their Fig. 2 for section location). b) Best fit antithetic ($a=-20$) and vertical
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the leveling profile crosses the Lost River fault. Topography along leveling line from
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inverse modeling approaches. See Fig. 6 for general explanation. a) Elastic BEM
model of the subsurface geometry of the Frog fault based on best fit to relative
elevation of the Esplanade Fm. in the Lone Mountain monocline surveyed using
differential GPS (Resor, 2008, see their Fig. 6, section c-c', intermediate fault block
data removed). b) Best fit antithetic (a=-20) and vertical (a=-20) shear models for Lone Mountain monocline. Approximate depth to basement is from Billingsley and Wellmeyer (2003). Topography from National Elevation Dataset.

Figure 8. Example 3 of fault geometry fitting using mechanical and kinematic inverse modeling approaches. See Fig. 6 for general explanation. a) Elastic BEM model of the subsurface geometry of the Paganica fault based on best fit to InSAR-derived line of sight displacements during the L'Aquila earthquake. Gray circles are aftershock hypocenters from Di Lucia et al. (2009) their section 3. Displacement data projected from 9 km wide swath onto section line oriented N36E. Topography from Shuttle Radar Topography Mission. b) Slip distribution of best-fit model shown in a.
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b) Vertical displacement field. ±10 m contours used to define fold width are highlighted in dark gray.

c) Least compressive stress (tension positive) with gray +10 MPa contour.

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