Chapter 3. Mechanical evolution of relay zones bounded by elliptical normal faults: Insights from three dimensional elastic-plastic finite element models

ABSTRACT

Relay zones in extensional tectonic settings transfer displacement between adjacent echelon normal fault segments and evolve under a combination of rotational and distortional strains. We present a generalized three dimensional elastic-plastic finite element model to understand the evolution of the fault interactions and the general displacement field within relay zones. The model uses listric fault surfaces, isotropic material properties, displacement based boundary conditions and models the faults as frictional sliding surfaces. The model results suggest that the fault overlap to spacing ratio, relative orientations of the adjacent faults, coefficient of friction (µ) on the faults and fault tipline shape exert significant control on the evolution of the strains and stresses in relay zones. For a given amount of regional extension, the maximum finite extensional strains (S1) are highest in antithetic convergent relay zones followed by synthetic relay zones and are lowest in antithetic divergent relay zones. The model demonstrates that even under orthogonal extension and an overall plane strain deformation, the three dimensional strain ellipsoid in the relay zone initiates oblique to the regional imposed extension direction and rotates towards this direction with progressive deformation on the faults. In all the three types of relay zones, the strains evolve along non-coaxial paths. The extent of the non-coaxial deformation varies with structural position within the relay zone. The obliquity of the S1 vectors within the relay ramp region decreases with increasing µ on the faults; however the anticipated position of linkage in the subsurface is not affected by µ. Breaching of the relay zone is most likely to initiate at the lower branch line when bounded by rectangular faults, and in the upper part where the tip lines of the faults are closest, when bounded by elliptical faults.
In nature, the non-coaxial deformation may be even higher due to anisotropy in rocks. Therefore a careful kinematics based approach is recommended for interpreting structures in natural relay zones.

3.1. INTRODUCTION

Over a broad range of scales from outcrop to continental rift zones, normal faults typically comprise sub-parallel en echelon fault segments (Larsen 1988; Peacock and Sanderson 1991; Cartwright et al. 1996; Peacock 2002, Faulds and Varga 1998). The initiation and growth of faulting in these areas is dependent on the interaction between adjacent en echelon fault segments. While the mechanism of fault growth changes with scale, the process of fault interaction and linkage is fundamental across a broad range of scales. Understanding the kinematics and mechanics of fault segment linkage will therefore provide insights into the displacement transfer mechanism between adjacent fault segments, and into fault growth mechanisms in various tectonic settings.

The interaction between adjacent fault segments is accomplished by displacement transfer through the intervening rock volume which is referred to as a relay zone (Larsen 1988, Morley et al., 1990, Ferrill and Morris 2001). Opposing displacement gradients on the adjacent faults segments result in a complex 3D displacement field (Means 1976, Mitra 1994) involving translation, distortion and inclined axis rotation in which the relay zone evolves. Therefore invoking common assumptions of irrotational and/or plane strain deformation can lead to a potential underestimation of the strain in a relay zone. Three dimensional analyses that can take into account the 3-D fault surfaces, tip line geometries, and realistic rheological properties for the deforming rock volume are necessary to understand the evolution of the displacement field in a relay zone.

Commonly accepted end-member geometries for the tip line shape of a normal fault are rectangular faults and elliptical faults. Simplistic elastic dislocation
modeling of planar faults (e.g. Ma and Kuznir, 1993) suggests that the slip patterns for these tipline shapes are significantly different. Therefore the strains that develop in relay zones, due to the opposing displacement gradients between adjacent faults, are critically dependent on the shape of the fault tip lines. It has been suggested that the energy difference between screw and edge dislocation favors the formation of elliptical fault surfaces (Walsh and Watterson, 1989) and this could partially explain the prevalence of elliptical faults over rectangular faults. This is also supported by field observations which suggest that normal faults are predominantly elliptical in shape, with a sub-horizontal major axis of the ellipse (Nicol et al. 1996). Therefore understanding the evolution of relay zones bounded by elliptical faults is useful for gaining insights into the evolution of a major class of normal fault systems.

Earlier numerical analysis of rectangular listric faults embedded in an elastic-plastic medium has given important insights into the evolution of the strain field within relay zones with progressive extension on the primary faults (Goteti et al., in review). That analysis suggested that relay zones evolve in a three dimensional strain field and along non-coaxial strain paths. An important factor influencing the strain field in such relay zones is the fault O/S ratio (Fig. 3.1). In the case of rectangular faults, the spacing between the faults is an important variable, since the fault overlap is generally constant at all depths. In the case of elliptical listric faults, however, both the fault overlap and spacing change so that one should expect more drastic variations in the strain field with depth.

Three dimensional numerical modeling is a useful technique to understand the interaction between complex elliptical faults and their influence on the evolution of relay zone structures. In this paper, we present the results from 3D elasto-plastic finite element models to understand the evolution of relay zones bounded by listric normal fault segments. In particular, we will address the following questions. For surface breaking, en echelon normal fault segments,

1. How do the relative orientations and overlap to spacing ratio of the bounding faults influence the displacements in the relay zone?
Figure 3.1. Map views showing the relationship between the primary faults in the various types of relay zones considered in this study. The terminology used is similar to the accommodation zones of Faulds and Varga (1998).
2. How does the total inelastic strain (i.e., permanent deformation) in the relay zone evolve with increasing slip on the faults?

3. How does the coefficient of sliding friction on the faults influence the evolution of total strains in relay zones?

4. How does the shape of the fault tip line (elliptical vs. rectangular) influence the strains and possible location of linkage in a relay zone?

5. What are the implications of the 3-D model results for the development of hard linkage between adjacent en echelon faults?

3.2 BACKGROUND

The en echelon arrangement of rift faults, basins and intervening transfer zones is generally observed at a broad variety of scales in extensional settings (Faulds and Varga 1998). Displacement transfer between adjacent normal fault segments is accomplished by (1) tilting and warping of the intervening rock volume without any well developed oblique fault system, resulting in the formation of a soft-linked relay zone, or (2) the formation of a through-going strike slip or oblique slip fault that transfers the strain between the adjacent basins resulting in the formation of a hard-linked relay zone (Ebinger, 1989; Morley et al. 1990, Peacock and Sanderson 1994, Peacock et al 2000, Ferrill and Morris 2001, Peacock 2003). A soft-linked relay zone may evolve into a hard-linked relay zone with the growth of an intervening transfer fault.

Field studies in various tectonic settings (e.g., Dahlstrom 1969, Aydin 1988, Nicol et al. 2002, Peacock and Sanderson 1991, 1994, Ferrill and Morris 2001) have clearly demonstrated the complex nature of deformation in relay zones that results in a complex array of structures. These structures do not necessarily conform to the regional strain field causing the deformation on the faults (Griffiths 1980, Watterson et al. 2000). Various theoretical and conceptual models have been proposed for the temporal variations in the kinematics of relay zones (e.g., Kelson et al 1997,
Baldridge et al. 1994), and for the stress regimes that give rise to such en echelon faults (e.g., Laztai 1969, Kelley 1979). Numerical modeling of mechanical interaction between normal faults embedded in a linear elastic medium, has given insights into the modification of the stress fields at the tips of adjacent normal faults (Crider and Pollard 1998, Kattenhorn and Pollard 2001, Marshall et al. 2008). However, little work has been done (e.g., Imber et al. 2003) in understanding how the rotational and distortional components of strains evolve in a relay zone bounded by listric normal faults. Our 3-D modeling results reveal that for realistic material properties, significant plasticity can develop in the rock volume comprising a relay zone, and provide a mechanical rationale for interpreting natural relay zone structures developed in listric normal fault systems. The results are complementary to our earlier analysis of the strains in relay zones bounded by rectangular faults.

In this paper, we use the following terminology to define various types of relay zones. A Relay Zone is an intervening zone between adjacent normal fault segments which are overlapping or underlapping. A Synthetic Relay zone (Fig. 3.1) (SRZ) transfers strain between adjacent normal fault segments dipping in the same direction. An Antithetic Relay zone (ARZ) transfers strain between fault segments dipping in opposing directions. ARZ can be further classified into two subtypes: (1) Antithetic Convergent Relay zone (ACRZ) in which the normal faults dip towards each other, and (2) Antithetic Divergent relay zone (ADRZ) in which the faults dip away from each other. This terminology is similar to the Accommodation zones of Faulds and Varga (1998).

The evolution of relay zones can be envisaged from the conceptual geometric models of Peacock and Sanderson (1994) and Ferill and Morris (2001). Various analogue models have improved our understanding of the influence of fault segment overlap ratio (Lecalveze and Vendeville, 2002), mechanical stratigraphy (e.g. Antonio et al., 2004) and type of fault slip (McClay et al. 2002) (orthogonal vs. oblique) on the evolution of relay zone structures. The models point to some basic
variables that control the progressive deformation such as (1) Dip of the faults (low angle vs. high angle), (2) Shape of the fault surface (planar vs. listric), (3) Shape of the fault tip lines (elliptical vs. rectangular), (4) Fault overlap to spacing ratio and (5) Relative orientation of the faults. The evolution of the magnitudes and relative proportions of the distortional and rotational components of the 3-D displacement is a function of these basic variables.

We present details of 3D finite element models to understand the evolution of relay zones defined by listric normal faults with elliptical tip lines. This is the most general (and most commonly observed) geometry of normal faults, and our analysis yields general results that can be easily modified to address special cases such as straight tip lines and planar faults.

3.3 MODEL SET-UP

3.3.1 Introduction

Finite element modeling is a well-established numerical technique to address the influence of the complexities that arise from non-linear behavior in geological deformations (Beaumont et al 1992, Erickson and Jamison 1995, Kwon et al. 2007). We have developed a displacement-based, non-linear numerical model for fault relay zones using a general purpose, commercial finite element package ABAQUS. An Updated Lagrangian formulation is used (e.g. Bathe 1996) to address various nonlinearities that may arise during the deformation. The main sources of nonlinearities in the model are frictional sliding contacts (e.g. faults), material properties (e.g. inelastic materials), kinematics of deformation involving large rotations, strains and changing boundary conditions (e.g. contact problems with friction and deforming contacts), or a combination of all these factors acting simultaneously during the deformation. Early numerical analyses of shear fractures as two-dimensional discontinuities in an isotropic, linear elastic medium (Rudnicki and
Wu 1995) gave first-order insights into the evolution of stresses, accumulation of displacements and interaction between adjacent fracture tips. Recent advances in numerical modeling have led to analyses of elastic interactions between en echelon fault segments and their influence on fault segment linkage (Pollard and Segall 1987, Pollard and Aydin 1988, Willemse et al 1996, Crider and Pollard 1998, Crider and Peacock 2004). However, most of these analyses have idealized the deformation near a fault tip as plane strain deformation (i.e. 2D analysis) and/or analyzed the displacement gradients at tip lines of planar fault surfaces.

Field studies of large-scale normal faults (e.g. Cowie and Scholz 1992, Cartwright and Mansfield 1998) demonstrate significant departures from this idealized deformation, revealing complex fault damage zone structures and displacement gradients that are not consistent with linear elastic fracture mechanics and planar fault surfaces. The influence of the three dimensional geometry of fault surfaces and tip lines (Boyer and Elliott 1982) on fault interactions has also not been fully considered in these earlier analyses. The model presented here incorporates inelastic material properties and 3D listric fault geometries, and thus will provide a significant and necessary improvement in our understanding of the evolution of the stresses and strains in relay zones in 3D.

3.3.2 Geometric configuration of the model relay zone

The model comprises two rectangular blocks with their edges parallel to the axes of the Cartesian coordinate frame (X, Y, and Z). The XY plane is horizontal, with the X axis parallel to the strike of the normal faults, and the Z axis vertical. An upper ‘active’ block slides frictionally on top of a lower, relatively rigid ‘basement’ block (Fig. 3.2). The rigid lower block allows us to set-up a model that is in mechanical equilibrium at the beginning of the analysis. The frictional contact between the two blocks is analogous to the contact between ‘brittle’ upper crustal
Figure 3.2. Set-up of the 3D model (a) Perspective view of the model blocks showing the three dimensional geometry of the fault surfaces and the elliptical tip lines. (b) Map view of the model set-up showing the imposed boundary conditions on the upper block, and (c) Cross-sectional (YZ) view of the model block. g – acceleration due to gravity.
rocks and the crystalline basement in various geological settings (e.g., crustal scale normal fault detachment surface).

The upper block has two en echelon pre-defined slip surfaces (strike parallel to X axis), which act as normal faults in the analysis. We consider fault half-surfaces in our model with the underlying assumption that the geometric middle portions of fault segments (corresponding to the lateral faces parallel to the YZ coordinate plane in the model) evolve under overall plane strain deformation when subjected to orthogonal extension. The model faults are listric in cross-section (YZ section in Fig. 3.2b) and asymptotic to a basal decollement, and their ends are defined by elliptical tip lines (Fig. 3.2d) – both common attributes of fault surfaces in extensional tectonic settings (e.g. Basin and Range province, Proffett 1977, Kattenhorn and Pollard 2001). The dip of the faults is 80° at the horizontal ground surface and gradually decreases to 0° at the contact between the upper and lower blocks. The interaction between normal faults with planar geometries has been considered before (Mansfield and Cartwright 1994, Cartwright and Mansfield 1998, Crider and Pollard 1998). Incorporating curved faults with elliptical tip lines, in the models discussed here, offers some critical insights into the variations in the three dimensional stress fields in relay zones at different structural depths due to varying distance between the faults with increasing depth.

3.3.3 Material properties for the model blocks

The depth to which rift scale normal faults extend is typically restricted by the ‘brittle’ thickness of the upper crust. Traditionally, linear elastic material properties have been used to model deformation at shallow crustal depths (e.g. Rudnicki and Wu 1995, Crider and Pollard 1998, Grant and Kattenhorn 2004). The choice of elastic rheology, however, precludes permanent deformation observed in rocks (e.g. fractures, faults, folds). In our analysis the upper block is assigned an isotropic, elastic-plastic rheology and average material properties of Adamswiller sandstone (Zhu et al. 1997). The Young’s modulus, Poisson’s ratio and the density are taken as
15 GPa, 0.25 and 2300 kg/m³ respectively for the elastic component of the rheology. For the plastic component of the rheology, inelastic behavior of Adamswiller sandstone deformed under triaxial extension experiments is used (Zhu et al., 1997). The material properties are discussed in detail in Appendix 1. Deformation of Castlegate sandstone (~25 % porosity) at confining pressures in excess of 69 MPa (Rudnicki and Olsson, 1998) have shown that the internal angle of friction reduces to 0.3. To be consistent with the material properties chosen in this study, we have used lower coefficient of sliding friction (µ) of 0.25. The influence of varying µ is discussed in section 3.5.

3.3.4 Displacement based boundary conditions

Extension in the upper block is achieved by imposing displacement based boundary conditions on the model block (Fig. 3.2a). A total orthogonal extension of 20% is imposed in 20 equal increments stretching the model block along the Y axis. The increment size is the maximum step size that allows a convergent solution of the simulation and hence is computationally effective. Imposing displacements instead of traction vectors allows us to formulate a model that is consistent with field observations and obviates the need to infer stresses. Such boundary conditions require fewer assumptions to be made on the model block rheology (Tikoff and Wojtal 1999, Kwon et al. 2007). Faces normal to the X axis are constrained laterally to ensure an overall plane strain deformation. This boundary condition is consistent with the common observation that the central portions of fault segments evolve in an overall plane strain deformation (Elliott 1976, Barnett et al. 1987). However, the edge effects that arise from this constraint do not affect the relay zone in the interior of the model block. The relay zone evolves in a general 3D displacement field. In addition to the displacement boundary conditions, an inertial load corresponding to the acceleration due to gravity (9.8 m/s²) acts on the model blocks throughout the deformation. Incorporation of gravity is critical to understanding the evolution of the rift scale relay zones considered in our analysis.
For the finite element (FE) analysis, the model block is discretized into ~5789 three dimensional quadratic modified tetrahedral elements. Upon imposing the far-field displacement boundary conditions and gravity, the stiffness of each finite element is calculated using 8-node Gaussian integration during each increment of the deformation (Bathe 1996).

Due to the continuum nature of the finite element analysis, the model presented here cannot simulate the ‘brittle’ failure (i.e. Coulomb plastic behavior) of rocks characteristic of shallow crustal levels. However by using the orientations of the principal strains and stresses that develop in the model relay zone, it is possible to predict the most probable orientations of new fault/fracture networks that might develop during the deformation (Anderson 1951, Reches 1983).

3.4 RESULTS

We have analyzed the influence of various controlling factors on the evolution of relay zones (Table 1) and will discuss in detail each of the factors below. Influence of yield strength and mechanical stratigraphy on the evolution of relay zones will be discussed in chapter 4.

3.4.1 Displacements

The deformed model reproduces the key features observed in natural relay zones, namely tilting and warping of the relay ramp region along with distortion throughout the relay zone (Fig. 3.3a). This overall conformance of the model geometry with the geometry of natural relay zones gives us confidence in the model results. The spatial variations in the plunge of the total displacement vectors (Fig. 3.3b) are consistent with displacement fields in listric normal fault systems. The imposed displacements on the XZ faces result in thinning of the model block and therefore the displacement vectors have a significant plunge at higher structural levels throughout the model block. The magnitudes of displacements are in general highest close to the model faults and at the XZ faces on which the far-field displacements are
Table 3.1. Parametric studies discussed in the paper

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geometry of relay zone</td>
<td>Synthetic relay zone (SRZ)</td>
</tr>
<tr>
<td>(O/S = -0.33, 0, 0.33)</td>
<td>Antithetic Convergent relay zone (ACRZ)</td>
</tr>
<tr>
<td></td>
<td>Antithetic Divergent relay zone (ADRZ)</td>
</tr>
<tr>
<td></td>
<td>Influence of fault overlap to spacing ratio</td>
</tr>
<tr>
<td>2. Influence of sliding friction on the faults</td>
<td>$\mu = 0, 0.1, 0.25, 0.5, 0.75, 1.0$</td>
</tr>
<tr>
<td>3. Shape of fault tipline</td>
<td>Elliptical tipline (reference case)</td>
</tr>
<tr>
<td></td>
<td>Rectangular tipline</td>
</tr>
<tr>
<td>4. Influence of yield strength</td>
<td>Model runs with Yield strength varying from 150 MPa to 890 MPa</td>
</tr>
<tr>
<td>5. Influence of layering</td>
<td>Incompetent unit overlying competent unit</td>
</tr>
</tbody>
</table>
Figure 3.3. (a) Contour plot of total vertical displacements in the model block in a synthetic relay zone after imposing 20% regional extension. (b) Total displacement vectors on the lateral faces of the model block.
imposed. The finite displacement magnitudes in the rest of the block are lower, but clearly suggest that internal deformation within the block is accommodating the imposed extension. More importantly, the footwall blocks of the faults also undergo deformation, and are not necessarily rigid blocks as simplified in some kinematic studies. This model behavior is particularly important for understanding the evolution of a Synthetic relay zone that develops in the footwall of a leading fault, and a Divergent relay zone that develops in the common footwalls of two echelon normal faults (Fig. 3.1).

With increasing extension the displacement vectors within and outside a relay zone evolve along contrasting paths. Outside the relay zone, displacement vectors are predominantly oriented parallel to the regional transport direction (parallel to Y axis ± 10°) (Fig. 3.4a). For a given set of finite elements, the proportion of vectors parallel to the regional extension direction increases with increasing extension of the model block. Vertical displacements due to thinning of the model block are constrained to the regional transport plane (YZ). Hence, outside the relay zone, the model block undergoes a predominantly plane strain deformation.

Within the relay zone, however, the displacement vectors evolve along complex but systematic paths. At the onset of slip on the faults, the predominant material movement direction is oblique to the regional transport direction and with progressive deformation the displacement vectors change through varying amounts depending on position with respect to the faults. Due to opposing displacement gradients on the normal faults, the displacement vectors define a counterclockwise vertical axis rotation of the model relay ramp (Fig. 3.4b).

3.4.1.1 Synthetic Relay Zone (SRZ)

Overlapping faults

For overlapping faults, the magnitudes of displacements in the relay zones vary with the O/S ratio. Due to the elliptical fault tip lines considered in this
Figure 3.4. (Map view) Arrows indicate azimuths of the near-surface displacement vectors at last increment of deformation. (a) Outside the relay zone, the vectors remain parallel to the regional transport direction (RTD), (b) Within the relay zone, displacement vectors define the opposing displacement gradients and the counterclockwise rotation of the relay ramp (length and direction of the arrows represent magnitude and direction of the displacement vectors).
study, both the overlap and spacing change with structural depth. Therefore the displacements (both magnitudes and orientations) vary in a complex manner in the relay zone rock volume. Overall, the highest displacement magnitudes occur at near surface levels where the faults have maximum overlap (Fig. 3.5a). The simultaneous slip on both the bounding faults results in high displacements in the relay zone. Decreasing overlap between the faults with increasing depth results in significantly lower displacements at deeper structural levels (Figs. 3.5b, c).

The orientations of the displacement vectors also gradually change with depth. Near surface, the displacements clearly define a counterclockwise vertical axis rotation of the relay ramp region. At deeper structural levels, the displacement vectors are less oblique to the regional transport plane (RTP). In addition, where the tip lines of the faults are closest (Fig. 3.5b), the displacement vectors are more steeply plunging than those at surface levels. Close to the basal detachment (Fig. 3.5c), the displacements are essentially sub horizontal and parallel to the RTP. These drastic variations in the displacements at different structural depths are predominantly caused by the changing O/S ratio with depth. This results in varying proportions of distortion vs. translation (slip on the faults) and/or rotation at different structural levels.

Zero-overlap faults

Fault segments with zero overlap are characterized by lower displacements than in the case of overlapping faults. The magnitudes of rotations in the relay ramp region are also significantly lower. In this configuration, the maximum physical proximity between the faults (O/S) is at the surface (Fig. 3.6a). Therefore the maximum displacements are also observed at the surface levels. At intermediate structural levels (Fig. 3.6b), the under-lapping configuration between the faults results in lower displacements and rotations. Vertical thinning and the absence of faults result in relatively steeply plunging displacement vectors at this level. Close to the basal detachment, the displacements are exclusively confined to the RTP with the lowest
Figure 3.5. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an overlapping synthetic relay zone (surface O/S = 0.33) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.6. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in a synthetic relay zone with zero overlap (surface O/S = 0.0) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
vertical axis rotations (for this configuration) in the relay zone rock volume (Fig. 3.6c).

**Underlapping faults**

Similar trends in variations of displacement vectors and rotations are observed in under-lapping faults (Fig. 3.7). The maximum displacements in the relay zone are observed at the surface, where the O/S ratio is the highest. Due to the thinning of the model blocks and the underlapping faults, displacement vectors are steeply plunging at all structural levels excepting close to the basal detachment surface where they are sub-horizontal.

The results discussed above suggest that, (a) fault O/S ratio plays a prominent role in the evolution of the magnitudes and orientations of the displacement vectors in relay zones; (b) for a given spacing, overlapping faults result in higher rotations in synthetic relay ramp regions than under-lapping faults; (c) the orientations of the displacement vectors in the relay zone are dependent on the position with respect to the primary faults, the O/S ratio, and the structural elevation; (d) rotations of the relay ramp region are most prominent in the case of overlapping faults.

### 3.4.1.2 Antithetic Convergent relay zones (ACRZ)

**Overlapping faults**

For overlapping faults (O/S = 0.3) (Fig. 3.8), opposing movements of the hanging wall blocks result in different displacement patterns compared to those in synthetic relay zones. Convergent relay zones have a characteristic displacement minimum in the central portion of the relay ramp region. Due to opposing movements of the hanging wall blocks and opposing displacement gradients, ACRZ show significant rotations; the largest rotations in the relay ramp are observed with fault overlap (Fig. 3.8a). Outside the relay zone, the displacement vectors are
Figure 3.7. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an underlapping synthetic relay zone (surface O/S = -0.33) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.8. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an overlapping antithetic convergent relay zone (surface O/S ~ 0.3) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
predominantly confined to the regional transport plane (RTP). The displacement vectors define a counterclockwise rotation within the relay ramp. The plunge of the displacement vectors decreases from the central portion of the relay zone towards the primary faults.

At intermediate structural depth, where the tip lines of the faults are closest, the extent of fault overlap decreases (Fig. 3.8b). Correspondingly, the magnitude of displacement is lower and the displacement vectors have the steepest plunge. The lowest displacements within the relay zone are observed at the deepest structural levels, close to the basal detachment surface (Fig. 3.8c). At these depths, similar to the observed deep level displacements at deep levels in synthetic relay zones, the displacement magnitudes are the lowest and the displacement vectors are predominantly parallel to the RTP. We also note that at depths, the fault traces define a left-stepping divergent relay zone configuration.

Zero overlap and Underlapping faults

In ACRZs defined by underlapping and Zero-overlap faults, the near-surface displacement vectors are lower in magnitudes and relatively steeply plunging (Figs. 3.9, 3.10) compared to those for overlapping faults. The magnitudes of displacements decrease with increasing depth.

3.4.1.3 Antithetic Divergent relay zones (ADRZ)

For similar amounts of extension on the faults, overlapping ADRZs (O/S = 0.3) are characterized by the least amount of deformation compared to both antithetic convergent and synthetic relay zones (Fig. 3.11). The relatively low (but finite) deformation in the footwall blocks of all the models (Figs. 3.5 – 3.13) suggests that divergent relay zones, defined by the common footwall of the primary faults, undergo the least amount of deformation. Note that both at the surface and at deeper structural levels (Fig. 3.11), the displacement vectors are consistently steeply plunging. In
Figure 3.9. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an antithetic convergent relay zone with zero overlap (surface O/S = 0.0) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.10. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an underlapping antithetic convergent relay zone (surface O/S = -0.3) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.11. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an overlapping antithetic divergent relay zone (surface O/S = 0.3) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
contrast, displacement vectors in the hanging wall blocks are gently plunging and
document the extensions and rotations in the hanging wall blocks. Therefore, while
the hanging wall blocks accommodate the extension by slip on the underlying faults,
the relay zone predominantly undergoes subsidence associated with tectonic thinning
due to far-field extension. In other words, the influences of fault interactions are
significantly lower in divergent relay zones. The O/S ratio is highest at the surface
and therefore the fault interactions progressively decrease with increasing depth.
These variations in the displacement vectors are also observed in both zero-overlap
and underlapping configurations (Figs. 3.12, 3.13).

3.4.2 Rotations

The evolution of relay zones of various types described above results in
systematic variations in rotation with increasing deformation (Fig. 3.14). The
superposition of opposing displacement gradients of adjacent normal faults on the
regional extension always results in oblique displacements within the relay zone rock
volume. Rotation of the displacement vectors with increasing extension clearly
suggests that the relay zone evolves under an overall non-plane strain deformation.
The finite vertical axis rotations reveal that the largest rotations occur in ACRZs, due
to the opposing movements of the hanging wall blocks of both the faults. The absence
of significant footwall rotations in all the models result in the lowest rotations in
ADRZs as these are defined by the common footwall of the primary faults. For
synthetic relay zones, on the other hand, the rotations are higher than in an ADRZ;
due to the movement of the hanging wall blocks in the same direction, the relative
rotations are lower than in the case of an ACRZ (Fig. 3.14). Away from the lateral
(YZ) faces of the model, vertical axis rotations increase along-strike of the primary
faults towards the relay zone.

Horizontal axis rotations are also most pronounced in an ACRZ in which the
relay ramp evolves into an antiformal surface. The hinge line of the antiform trends
Figure 3.12. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an antithetic divergent relay zone with zero overlap (surface O/S = 0.0) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.13. (Map view) Contours of the total displacements (top) and displacement vectors (below) at different structural depths in an underlapping antithetic divergent relay zone (surface O/S = -0.3) after 20% regional extension. Steeply plunging vectors appear as dots or crosses in plan view.
Figure 3.14. Vertical axis rotations in the relay ramp region (i.e., surface level) for overlapping (O/S = 0.33) synthetic, antithetic convergent and antithetic divergent relay zones. Note the increase in the rate of rotation at the last increments of deformation.
oblique to the strike of the primary faults. The obliquity of the hinge line with respect to the fault strike decreases with increasing fault overlap and trends parallel to the faults in the case of collateral (fully overlapping) fault zones. Horizontal axis rotations are predominantly dependent on the rollover folding in the hanging wall of listric faults and decrease along-strike from the lateral (YZ) faces of the model towards the relay zone.

In SRZs, the warping of the relay ramp region is mainly related to the opposing displacement gradients on the faults. Since the hanging wall blocks move in the same directions, the local structural relief in the relay ramp is not as pronounced as in antithetic relay zones. The lowest horizontal axis rotations are observed in ADRZs.

A consistent set of observations in all the relay zones discussed above are (1) fault O/S ratio plays a prominent role in the evolution of displacements in relay zones; (2) the magnitude of vertical axis rotations in the relay ramp region are highest in the case of overlapping faults and generally increase from Antithetic Divergent to Synthetic to and Antithetic Convergent relay zones; (3) horizontal axis rotations in the relay ramp vary with position with respect to the fault tips and are predominantly controlled by the amount of rollover associated with the underlying fault; and (4) the rate of vertical axis rotation increases with increasing extension on the faults (Fig. 3.14). Due to the absence of such rotations in the footwall, horizontal axis rotations are lowest in divergent relay zones.

3.4.3 Evolution of finite strains

3.4.3.1 Influence of fault overlap to spacing ratio

The fault overlap to spacing ratio is one of the key factors controlling the deformation in relay zones. The O/S ratio can be used as a variable to understand the evolution of strains in relay zones as a function of physical proximity between the faults.
The consistency of the model displacement patterns with geometries observed in natural relay zones (Peacock 2002, Ferrill and Morris 2001) gives us confidence on the estimates of the strain field. All the model results consistently reveal that fault interactions within the relay zone result in local modification of the regional imposed strain field. Outside the relay zones, the maximum principal extensional strain vectors are consistently oriented parallel to the imposed regional transport direction (RTD - parallel to Y axis) throughout the deformation and the proportion of the total strain vectors parallel to the regional extension direction increases with increasing extension of the model block (Fig. 3.15a). These results, in combination with the displacements discussed earlier, clearly suggest that interpretations involving assumptions of plane strain are reasonably valid outside the relay zone and this portion of the model evolves under progressive pure shear deformation.

The relay zone rock volume however evolves along a complex strain path (Figs. 3.15 b, c, d). Triaxial model strains at various increments of deformation clearly suggest that the relay zone continually evolves in a three dimensional strain field. At the onset of the deformation, the total strain vectors are oblique to the regional extension direction and, in general, remain deflected during the progressive evolution of the relay zone. However, with increasing overall extension, the maximum extensional strain vectors rotate in a counter-clockwise direction towards the regional extension direction and the proportion of vectors with higher deflections decreases (Fig. 3.15). Thus local structures that are oblique to the primary faults should be relatively common in incipient relay zones. In subsequent stages of deformation, these local structures may be rotated into a less oblique orientation or overprinted by younger generations of less oblique structures; alternatively, they may be reactivated in conformance with the strain field in the subsequent increments of deformation giving rise to multiple orientations of slickenlines. In addition, the
Figure 3.15. Map view showing azimuths of the near-surface maximum strain vectors. (a) Outside the relay zone, strain vectors remain parallel to the regional transport direction (RTD) throughout the deformation. Strain vectors at 30% (b), 60% (c) and 100% (d) of the total imposed extension inside the relay zone. The obliquity of the strain vectors decreases with increasing extension. (arrows / lines indicate the azimuth of the maximum principal strain)
component of rotation superimposed on the distortion zones clearly resulted from a three dimensional strain field that varies significantly from the regional strain field.

3.4.3.2 Evolution of the Maximum extensional strains

The evolution of the strain field in the relay zones can be tracked using the incremental evolution of the maximum extensional strains ($S_1$) near surface (Fig. 3.16).

**Synthetic Relay Zones (SRZ)**

For an overlapping SRZ (Fig. 3.16a), the near surface $S_1$ vectors initiate oblique to the RTD and with increasing extension on the faults, these $S_1$ vectors rotate towards the RTD. In the initial stages of deformation, the strains are low (~5%) and within the linear elastic regime. With increasing slip on the faults, the magnitudes of extensions in the relay zone reach values of up to ~ 35%. These high values clearly suggest that, even though the total extension on the faults (by slip) is about 20 %, the distortional strain magnitudes within the relay zone fall well within the inelastic strain regime. The high inelastic strains at the model fault tips are partly an artifact of the model limitation as the faults cannot grow. However, simultaneous accumulation of plastic strains elsewhere, suggests that internal distortion plays a role in the evolution of permanent deformation in the relay zone. The results are most applicable in situations where the fault length has been established early in the fault growth history.

In ‘zero-overlap’ or ‘underlapping’ SRZs (Figs. 3.16b, c), the $S_1$ vectors initiate and evolve along similar trends as in overlapping faults. In ‘zero-overlap’ faults, the sense of deflection is preserved throughout the deformation. In underlapping faults, however, $S_1$ vectors show both clockwise and counter-clockwise deflections. The magnitudes of total strains in the latter two cases are higher than in overlapping SRZs and clearly fall within the inelastic regime. The presence of
Figure 3.16. Evolution of the azimuths of the maximum extensional strains in various types of relay zones (Zero deflection corresponds to Regional Transport Direction). Symbols are for increments corresponding to the total regional extension. RTD – Regional transport direction.
bounding faults in overlapping relay zones, results in partitioning of the total
deformation in the relay zone into slip on the faults and strain of the relay zone. This
results in relatively low strains in overlapping relay zones.

*Antithetic Convergent Relay zones (ACRZ)*

Overlapping ACRZs show initial oblique orientations of near surface $S_1$
vectors, and a progressively decreasing clockwise deflection of $S_1$ with increasing
extension on the faults. In addition, the $S_1$ vectors orientations show a significant
spread in the deflection (Fig. 3.16d). Typically, maximum deflections are observed
closest to the fault tips and lower values are observed in the central portions of the
relay ramp. The spread in the orientations suggests that spatial variations in extension
direction will be more prominent in ACRZ than in SRZ. ‘Zero overlap’ and
underlapping configurations also show a clockwise deflection of the $S_1$ vectors (Figs.
3.16 e, f). Due to the low O/S ratio, the changes in the $S_1$ vectors orientations with
progressive deformation are more gradual than in the overlapping configuration. The
magnitudes of $S_1$ deflections are higher in the underlapping and ‘zero overlap’ ACRZ
than in the overlapping zone. Unlike in the case of SRZ, the sense of obliquity of the
$S_1$ vectors is preserved in underlapping ACRZ (Fig. 3.16f). For the same amount of
extension on the primary faults, the magnitudes of deflections are higher in
underlapping ACRZ than in underlapping SRZ.

*Antithetic Divergent Relay zones (ADRZ)*

Overlapping ADRZ (Fig. 3.16g) show a clockwise deflection of the near
surface $S_1$ vectors. With progressive extension on the faults, the magnitudes of the $S_1$
vectors increase; however the obliquity of the maximum extensions in the relay ramp
remains relatively constant. Note that the magnitudes of the maximum extensional
strains are significantly lower than in the case of synthetic and antithetic convergent
relay zones with the same fault O/S ratio (compare X axes of plot in Fig. 3.16g versus
Figs. 3.16a, d). Therefore, for the same amount of extension on the primary faults,
ADRZ undergo significantly lower plastic deformation than other types of relay zones. With decreasing fault O/S ratio, the decrease in the obliquity of the $S_1$ vectors is prominent in ADRZ (Fig. 3.16h). Underlapping ADRZ (Fig. 3.16i) is characterized by $S_1$ vectors that are essentially parallel to the RTD. In contrast, underlapping SRZ show $S_1$ vectors that are deflected both clockwise and counter-clockwise from RTD.

The results discussed thus far are for maximum extensional strains near surface in the relay ramp region. As discussed in the earlier section, due to the 3D listric tip lines of the faults, the O/S ratio changes with depth and so do the orientations and magnitudes of the $S_1$ vectors. In general, with increasing depth, (a) in ADRZ, the magnitude of $S_1$ increases and the obliquity decreases, and (b) in overlapping SRZ and ACRZ, both the magnitude and obliquity increase up to a depth corresponding to minimum distance between the tip lines of the primary faults; beyond this depth the obliquity decreases and the magnitude increases.

These temporal and spatial variations of the $S_1$ vectors and strain magnitudes suggest that relay zones are characterized by complex strain histories. Structures in a broad variety of orientations can form within the relay zones and the kinematics of these local structures cannot be directly correlated to the magnitude and orientations of deformation on the primary faults and vice-versa. Our model results suggest that fault interactions result in a complex strain field within the relay zone and a broad variety of local structures can be explained in terms of the variations in the strain field predicted by the model.

3.4.3.3 Evolution of the total strain ellipsoids

The evolution of the 3D strain field associated with model relay zones can be described in terms of incremental evolution of the strain ellipsoid using Hsu diagrams (Hsu, 1965). The strains in all the three types of relay zones defined by overlapping faults evolve along non-coaxial paths (Fig. 3.17). In an SRZ, the strains evolve along a non-coaxial path in the prolate ellipsoid field at near surface levels and at depths corresponding to closest approach between the fault tip lines (Fig. 3.17a). However, at
Figure 3.17. Evolution of the finite strain ellipsoids with progressive extension on the primary faults in (a) synthetic, (b) antithetic convergent and (c) antithetic divergent relay zones, all showing overlapping relationships (O/S = 0.33).
greater depths within the relay zone, the strain ellipsoids evolve in the oblate ellipsoid field. The superposition of the imposed extension, shortening due to thinning of the upper block and the flattening effects of gravity probably result in the oblate strain ellipsoid at deeper levels. Note that the strain path is closer to plane strain ($\nu = 0$) at deeper structural levels and this is consistent with the observation of displacements confined to the RTD throughout the deformation at these depths. Due to the absence of faults accommodating slip (i.e., translation), the octahedral strain magnitudes (radial axis in Fig. 3.17a) are higher closer to the detachment.

In an ACRZ, on the other hand, the strain ellipsoids continually evolve as oblate ellipsoids at all structural levels (Fig. 3.17b). The indirect ‘shortening’ in a convergent relay zone, due to the HW blocks moving towards each other, results in the oblate ellipsoids. This is especially the case near the free surface where vertical extension is possible. Points closer to the detachment surface initiate in a predominantly oblate strain ellipsoid field, and evolve towards a plane strain deformation with increasing extension. This transition is probably associated with superposition of the imposed extension and vertical shortening of the model block, and due to the flattening effect of the overlying load.

ADRZs (Fig. 3.17c) evolve along non-coaxial paths. Near the free surface and at depths up to 4 km, strains evolve in the prolate ellipsoid field. With increasing depth, the non-coaxiality of the strain ellipsoids decreases and they transition into the oblate field of the Hsu plot. Note that, consistent with the observations in the other two types of relay zones discussed above, absence of faults closer to the detachment results in significantly higher distortional strains. In addition the lower part of the relay zones evolve under plane strain deformation.

These results suggest that relay zones in general evolve along non-coaxial strain paths. Therefore the finite strains measured in the field need not correspond to the orientations of the paleostresses that caused the structures to form. Structures that formed early in the history of a relay zone may be rotated or they may be overprinted
by younger structures that develop in a differently oriented local stress field. Alternatively, the earlier structures may be periodically reactivated with different kinematic orientations as the stress and strain fields rotate with increasing slip on the primary faults.

3.4.4 Evolution of Stresses

Earlier elastostatic analyses of relay zones (e.g., Rudnicki and Wu 1995, Willemse 1997, Crider and Pollard 1998) have revealed that the amplification and the subsequent interactions of the stress fields at adjacent fault tips result in complex 3D stress fields in relay zones. Inelastic materials considered in our analysis also take into account more realistic rheological behavior of rocks and allow us to study the complex interactions between 3D stresses and plastic strains within the relay zone. The evolution of the stresses in the various types of relay zones considered in our study clearly suggest that the regional stress field is perturbed locally near the fault tips and as the proximity between the fault tips increases the modification of the stress field in the relay zone becomes more prominent.

Unlike the cumulative strains discussed earlier, the stresses described below are calculated at each increment of deformation (Fig. 3.18). Map view patterns of the von Mises stress reveal that the relay zones evolve in a stress field that is different from the far-field stresses outside the relay zone. This modification of the stress field is more prominent in the case of overlapping relay zones than in the case of underlapping or zero-overlap relay zones. In overlapping SRZ and ACRZ the O/S ratio increases from the surface up to a depth where the tip lines of the faults are closest (Figs. 3.18, 3.19a, 3.19b). Consequently, the stress values between overlapping faults reach a maximum at this depth. At greater depths, the O/S ratio decreases progressively and the distance between the fault tip lines increases. Absence of faults accommodating slip at deeper levels in the relay zone, results in higher von Mises stresses, but note that the stress orientations in the relay zones at these depths are
Figure 3.18. The along strike and vertical variations in the von Mises stresses and the orientations of the minimum compressive stresses (σ₁) in the model block.
similar to those outside the relay zone (Fig. 3.18). Therefore the modification of the regional stress field and hence the influence of fault interactions gradually decrease with increasing depth. These results suggest that structures at deeper levels where the fault traces define an underlapping relationship evolve in a stress field that is relatively in conformance with the stresses outside the relay zone. At higher structural elevations, due to the more pronounced influence of fault interactions, structures that are kinematically oblique to the primary faults are likely to develop in the relay zone. These inferences are also supported by the variations in the orientations of the minimum compressive stress vectors with structural elevation within the relay zones.

Zero-overlap or underlapping faults result in higher distortional strains in the relay zones than in the case of overlapping faults. Consequently, faults with lower overlap or underlapping relationship at the surface are characterized by higher von Mises stresses in the relay zone compared to the case of overlapping faults. This is because, distortion of the relay zone elements (and not slip on overlapping faults) accommodates most of the extension. Depending on the proximity between the faults, these high stresses can promote fault growth along strike if the initial spacing between the faults is large or can promote the formation of oblique structures linking the primary faults if the faults are already closely spaced.

In the model block the stresses are highest close to the far-field boundaries where displacements are applied and this is an artifact of the model set-up. Within the area close to the primary faults, stresses are generally highest near the fault tips and within the relay zone. The von Mises stresses increase along strike from the lateral (YZ) faces towards the model relay zone. The orientations of the minimum compressive stress vectors (σ₁) in underlapping SRZs, excepting in cases where the fault spacing is low, are generally sub-parallel to the RTD. These orientations of the stresses and the associated high plastic strains suggest that linkage can occur between closely spaced underlapping faults more readily than in the case of closely spaced overlapping faults in which the stresses are more oblique but the magnitudes of plastic strains are relatively low. This observation is consistent with other numerical
modeling studies that employed linear elastic analysis of relay zones (e.g. Kattenhorn and Pollard, 2001). With increasing spacing between the faults, along-strike propagation of the faults is more likely than developing a hard linkage.

The changes in the fault overlap to spacing ratio with depth results in a complex 3D stress field in the relay zone. In SRZ and ACRZ, at structural depths corresponding to closest distance between the tip lines, the obliquity of $\sigma_1$ is the largest. At greater depths, the obliquity of $\sigma_1$ progressively decreases. In an ADRZ, fault interactions decrease monotonically with increasing depth.

The variations in the von Mises stresses across the relay zones at various structural depths reveal that stresses in the various types of relay zones can result in contrasting structures at different depths. In an SRZ, the von Mises stress exceeds the yield strength throughout the relay zone. Therefore deformation within the relay ramp region and at greater depths (Fig. 3.19a) will occur essentially in the inelastic regime. Near the free surface, the magnitudes of stresses exceed the yield strength and are highest closest to the fault tips. At structural depths corresponding to the closest approach between the faults, the ratio reaches a maximum in the relay zone. At greater structural depths, the stress magnitudes proximal to the tip of the trailing fault are high and exceed the yield strength at all points.

In an ACRZ (Fig. 3.19b), the variations in the fault O/S ratio with depth are more drastic as both spacing and overlap change; consequently the variations in stresses and strains with depth are more prominent than in an SRZ or an ADRZ. At near surface levels the magnitudes of the von Mises stresses at the last increment of deformation are lower than the yield strength. However, the stress values are higher than the remote stresses outside the relay zone and away from the far-field boundaries (YZ faces) of the model. At a depth corresponding to closest distance between the fault tip lines, the stresses are significantly higher than at the free surface and exceed the yield strength. In addition, the overall magnitudes of stresses at this structural depth are higher than the stresses at greater depths. This local high in the stress field
Figure 3.19. Ratio of von Mises stresses to the yield strength versus distance across horizontal profile AA’ at different structural depths in an overlapping (a) Synthetic relay zone, (b) Antithetic convergent relay zone, and (c) Antithetic divergent relay zone.
is caused by the locking of the hanging wall blocks in the upper part of the relay zone which results in build up of stresses.

In an ADRZ (Fig. 3.19c), on the other hand, the stresses are in general lower than the yield strength and the inelastic strains observed in a Hsu plot (Fig. 3.17c) also suggest that these relay zones generally evolve under relatively low strains. The stresses exceed the yield strength at the deepest level as the 20% regional extension is entirely taken up by distortion. However, the associated von Mises stresses are only about 50-75% of the maximum stresses in similar SRZs and ACRZs (Fig. 3.19c).

These results clearly suggest that relay zones evolve in different stress (Figs. 3.18, 3.19) and strain regimes (Fig. 3.17) at different structural depths. Structures in the relay zones need to be interpreted with caution keeping these variations in mind, together with the overall nature of non-coaxial deformation. In all three types of relay zones discussed above, the most drastic variations in the strain and stress fields can be observed in ACRZs followed by SRZs and finally ADRZs. For the same amount of extension on the primary faults, deformation is most intense in ACRZs due to locking of the hanging wall blocks at shallow structural depths. It is noteworthy to mention that the yield strength being used in our study is based on controlled high strain rate experiments ($10^{-5} - 10^{-6} /s$) in the laboratory. Under typical geological strain rates ($\sim 10^{-12} - 10^{-14} /s$), in particular during inter-seismic deformation, rock yield strengths are lower than these values. The plastic strains in natural relay zones should therefore be expected to be higher. Nevertheless, the high stresses and plastic deformation observed in our models give important insights into how permanent deformation can evolve in relay zones.

3.5. INFLUENCE OF FRICTION ON THE FAULTS

The effective coefficient of sliding friction ($\mu$) on fault zones plays a major role in the evolution of the stress field proximal to the faults and therefore in the relay zones. To investigate the influence of varying friction, we analyzed models with different values of $\mu$ for SRZ and ACRZ, and have compared the stress profiles
across relay zones for various values of \( \mu \) for (1) equal slip on the central portions of the faults (corresponding to 1 km slip on the faults at the lateral ends of the models), and (2) equal far-field displacements (corresponding to an overall extension of 20%). The results suggest that the value of \( \mu \) plays a prominent role in the partitioning of the imposed extension into slip on the faults and distortion of the surrounding rock volume.

### 3.5.1 Equal slip on the faults

In synthetic relay zones, for equal slip on the central portions of the faults, the average von Mises stresses increase with increasing \( \mu \) on the faults (Fig. 3.20). The interaction between shear stresses of adjacent frictional faults increases with increasing physical proximity i.e., fault O/S ratio. The influence of friction is therefore most prominent at a structural depth where the tip lines of the faults are closest to one another where the average von Mises stresses increase from 171 Mpa (for \( \mu = 0 \)) to 199 MPa (for \( \mu = 1 \)) (Fig. 3.20). The stresses outside the relay zone increase with increasing \( \mu \) on the faults. This is quite prominent close to the basal detachment where the model block slides frictionally on top of the detachment surface. The ratio of the average von Mises stress in the relay zone to that of far-field stresses at the lateral ends of profiles is inversely related to the value of \( \mu \) (Fig. 3.20). For lower values of \( \mu \), stresses in the relay zone are relatively higher when compared to far-field stresses at the ends of the profiles. But at higher values of friction on the faults, the relay zone stresses are comparable to or lower than these far-field stresses.

Similar patterns for the influence of friction can be seen in Antithetic convergent relay zones (Fig. 3.22). Although the maxima in the von Mises stresses at closest approach between fault tip lines are comparable with those in a synthetic relay zone, the overall stresses are significantly higher in ACRZ for all the values of \( \mu \) considered in this analysis. At all structural elevations, the stresses within the relay zone increase with increasing \( \mu \) on the faults. With all the other parameters being identical, it is reasonable to conclude that plastic deformation will be higher in relay
Case I: Same slip on the central portion of the model fault

Figure 3.20. Influence of the coefficient of sliding friction ($\mu$) on the profiles of the von Mises stresses at different structural depths in a synthetic relay zone. Data are for equal slip (1 km) on the central portions of the faults.
zones bounded by “strong” faults and will be more pronounced in ACRZs than in SRZs.

3.5.2 Equal far-field extension

For identical imposed far-field extension (Figs. 3.21, 3.23), the magnitudes of the von Mises stresses are highest for frictionless faults in both SRZs and ACRZs. This is prominent at depths corresponding to closest distance between fault tips and to the detachment level. Lower resistance to slip on “weak” faults allows a substantial amount of the far-field extension to be accommodated by slip on the faults. Therefore the tilting and warping within the relay zone is higher; resulting in higher distortion in the relay zone. Note these results are the opposite of the observed stress magnitudes in the case of equal slip on the faults (section 5.1) where the surrounding rock volume accumulates more stresses before a “strong” fault overcomes the resistance to slip.

Results shown (Figs. 3.20 – 3.23) suggest that the coefficient of friction exerts an independent and significant influence on the deformation in relay zones. Both the shear stresses built up to overcome friction on the faults and the overall distortion due to slip on the faults play competing roles in the evolution of relay zones. For equal slip on the faults, higher $\mu$ faults are associated with more plastic deformation in the relay zone. On the other hand, for the same far-field regional extension, faults with lower $\mu$ will result in more distortion and plastic deformation in the relay zone.

3.5.3 Influence of $\mu$ on strain orientations in the relay ramp

In order to understand the influence of $\mu$ on measurable quantities in the field, it is useful to study its influence on the orientations of the long axis of the strain ellipsoid ($S_1$ vectors). In the central parts of a synthetic relay ramp ($O/S = 0.33$), the $S_1$ vectors rotate towards the RTD with increasing slip on the fault (Fig. 3.24a). While this trend is observed for all values of $\mu$, in general, the overall obliquity decreases with increasing $\mu$. Similarly in an ACRZ, the obliquity of the $S_1$ vectors decreases with increasing slip on the faults (Fig. 3.24b) and the overall obliquity decreases with increasing $\mu$. Therefore, for the same value of O/S, interaction between faults with
Case II: Same far-field Displacement-based Boundary conditions

Figure 3.21. Influence of the coefficient of sliding friction ($\mu$) on the profiles of the von Mises stresses at different structural depths in a synthetic relay zone. Data are for equal total regional extension (20%) on the upper block.
Case I: Same slip on the central portion of the model fault

Figure 3.22. Influence of the coefficient of sliding friction ($\mu$) on the profiles of the von Mises stresses at different structural depths in an antithetic convergent relay zone. Data are for equal slip (1 km) on the central portions of the faults.
Case II: Same far-field Displacement-based Boundary conditions

Figure 3.23. Influence of the coefficient of sliding friction ($\mu$) on the profiles of the von Mises stresses at different structural depths in an antithetic convergent relay zone. Data are for equal total regional extension (20%) on the upper block.
Figure 3.24. Effect of the coefficient of sliding friction on the model faults on the average azimuth of maximum total extensional strain in a (a) Synthetic relay zone and an (b) Antithetic Convergent relay zone.
higher coefficient of friction might result in structures that are kinematically less oblique to the regional extension, unlike the case of interaction between faults with low coefficient of friction.

The end-member values of $\mu$ used in the analysis (i.e., 0 or 1), clearly represent extreme cases among the spectrum of frictional faults. Many factors such as diapiric rise of salt into fault zones observed in passive margin settings, presence of incompetent units, and high pore fluid pressures in fault zones can result in a very low effective $\mu$ on a fault. On the other hand, locking at asperities and presence of strain hardening fault gouge can results in a higher effective $\mu$ on faults. These end member cases can be used to understand the evolution of relay zones bounded by such faults.

In summary, when the surface slip maxima in the central portions of the faults are identical, faults with higher coefficient of friction results in greater plastic deformation in relay zones. For the same far-field extension, on the other hand, faults characterized by lower effective $\mu$ will result in higher plastic strains in the intervening relay zones. In our models, when the maximum plastic strains exceed 3 % in SRZ and 5% in ACRZ, distortional strains due to frictionless faults remain consistently higher than those due to “strong” faults ($\mu = 1$).

### 3.6. INFLUENCE OF FAULT TIPLINE SHAPE

Fault tip line shape is a principal factor in influencing the slip distribution in the relay zone (Ma and Kuznir, 1993). Here, we compare two end-member geometries of fault surfaces — rectangular listric and elliptical listric fault surfaces. For comparison, we use a fault O/S ratio of 0.33 at the top surface of the model block to define relay zone geometry for both the fault surfaces. The fault spacing is equal to 20 % of the along-strike fault length at the top surface. The faults have an aspect ratio of 2, defined by the ratio of along-strike length of the fault at the surface and the down-dip length of the fault. For the ACRZ defined by rectangular faults (Figs. 3.25, 3.26), we use a fault O/S ratio of 0.28 as this allows us to model non-intersecting
Figure 3.25. Profiles of the ratio of von Mises stress to the elastic yield strength across (AA’) an overlapping synthetic relay zone (top) and an overlapping antithetic convergent relay zone (bottom) bounded by (a) rectangular faults and (b) Elliptical faults.
faults; the rest of the parameters such as the strike dimension and the curvature of the fault surfaces are the same as in ACRZs bounded by elliptical faults.

On an elliptical fault surface, the maximum displacement gradients are observed increasingly closer to the central portions of the fault surface with increasing depth. For rectangular faults, on the other hand, the highest displacement gradients are observed at the lower branch line. Consequently, the associated strains and stresses differ for the two fault shapes. For elliptical faults, the fault O/S varies with depth and is a function of both the fault spacing and overlap. As discussed earlier, the O/S in relay zones for overlapping or zero-overlap elliptical faults increases with increasing depth and the maxima are generally in the subsurface. At depths greater than the closest approach between the fault tips, the O/S decreases with increasing depth as a result of variations in both overlap and spacing between the fault at different depths. For parallel rectangular fault surfaces, however, the O/S remains constant at all structural elevations for SRZs as both the overlap and spacing are preserved, and increases with increasing depth for ACRZs as the overlap remains constant and the spacing decreases with increasing depth. The displacement magnitudes at structural levels corresponding to maximum O/S ratio between the fault traces for elliptical and rectangular faults clearly reveal distinct patterns. These distinct patterns will result in contrasting strain fields for the two types of fault surfaces.

Profiles of the von Mises stress at different structural elevations reflect these variations in O/S for rectangular faults (Fig. 3.25a). In SRZs, the von Mises stresses are comparable at near-surface and intermediate structural depths after 20% regional orthogonal extension. Overall, there is a slight increase in the von Mises stress from surface to intermediate depths. The magnitude of von Mises stress relative to the yield strength reveals that the deformation occurs in the elastic strain regime at shallow depths. Close to the detachment, significant inelastic strains can accumulate. This is very different from the stress profiles in the reference models of elliptical fault surfaces (Fig. 3.25b). For elliptical faults, von Mises stresses suggest that substantial
plastic strains accumulate in the upper part of the relay zone for the same amount of regional extension as in the case of rectangular faults. This is partly because, for the same aspect ratio, elliptical faults accommodate the regional extension by slip on a fault surface that is ~22.5% smaller than in the case of rectangular faults. Therefore the distortional strains in the relay zones are higher for elliptical faults. The high von Mises stresses close to the basal detachment in the case of rectangular faults are due to shear stresses that cause sliding on the frictional detachment surface (bold line, Fig. 3.25).

For ACRZs bounded by rectangular faults (Fig. 3.25a), the von Mises stress increases with increasing depth; more interestingly, these stresses exceed the yield strength at all structural depths. This is similar to the trends observed in elliptical faults (Fig. 3.25b), although the magnitudes are lower than in the case of elliptical faults. The highest stress occurs close to the detachment surface where the spacing between the faults is the lowest. ACRZs defined by elliptical fault surfaces, on the other hand, are characterized by the highest von Mises stresses at relatively higher structural elevations (Fig. 3.25b). Therefore for a given fault O/S ratio at the surface, plastic deformation and possible linkage is most likely to develop near the detachment surface for faults with rectangular tip lines. For elliptical faults surfaces, linkage is most likely to initiate at higher structural elevations where the fault tips are closest.

There are also significant differences in the orientations of the maximum finite extensional strains between an elliptical fault surface and a rectangular fault surface. In the case of elliptical faults, the obliquity of the S_1 vectors with respect to the RTD increases with increasing depth up to a depth corresponding to the maximum O/S ratio between the faults and decreases at greater depths (Fig. 3.26). As discussed earlier, this trend is seen in both SRZs and ACRZs. In the case of rectangular faults, the obliquity increases monotonically with increasing depth and the maximum obliquity is observed close to the lower branch lines of the faults (Fig. 3.26) in both SRZs and ACRZs. The maximum deflections at intermediate to deep structural
Figure 3.26. Influence of the fault tip line shape on the azimuths of maximum total extensional strain ($S_1$) at different structural elevations in a synthetic relay zone and antithetic convergent relay zone. Total regional extension ~ 20 %. 
elevations in the relay zones are significantly higher for rectangular faults than elliptical faults (Fig. 3.26). This increase in obliquity and von Mises stresses with increasing depth suggests that fault linkage is most likely to develop in the lower part of the relay zone for rectangular faults. For elliptical faults, orientations of $S_l$ vectors and von Mises stress magnitudes suggest that oblique linking structures are more likely to develop in the relay zone at intermediate depths.

### 3.7. DISCUSSION AND CONCLUSIONS

We have presented the details of a series of numerical experiments to understand the influence of various factors in the mechanical evolution of relay zones in listric normal faulted terranes. 3D nonlinear finite element models have been used to gain insights into the evolution of the displacements, strains and stresses in SRZs, ACRZs and ADRZs. The models use frictional faults, elasto-plastic material properties for the deforming rock volume and 3D listric tip line geometries. These features introduce both geometric and material non-linearities commonly observed in natural relay zones and provide a necessary improvement over the 3D linear elastic models of relay zones developed earlier by others (e.g., Crider and Pollard, 1998).

Earlier numerical studies of relay zones (e.g. Rudnicki and Wu, 1995; Crider and Pollard, 1998) helped in understanding the stress drop in relay zones associated with single slip fault events. However, the incremental evolution of strains and stresses in relay zones with increasing slip on the normal faults is relatively less understood. The models presented in this paper, give insights into temporal as well as spatial variations in the extensional kinematics and mechanics of relay zones. The models presented here are for end-member geometries of fault surfaces (i.e., elliptical listric and rectangular listric). However, many of the results can be used to understand the evolution of relay zones bounded by other fault shapes.

The models clearly demonstrate the 3D displacement field in relay zones and the need to analyze the deformation in terms of 3D strains. The local modification of
the regional strain field at fault step-overs and the feedback between locally modified strains and those arising from structures within the relay zone play a prominent role in how relay zones evolve over time. The deflection of the relay ramp region and the associated folding in relay zones varies in a complex manner with structural elevation. In both overlapping SRZs and ACRZs, the amplitudes and the widths of the folds decrease with increasing depth. These variations in fold shape are important in understanding the location of structurally controlled reservoirs or locales of enhanced fracturing within relay zones. In ACRZs, due to the change in the step sense between the faults at deeper levels, the asymmetry of the folding associated with displacement gradients on adjacent faults, changes with depth.

Rotational strains are highest in ACRZs followed by SRZs and ADRZs. The relatively high deformation in the hanging walls compared to footwalls of the faults results in the most intense deformation being observed in ACRZs. While the horizontal axis rotations in a relay ramp are predominantly controlled by the rollover associated with the underlying fault geometry and structural position with respect to the fault tip, vertical axis rotations are affected by relative movements of the hanging wall blocks of adjacent faults. Among the three types of relay zones considered, the largest vertical axis rotations are observed in ACRZs. Overlapping faults result in the largest rotations in relay zones. Faults with minimal overlap or underlapping faults typically accommodate the opposing displacement gradients on adjacent faults by a combination of torsion in the relay zone and smaller vertical axis rotations than overlapping faults.

The model results presented above clearly show that strains and stresses vary in a complex manner with structural elevation but at a given structural level evolve in a systematic manner with increasing slip on the faults. Kinematics of fracture and fault assemblages observed in relay zones need to be carefully interpreted in terms of the incremental strain field predicted by such models. The various components of the total displacement field in relay zones evolve as a function of fault proximity defined by the fault overlap to spacing ratio, relative orientations of the faults, coefficient of
friction on the faults, fault surface tip line shape, material strength of the deforming rocks in the relay zones, and structural position in the relay zone.

The incremental changes in the orientations of maximum extensional strains have critical implications for the orientation and kinematics of subsidiary faults or fractures that form in relay zones. Detailed field analysis of faults in natural relay zones have clearly revealed the three dimensional nature of the strain field in relay zones and reorientation of the strain with increasing extension on the primary faults (e.g., Ciftci and Bozkurt, 2007; Miller et al., 2007). In addition, the lack of a direct kinematic relation between subsidiary structures and the primary faults observed in natural relay zones is probably related to the complex strain field arising from fault interactions (Griffiths 1980, Morewood and Roberts 2000, Peacock 2002). The evolution of the 3D strain magnitudes and orientations predicted by our models can be used to understand the evolution of these subsidiary faults in relay zones in comparable lithologies. In the various types of relay zones considered in this analysis, the evolution of maximum extensional strains and von Mises stresses give us insights into the structural evolution of relay zones and a possible mechanical framework in which to interpret the structures in relay zones.

The superposition of strike parallel extension on the regional strain is prominent for closely spaced faults. In our models, the relative values of spacing (S) between the faults and the width of the hanging wall (W) (Fig. 3.2c) play a prominent role in the obliquity of the relay zone strains. In cases where the spacing is much smaller than the width (S « W), the maximum extensional strains are reoriented towards the strike of the fault with increasing extension on the primary faults. For faults that are spaced by a greater amount (S > W), rotations could result in S1 vectors that are reoriented towards the RTD with increasing slip on the faults. These variations with the structural level and extent of overlap between the faults have critical implications for the development of dominant fracture trends and faults within the relay zone. If we assume that, in response to the 3D strain field in a model relay zone, fractures or faults would form in orthorhombic (Reches 1978) or monoclinic
(Krantz, 1988) symmetry, then the orientation of the model S\(_1\) vectors can be used to predict the most likely trend (perpendicular to S\(_1\)) of the average strike of such fault and fracture sets.

Orientations of the maximum extensional strains at the fault tips suggest that the maximum obliquity of S\(_1\) vectors in the hanging wall increases with increasing O/S ratio. If we assume that the average strike of the subsidiary faults in the relay zones trend perpendicular to the S\(_1\) vectors, these gradual changes in obliquity with O/S suggest that in ACRZs the following structures might develop.

1. Underlapping fault segments may be linked by transverse structures if the spacing between the faults is below the critical value (W; Fig. 3.2c). With increasing spacing between the faults, the orientations of the S\(_1\) vectors suggest that there will be an increasing tendency for the faults to propagate along strike.

2. Overlapping fault segments result in ‘locking’ of the relay zone volume due to opposing movements of the hanging wall blocks. The orientations of the S\(_1\) vectors suggest that both fault segments tend to propagate towards one another. This can eventually result in the formation of a Horse block upon breaching of the relay ramp region.

In the case of synthetic relay zones the following structures might develop.

1. Underlapping fault segments may be linked by transverse structures if the spacing between the faults is below the critical value. With increasing spacing between the faults, the orientations of the S\(_1\) vectors suggest that there will be an increasing tendency for the faults to propagate along strike.

2. Overlapping fault segments accommodate the extension more efficiently than in the case of a convergent relay zone. Breaching will most likely initiate near the tip of the fault with the relay zone in its hanging wall and propagate towards the adjacent fault segment. Based on the orientation of the S\(_1\) vectors, the tendency to form a Horse block is lower than in Convergent relay zones.
Divergent relay zones, defined by the common footwall block of adjacent echelon faults are characterized by a strain field that is relatively in conformance with the regional strain field. The $S_1$ vectors suggest that overlapping divergent faults propagate away from one another.

Magnitudes of the von Mises stresses in the relay zones exceed the yield strength suggesting that inelastic deformation will be pronounced in relay zones. Maximum von Mises stresses are consistently observed at structural depths where the tip lines of the faults are closest. This observation is consistent with numerical models of relay zones in a linear elastic medium (Crider and Pollard, 1998; Kattenhorn and Pollard, 2001). Even though the deviatoric stresses reach maximum values typically close to the basal detachment, the orientations of strains suggest that relay zone structures will be in conformance with the regional strains at these levels. In particular, in ACRZ, oblique strains and highest stresses occur where the tips of faults are closest, suggesting that most intense fracturing and hence linkage can develop at this level.

Divergent relay zones, on the other hand are characterized by lower Mises stresses within the relay zones relative to outside the relay zone and in the hanging walls of the faults. Plastic strains will be substantially lower in this case. In an end-member scenario where hard linkage between faults will develop after accumulation of substantial plastic deformation within the relay zone (e.g., Stage 4 of Peacock and Sanderson 1994), the relatively low plastic strains (compared to SRZs and ACRZs) suggest that hard linkage is less likely to develop in ADRZs.

The influence of friction on fault surfaces plays a major role in controlling the orientations of displacement within the relay zone. Relay zones bounded by “weak” (low $\mu$) faults are characterized by structures that are more oblique to the primary faults than in the case of faults with high $\mu$. The orientations of maximum plastic strains are significantly affected by the coefficient of friction on the faults, although the anticipated position of linkage is less affected by $\mu$. 
The fault surface shape exerts substantial influence on the possible location of linkage between the primary faults within relay zones. For elliptical fault surfaces, linkage is most likely to develop where the tips of the faults are closest and at higher structural levels where the overlap between the faults is greatest. For rectangular faults, on the other hand, linkage in the relay zones is most likely to develop closer to the detachment surface where the stresses reach the highest magnitudes.

All the model results suggest that the distortional strains in the model blocks are significantly higher in the hanging walls of the normal faults. Depending on the relative orientations of the bounding faults, the overall intensity of deformation increases from ADRZ to SRZ to ACRZ. For a given amount of extension on the faults, ACRZs are characterized by higher von Mises stresses and therefore may show more fracturing and faulting than in the case of SRZs and ADRZs of similar surface configuration.

The results discussed here are for isotropic material properties. The partitioning of strain into its various components will vary in a much more complicated manner in natural relay zone rock volumes. Competent units such as granite, sandstone/quartzite and massive Limestones are more likely to develop fracturing and throughgoing faults at shallow crustal levels. Incompetent units such as shale, coal and anhydrites may undergo distributed deformation (i.e., more ductile behavior) within the relay zones. In the following chapter, we will discuss the influence of mechanical stratigraphy on the evolution of relay zones in layered rocks. Anisotropy in natural rocks (such as defects and other stress raisers) may enhance while other features (such as bedding or tectonic fabric) may impede the formation of fractures and faults in relay zones. While these parameters will have significant impact on the evolution of relay zones and are not addressed in this study, the isotropic models presented here give important insights into the influence of some of the fundamental variables on the evolution of relay zone structures.
REFERENCES


Kelley, V.C., 1979, Tectonics of the Middle Rio Grande Rift, New Mexico, in Riecker, R.E., ed., Rio Grand Rift: Tectonics and Magmatism, American Geophysical Union, Washington D.C., p. 57-70.


Kwon, S., Mitra, G., and Perucchio, R., 2007, Effect of predeformational basin geometry in the kinematic evolution of a thin-skinned orogenic wedge: Insights from three-dimensional finite element modeling of the Provo salient,


