Kinematic development of upper plate faults above low-angle normal faults in Death Valley, CA

by

Eliza Sarah Nemser

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

University of Washington

2001

Program Authorized to Offer Degree:
Department of Earth and Space Sciences

University of Washington
Graduate School

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Eliza Sarah Nemser

and have found that it is complete and satisfactory in all respects,
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examining committee have been made.

Committee Members:

Darrel S. Cowan

Sean D. Willett

Date: 19 December 2001

Master's Thesis

Signature Eliza S. Nemser

Date 19 December 2001

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Chairperson of the Supervisory Committee: Professor Darrel S. Cowan
Department of Earth and Space Sciences

Abstract

The upper plates of detachment faults on the west side of the Black Mountains and on the west side of the Panamint Mountains in Death Valley are extensively faulted. Field observations of the diversity of intersection geometries between upper plate faults and the detachment, the presence of gouge oriented parallel/sub-parallel to upper plate structures, and the incorporation of upper plate material into the gouge reveal a strong kinematic coupling between slip on upper plate faults and slip on the detachment. Given this evidence for kinematic coupling between upper plate faults and the detachment fault, the distribution and orientation of upper plate faults can be used to learn about the shape of the detachment fault and the kinematic history of slip on the detachment.

The projection of field data onto a dipline along the detachment permits the analysis of meaningful trends in upper plate fault distribution and orientation downdip along the detachment; this projection also allows for a direct comparison between field data and experimentally-derived data. Based on established patterns generated in analog models of upper plate deformation above a planar detachment, the observed variation in the strike of upper plate faults downdip along the detachment at each locality suggests that slip along the detachment was not purely orthogonal, and/or the detachment is not planar. Downdip trends in the strike of upper plate faults may reflect a spatial variation

in the obliquity of slip along the detachment; the variation in slip direction may be due in part to the upper plate moving over an irregular detachment.

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ACKNOWLEDGEMENTS

First, I would like to thank Darrel Cowan for his invaluable support and interest in this project, and his editorial contribution. I would also like to thank Sean Willett for his helpful critique, and Nick Hayman, who helped to familiarize me with the geology of Death Valley, and has been an important resource throughout this project.

I would like to thank Matt Quann for his tremendous help in the field, and for his incredible support and patience. I would also like to thank my parents for their perpetual support and encouragement. This work was partially funded by a research grant from the Graduate Support Fund of the Department of Earth and Space Sciences, and by the Chevron Fellowship and the Peter Misch Fellowship.

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1. Introduction

Low-angle normal or "detachment" faults are widely recognized structures that play an important role in continental extensional tectonics in the Western US (e.g. Wernicke, 1981). Much attention has been focused on detachment faults in the Basin and Range, particularly in central Death Valley where detachments may have accommodated up to 90 km of extension since the Late Tertiary (Wernicke et al., 1988).

Many studies have addressed the role of upper plate deformation above a detachment fault in the kinematic and geochemical evolution of the detachment-system (e.g. Lister and Davis, 1989). Yet some fundamental questions remain, including: Is upper plate deformation kinematically related to slip on the detachment fault? Is deformation in the upper plate contemporaneous with slip on the detachment fault? Is upper plate deformation above a detachment fault an important element in the accommodation of extension in the Death Valley region? How do upper plate structural patterns reflect the kinematics of slip along the detachment fault? What can we infer about the kinematic development of the upper plate from field observations of upper plate faults?

It is important to resolve the question of whether the kinematics of upper plate deformation is coupled with slip along the detachment fault in order to determine whether the geometry of upper plate structures can provide insight into the kinematic history of detachment slip. This study examines the brittle structures that accommodated extension in the upper plate of detachment faults in Death Valley, CA (Fig. 1). Death Valley is a superb area to study detachment faults, as the structural geology is dominated by detachment-style faulting, and the exposure is excellent. In the field, I mapped in detail the geometrical relationships between detachment faults and upper plate structures at eight different sites along two major detachment faults in Death Valley, CA (Fig. 1). I chose localities where the detachment and a significant section of upper plate are well exposed. On the basis of structural relationships between upper plate faults and the detachment fault, I assert that there is strong evidence for kinematic coupling between upper plate faults and the detachment fault. Confirmation that upper plate faults are kinematically coupled with detachment slip provides the foundation for a consideration of upper plate fault geometries in the context of the kinematic evolution of the detachment-system.

In order to assess the influence of the kinematic development of the detachment fault on the evolution of upper plate deformation, field data are compared with published experimental studies, particularly analog experiments. Trends in the population of upper plate faults are analyzed using a geometric projection technique that converts field data onto a cross-section downdip along the detachment. This technique provides a useful tool for the visualization of upper plate fault geometry in the reference frame of the detachment fault, and allows for a direct comparison between patterns of deformation that can be observed in the field and patterns of deformation which have been generated in relevant analog experiments.

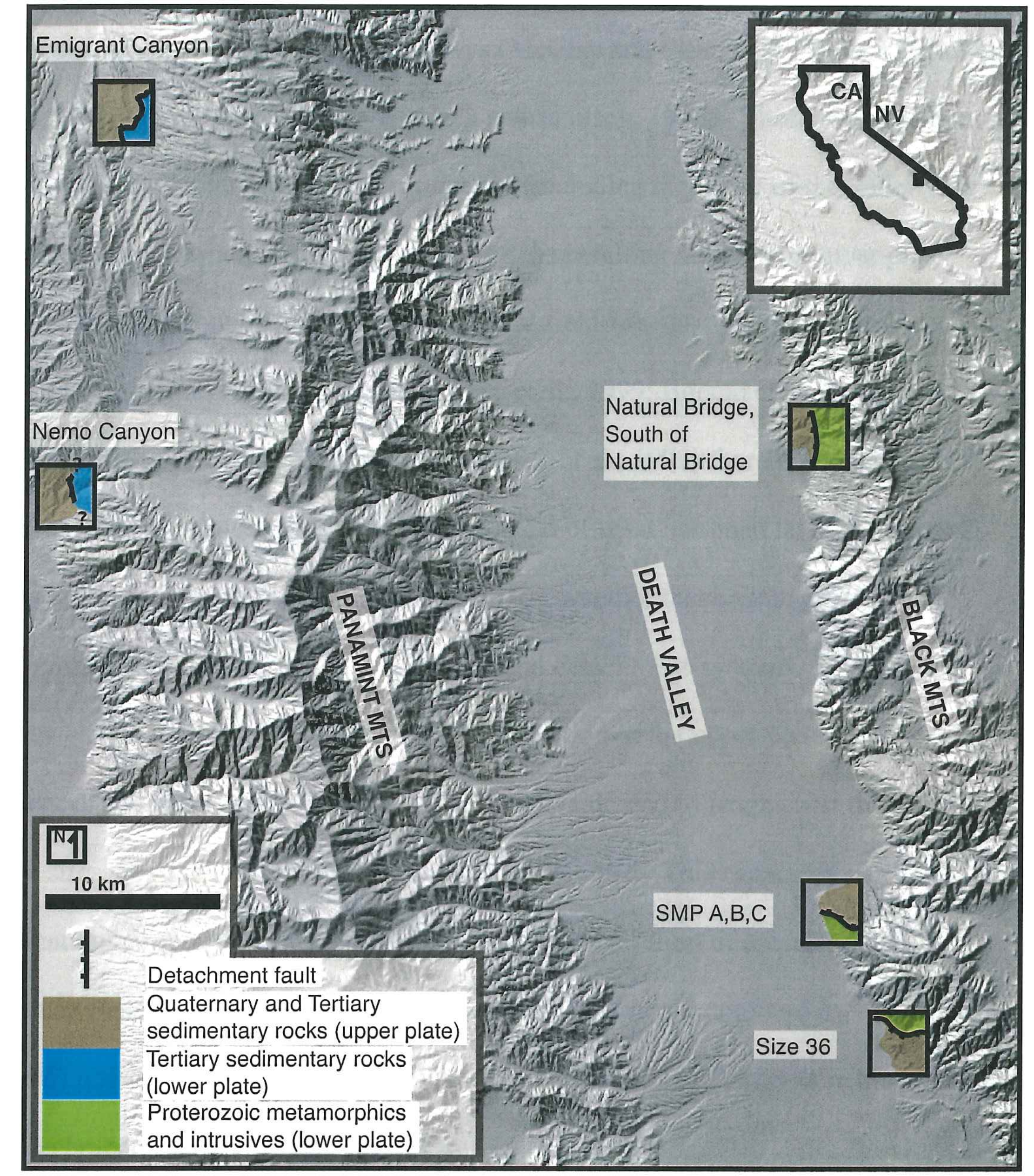

Figure 1. Map of the Death Valley area, showing field localities and generalized geology at those localities. DEM compiled by Nick Hayman; geology after Cladouhos (1999); Snyder and Hodges (2000).

Analog models of upper plate deformation above a low-angle normal fault have demonstrated that slip along a detachment fault drives upper plate deformation, initiating rollover geometries and normal fault arrays (McClay and Ellis, 1987; Ellis and McClay, 1988; Williams and Vann, 1987; Withjack and Jamison, 1986). These models have investigated the effect of different parameters (including the shape of the underlying detachment and variation in slip direction) on the resulting patterns of upper plate deformation. Although there have been several field-based studies of upper plate fault systems, (Gross and Hillemeyer, 1982; Axen et al., 1999; Boncio et al., 2000; Michel-Noel et al., 1990; Scott and Lister, 1992; Gautier et al., 1993) there has been little effort to systematically analyze field data in the context of what has been learned in the lab.

This study presents an opportunity to test whether these analog systems are appropriate for modeling the behavior of natural detachment-systems. If so, analog models can be used to predict patterns of deformation in the upper plate, to make inferences about the geometry of the detachment fault, and to reconstruct the orientation of the stress regime under which the detachment slipped. This capability has important implications for our understanding of the kinematic evolution of detachment fault systems. Based on the comparison between field data and analog models, this paper presents possible kinematic explanations for the observed fault patterns in the upper plate of detachment faults in Death Valley, CA.

2. Upper plate deformation above a detachment fault

The following features are common among major detachment-systems: (1) The detachment fault is marked by a zone of fault rocks and gouge with a sharp principal slip surface at the upper boundary, in contact with the upper plate (2) The principal slip surface separates fault rocks and the underlying highly deformed crystalline lower plate with ductile fabrics from an extensively faulted upper plate (3) Abundant high-angle normal faults in the upper plate commonly end at or sole into the principal slip surface. This relationship suggests that the upper plate faults are kinematically related to the detachment (e.g. Gross and Hillemeyer, 1982 (Whipple Mountains); Axen et al., 1999 (Cañada David detachment in the Sierra El Mayor, Baja California); Wernicke and Burchfiel, 1982 (Death Valley); Boncio et al., 2000, (Altotiberina detachment fault, central Italy)).

2.1. Visible faults

Faults (mostly high-angle, normal faults) appear to be the principal type of deformation in the upper plate of detachment faults. There are two general kinematic models that describe the development of fault systems in the upper plate above a detachment fault: (1) planar rotational faulting between domino-style blocks (Axen, 1987; Wernicke and Burchfiel, 1982; Ransome et al., 1910; Jackson and McKenzie, 1983), (2) slip along a system of listric faults above a master listric normal fault (Dorsey and Becker, 1995; Lister and Davis, 1989). Field data from natural systems (e.g. Lister and Davis, 1989) and experimental data from analog systems (e.g. McClay and Ellis,

1987) confirm that these are end-member models, and both types of faulting occur within a given detachment-system. The kinematic mechanism that governs upper plate faulting in a given system may also vary through time, as the geometry of faults and fault blocks evolves with increased extension (McClay and Ellis, 1987).

A discussion of the dynamic cause of faulting is beyond the scope of this study and would likely include one or more of the following mechanisms: (1) flexural isostatic uplift due to tectonic denudation along the detachment (Wernicke and Axen, 1988), (2) lower plate stretching in pure shear causing upper plate tensional failure, or (3) upper plate collapse due to translation above a listric master fault (Fowler et al., 1995).

2.2. Volume Problem

Although deformation in the upper plate above detachment faults appears to be dominated by slip on faults, several workers have observed that attempts to restore cross-sections of faulted upper plate terrain using only rotational and translational slip on faults results in significant void spaces (Gross and Hillemeyer, 1982; Davis and Lister, 1989; Axen, 1988; Jackson and White, 1989; McClay and Ellis, 1987). This discrepancy (the "volume problem") has led to efforts to explain the loss of upper plate material using faults and other mechanisms of upper plate deformation.

Initial attempts to reconcile the volume problem attributed extension in the upper plate to rotational slip on listric faults. However, Gross and Hillemeyer (1982) demonstrated that the volume problem arises regardless of whether the faults were originally planar or listric, and suggested that penetrative deformation, or microfaulting, can explain the apparent volume loss. Davis and Lister (1989) suggested that the theoretical volume problems can be explained if upper plate faults were originally listric, but were subsequently truncated by a younger, structurally higher detachment, such that all planar faults are truncated listric faults. This model is markedly different from the domino planar model, and will be explained in more detail in section 3.5.

Other workers have suggested that the apparent loss of upper plate material during extension can be explained if the detachment gouge (breccia) is derived (at least in part) from upper plate rocks. Geochemical and petrographic studies in the Whipple Mountains (Gross and Hillemeyer, 1982) and in Death Valley (Cowan et al., 1997; N. Hayman, pers. comm., 2001) indicate that detachment gouge is derived predominantly from the lower plate. However, Axen et al. (1999) made a special reference to a foliated brown clay gouge in the Cañada David detachment, Baja California, which they considered to be derived from the upper plate. My observations in Death Valley, CA indicate that while most of the detachment breccia appears to be chloritic and composed of material form the lower plate, a brown clay gouge is present at several localities where intersections between the upper plate and the principal slip surface of the detachment are particularly irregular. Although the upper plate rocks may contribute to the gouge locally, there is not enough evidence to indicate that the brecciation of upper plate rocks is the dominant cause of the erosion of upper plate material.

2.3. Other deformation mechanisms

While faults and fractures at the mesoscopic scale can be readily observed in the upper plates of detachment faults, there is also deformation at the microscopic scale that accommodates some strain. Efforts to quantify the percentage of extension that is accommodated by faulting in the upper plate of detachment faults suggest that visible faults may account for approximately half of the total extension. Kautz and Sclater (1988) modeled upper plate deformation above a detachment fault using clay and found that visible faults accommodated only 40-50% of the extension. In this experiment, they assumed that clay deforms exclusively by slip and rotation on faults; they based their assumption on early experiments by Oertel (1965), who established that faulting is the mechanism of deformation in clay modeling experiments. Yet Kautz and Sclater (1988) observed that fault blocks in sand models do undergo significant internal deformation causing the fault planes to change their shapes during progressive deformation. Given their assumption that all deformation occurs along faults, they concluded that this "hidden extension" due to internal deformation is accommodated on faults below the mesoscopic scale. These data are consistent with the findings of Clifton et al. (2000) who found experimentally that a systematic increase in the imposed strain does not cause a proportional increase in the amount of strain accommodated by brittle surface faulting, which they estimate accounts for up to 50% of the total imposed strain.

It is likely that deformation in the upper plate of detachment faults is accommodated by a combination of slip on visible faults, slip on faults below the visible scale, and by cataclasis of the upper plate material. It would be useful to determine the relative importance of these mechanisms in order to more accurately estimate total extension in the upper plate, which may be significantly underestimated if most of the deformation is assumed to be accommodated along faults (Axen, 1988; Jackson and White, 1989). For the purposes of this study it is important to acknowledge that visible faults represent only one mechanism of deformation of the upper plate. Recognizing this fact, this study is not intended to be an exhaustive analysis of upper plate extension, but rather a consideration of the role of macroscopic upper plate faulting within a detachment-system in Death Valley, CA. The incorporation of upper plate material into the detachment gouge by cataclasis is considered only insofar as this process is relevant to understanding the kinematics of upper plate faulting.

3. First-order kinematic coupling between upper plate faults and detachment slip

Although upper plate faults above detachment faults are seemingly ubiquitous, and appear to be kinematically associated with the underlying detachment fault, it is important to consider the fundamental question of whether the failure of these upper plate faults is kinematically coupled with slip on the detachment fault. The first basic level of kinematic coupling establishes that deformation in the upper plate is related to slip along the detachment fault. If this first-order kinematic coupling is established, the next level of coupling to be explored is the extent to which the distribution of deformation in the upper plate is controlled by the nature of slip along the detachment (e.g. obliquity of slip) and by the character of the detachment itself. In this section, structural relationships between the upper plate faults and the detachment fault will be examined in order to demonstrate a basic level of kinematic coupling. Subsequent sections will explore the features of this kinematic coupling.

Models that attempt to relate upper plate deformation to the kinematic history of the detachment fault fall into two categories: either the upper plate failed independently from failure along the detachment fault, or the upper plate deformation is kinematically linked to slip on the detachment fault (though not necessarily contemporaneous). These models rely on temporal relationships between the upper plate faults and the detachment fault (e.g. Do upper plate faults predate or postdate slip on the detachment? Was slip on upper plate faults contemporaneous with slip on the detachment? Has there been temporal alternation between upper plate fault slip and detachment slip?) Although kinematic coupling does not require any particular temporal relationship, it can be ruled out if all upper plate faults predate detachment slip. However, arguments that the upper plate kinematics is NOT kinematically coupled with detachment slip typically invoke a temporal independence wherein all upper plate faults either predate or postdate detachment slip.

To systematically address these models, I made field observations on the geometry of intersection between upper plate faults and the detachment fault where such relationships are exposed, in order to characterize the temporal relations between slip on upper plate faults and the detachment fault. Whereas it is theoretically impossible to observe evidence of contemporaneous slip (unless the system is active, as in analog models), it is straightforward to recognize whether upper plate faults all predate or postdate detachment slip, or whether both relationships exist within a given population.

3.1. Field Methods

Detachment faults in the Death Valley region have been extensively studied and mapped (e.g. Drewes, 1963; Wright and Troxel, 1984; Miller, 1992). The Black Mountain detachment fault on the west side of the Black Mountains records Quaternary slip, as it cuts the 0.76MA Bishop Ash. The minimum age of detachment slip is not well-constrained; though the detachment is locally cut by .18 MA lake gravels (Knott et al., 1999), elsewhere detachment slip may postdate these deposits. The Emigrant detachment on the west side of the Panamint Mountains has been mapped by Hodges et al., (1990); the age of slip on the Emigrant detachment is not well-constrained.

Field observations were made along traverses at 8 localities: 6 above the Black Mountain detachment, and 2 above the Emigrant detachment (Fig. 1). The localities in the Black Mountains are (from North to South): Natural Bridge Canyon, the canyon immediately south of Natural Bridge Canyon ("South of Natural Bridge"), 3 canyons immediately south of Mormon Point, referred to as SMP A, SMP B, SMP C, and Size 36. The localities in the Panamint Mountains are Nemo Canyon and a locality just south of the turnoff onto Emigrant Canyon Road.

Intersections between the detachment fault and upper plate faults were studied in detail at the 6 localities at which they are exposed: Nemo Canyon, Size 36, SMP A, SMP B, South of Natural Bridge, and Natural Bridge. Information about upper plate fault orientation (strike, dip, listricity, facing direction) and fault character (sense of displacement, amount of displacement) was recorded at all 8 localities. Information about upper plate fault distribution (spacing, density) was collected at the 4 localities where both of the following conditions are met: (1) the terrain permitted the distances between the faults to be accurately measured by pacing, and (2) the detachment is exposed so that the spatial relationship between the detachment and the upper plate faults could be accurately determined. At these localities (Natural Bridge, South of Natural Bridge, Size 36, and Nemo Canyon), the distances between the points where the faults intersect the traverses was measured using the pacing technique (Compton, 1985).

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Quaternary conglomerates and fanglomerates, colluvium and lacustrine deposits, which have been classified according to color and clast provenance by Burchfiel et al., (1995). Upper plate lithologies in the Panamint Mountains include the Upper Tertiary conglomerates and fanglomerates of the Upper Nova Formation (Snyder and Hodges, 2000). It is difficult to identify faults with 100% confidence in these lithologies given the extensive fracturing and the poor expression of bedding by which to judge offset. I measured structures that are planar to curviplanar which have accommodated at least 1cm of slip, relying on the presence of one or more of the following criteria: (1) a polished surface, (2) a marked change in clast size/composition across the structure, indicating the offset of beds, or (3) a sense-of-shear indicator, such as striations, slickensides or grooves. It is possible that in places where I measured the orientation of the upper plate faults well above the structural level of the detachment, I might have missed faults that intersect the principal slip surface of the detachment but die out with distance from the detachment. However, this is unlikely since most structures that were observed to "die out" within the exposed section were undulating rather than planar, with minimal to no offset, and thus are more appropriately characterized as fractures.

3.2. Field Observations and Discussion: Introduction

In this section I detail observations of the diversity of intersection geometries, the orientation of detachment gouge parallel to upper plate structures, and the incorporation of upper plate material into the detachment gouge. Based on these observations, I assert that some of the slip on upper plate faults predates some detachment slip whereas other slip on upper plate faults postdates some detachment slip. The processes that give rise to the incorporation of upper plate material into the detachment gouge and the remobilization of detachment gouge around upper plate faults provide strong evidence that the upper plate faults and the detachment operate as a coupled system. While some upper plate faults may record early uncoupled upper plate failure and some may record late uncoupled upper plate failure, I will demonstrate that the failure of the majority of upper plate faults was kinematically linked to detachment slip. The determination of this fundamental coupling provides the basis for further exploration of the degree to which the kinematics of upper plate faulting is controlled by properties of and slip along the detachment fault.

3.3. Observations: Diversity of intersections

There are three major types of intersections of upper plate faults with the principal slip surface of the detachment fault, so the faults have been categorized into three corresponding groups. Within each group, there is a planar subset (A) and a listric subset (B) (Fig. 2). Group I consists of upper plate faults which do not offset the principal slip surface (Fig. 3). Group II consists of upper plate faults which offset the principal slip surface, and where the fabric of the detachment gouge is oriented parallel/sub-parallel to the upper plate structure (Fig. 4). Group III consists of upper plate faults which offset the principal slip surface, but where the fabric of the detachment gouge is parallel/sub-parallel to the principal slip surface (Fig. 5). Each of the three groups includes faults that are antithetic and synthetic, high- and low-angle. None of the three groups (or six

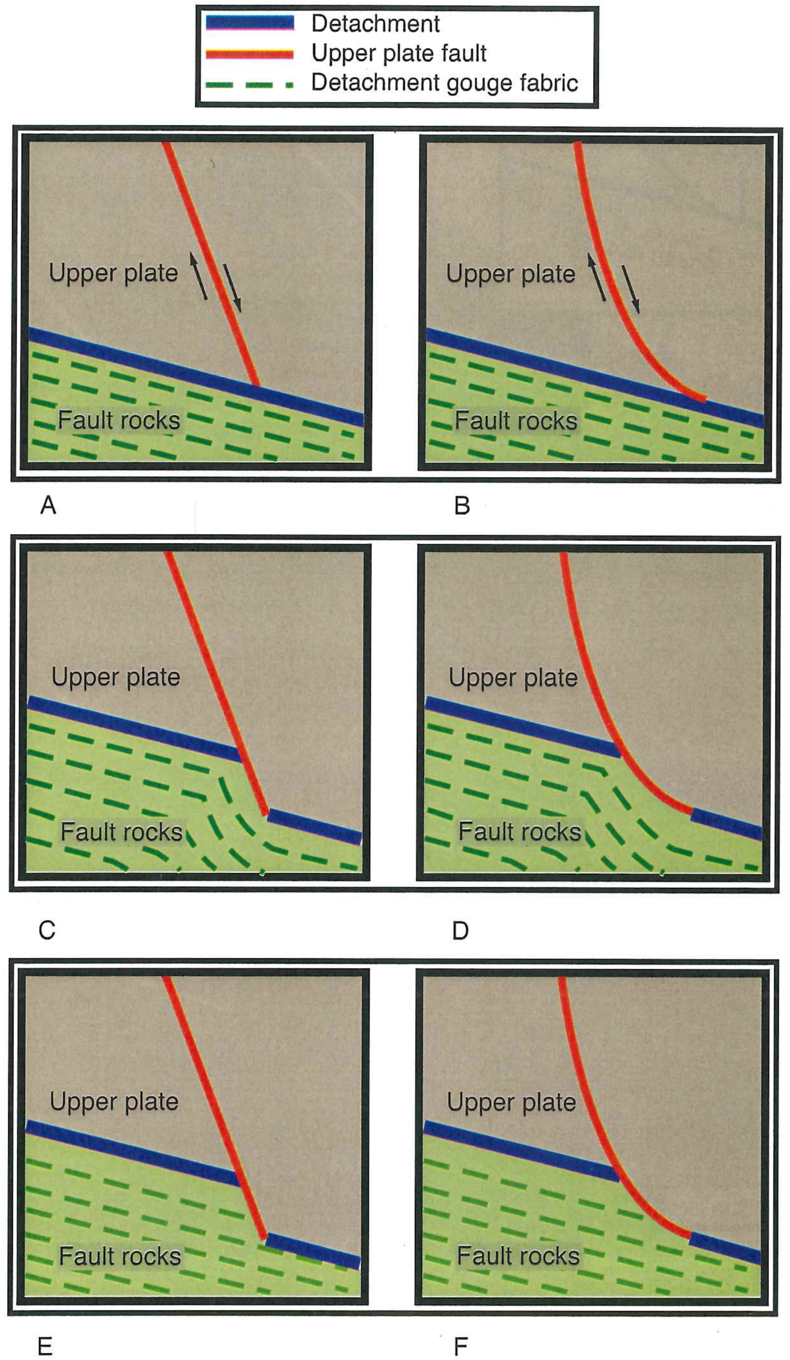


Figure 2. Schematic diagram showing the three groups of faults: (A) Group 1A, (B) Group 1B, (C) Group 2A, (D) Group 2B, (E) Group 3A, (F) Group 3B.

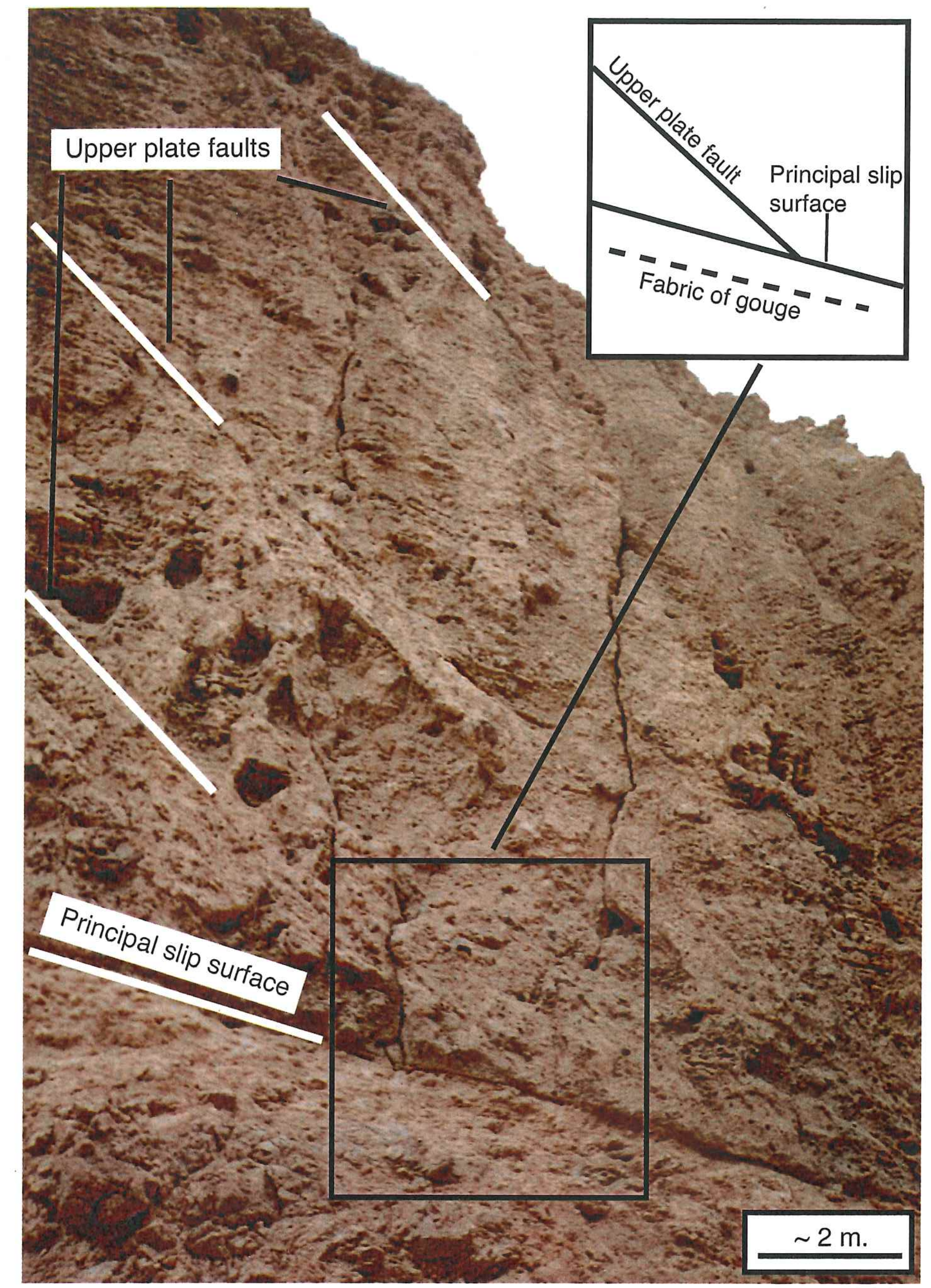


Figure 3. Example of Group 1 upper plate faults at SMP B. Note that the principal slip surface is not offset at the intersection, and the detachment gouge is oriented parallel/sub-parallel to the planar principal slip surface.

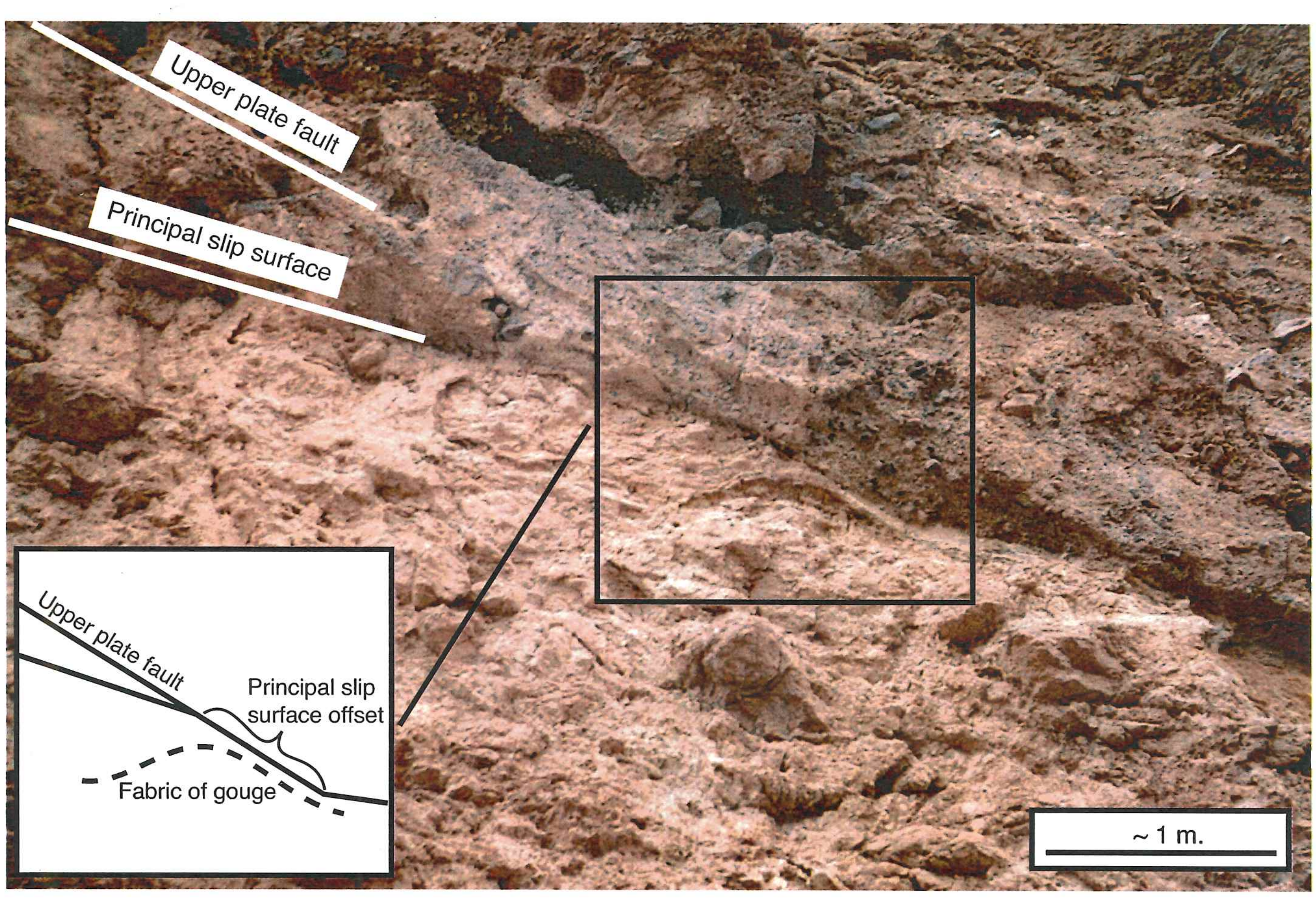


Figure 4. Example of a Group 2 upper plate fault at SMP B. Note that the principal slip surface of the detachment is offset at the intersection, and the fabric of the detachment gouge is oriented parallel/sub-parallel to the upper plate fault.

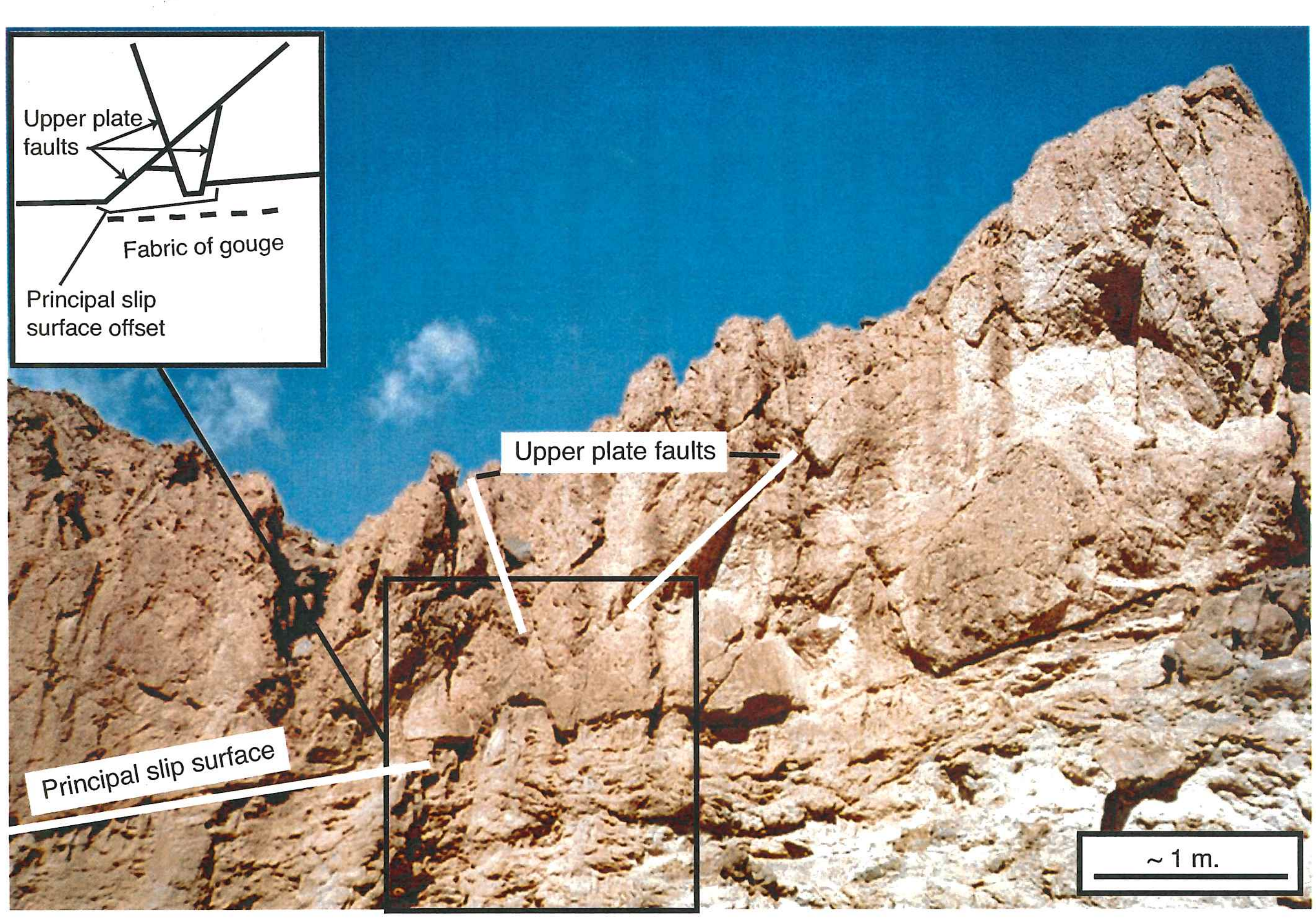


Figure 5. Example of Group 3 (planar) upper plate faults at Size 36. Note that the principal slip surface of the detachment is offset at the intersections, and the detachment gouge is oriented parallel/sub-parallel to the principal slip surface.

subgroups) of faults consistently offset faults in any other group.

3.4. Relative ages of different types of faults in the upper plate

Several workers have documented a lack of clear age relationships between different types of upper plate faults in other detachment fault systems. Lister and Davis (1989) found several types of faults in the Whipple Mountains: listric, high-angle planar and low-angle planar. They suggested that low-angle faults have been rotated from high angles, and therefore likely represent an older generation of faults. However, they noted that it is not possible to use the style of fault to discern between different generations, as it is unlikely that one type of fault operates exclusively of the other; rather extension is probably accommodated simultaneously along listric and planar faults. Jackson and McKenzie (1983) also noted that there is likely simultaneous movement on planar and curved faults. Scott and Lister (1992) reported no correlation between the age and the orientation of the antithetic and synthetic faults in the upper plate faults of the Rawhide detachment fault in Western Arizona, where high-angle faults are truncated by low-angle faults, and vice-versa.

Since there are no clear age relationships between different styles of faults in my field localities in Death Valley, CA, relating fault type to specific stages of temporal development is not a useful tool in analyzing the kinematic evolution of the system. It is likely that different types of faults, including synthetic and antithetic, high- and low-angle faults, accommodated slip contemporaneously. This conclusion is consistent with the findings of workers in different detachment-systems. For this reason, the faults have been assigned to three different groups, independent of orientation, according to the nature of their intersection with the principal slip surface of the detachment fault.

3.5. Models in which upper plate kinematics is not coupled with detachment slip

Current models of detachment-system evolution in which deformation in the upper plate is not kinematically coupled with slip along the detachment fault rely on one of two interpretations: either upper plate deformation predates detachment slip, or upper plate deformation postdates detachment slip. I will outline both lines of reasoning with emphasis on the element of relative timing rather than mechanism of deformation, which will become relevant in a section below. Then, I will demonstrate that these models do not adequately describe the kinematics of the system given the diversity of intersection geometries, which provide evidence that there were alternating or contemporaneous episodes of slip on the upper plate faults and on the detachment.

The least complex relationship to explain is when all of the upper plate faults predate detachment slip; in this case the system is necessarily uncoupled. If all of the upper plate faults postdate detachment slip, it is unclear whether the upper plate failed as a direct result of detachment slip albeit in a later stage after slip on the detachment had ceased (deformation of the upper plate is kinematically coupled but not contemporaneous with slip on the detachment) (Fowler et al., 1995), or whether the upper plate failed later for an independent reason (Anders et al., 2001). If some of the upper plate faults predate detachment slip whereas others postdate detachment slip, three possibilities emerge: (1) both sets may record different episodes of upper plate failure that were both kinematically uncoupled from detachment slip, (2) the faults that predate detachment slip failed in a uncoupled regime while failure along faults that postdate detachment slip was coupled with detachment slip, or (3) an ongoing dynamic interplay between upper plate fault and detachment failure, underscores a coupled relationship in which the system evolves according to a mutual feedback mechanism.

Models in which upper plate deformation predates detachment slip rely on the common observation that upper plate faults end abruptly at the principal slip surface of the detachment fault, and while some upper plate faults do appear to offset the principal slip surface by 1cm-1m, these displacements are not significant enough to require a period of upper plate faulting that postdates detachment slip (Gross and Hillemeyer, 1982). Davis and Lister (1989) interpreted this observation to mean that detachment slip is younger and not kinematically associated with the preexisting upper plate deformation. They suggested that the older upper plate deformation might have been either originally rooted at depth (so not originally upper plate deformation), or associated with an older detachment and subsequently truncated by a younger detachment. This hypothesis is based on observations in the Whipple Mts., but may apply to other detachment-systems.

Alternatively, upper plate faults that appear to be truncated by the principal slip surface of the detachment fault could be interpreted to demonstrate that all deformation in the upper plate postdates detachment slip. One explanation for this interpretation is the idea that late deformation in the upper plate might be unable to penetrate below the structural level of the detachment because of stress differences due to the weakness of the gouge. Or, slip on upper plate faults might have been contemporaneous with slip on the detachment; the detachment served as a synkinematic barrier to fault rupture and caused the upper plate faults to appear to be truncated (Fonseca, 1988; Dorsey and Becker, 1995).

In the case that upper plate deformation postdates detachment slip, the older stage of detachment slip must have had little or no associated upper plate deformation, and the younger upper plate failure must be attributable to either (a) gravitational collapse, or (b) tectonic failure under a stress field that is independent from the state of stress in the detachment. This model seems improbable, as it seems unlikely that a detachment could slip with no associated upper plate deformation since analog models of detachment slip all trigger upper plate deformation (e.g. McClay and Ellis, 1987).

Bruhn and Schultz (1996) investigated the distribution of slip along a master shear zone dipping at 50 degrees and an overlying synthetic and antithetic fault. They found that displacements along the shear zone triggered slip along both subsidiary faults. Conversely, it is unlikely that a stress field that could drive upper plate failure (post-slip along the detachment) would not also cause slip along the (very weak) underlying detachment fault, perhaps even reactivating inactive sections of the detachment.

3.6. Discussion: Alternating slip based on intersection geometries

The model of Davis and Lister, (1989) in which the detachment is younger than the upper plate deformation is explained by the hypothesis of a succession of major detachment faults rather than one long-lived structure. These multiple detachments emanate from the same shear zone during the evolution of the system, but migrate as new splays develop and old splays become inactive. Scott and Lister (1992) also found the multiple-detachment model compelling in the case of the Rawhide detachment, where truncated mylonitic fabrics in the lower plate were interpreted to be incompatible with the long-lived detachment model. This multiple-detachment model suggests that older, abandoned detachments, manifested as wide gouge and breccia zones, would be preserved in the upper or lower plate. Since there are no such structures, a reasonable conclusion is that while the principal slip surface may have migrated within the zone of the detachment during the life of the detachment, there were not multiple detachments.

It is true that the mere appearance of upper plate faults truncated by the principal slip surface of the detachment can not be taken at face value to mean that the upper plate faults predate detachment slip, since continuous evolution of the detachment could modify the intersection geometry (Lister and Davis, 1989). However, if the upper plate structures were all truncated by a younger detachment, tectonic modification of the upper plate structures would be expected to produce a uniformly planar intersection geometry. While some intersections are characterized by upper plate faults that are planar and do appear to be truncated by the principal slip surface, other upper plate faults are listric at their intersections with the principal slip surface. There is no uniformity in intersection geometries nor is there a systematic change in the type of intersection downdip along the detachment (see discussion of downdip trends in section 6). Faults in groups II, III are characterized by offset of the principal slip surface along listric and planar upper plate structures; this relationship indicates that these upper plate structures have been active (possibly initiated, possibly reactivated) post-slip along the detachment. Thus, on the basis of the variety of intersection geometries that can be observed it is apparent that slip on upper plate faults postdates at least some detachment slip. This does not preclude the possibility that there may have been preexisting faults in the upper plate that do predate the current principal slip surface.

3.7. Discussion: Alternating slip based on reactivation of gouge

Group II faults offset the principal slip surface and the fabric of the detachment gouge adjacent to the upper plate is oriented parallel/sub-parallel to the upper plate structure (Fig. 4). The remobilization of detachment gouge indicates slip along the detachment (with the possible exception of remobilized gouge derived from the upper plate (the brown clay gouge?)). The association of gouge fabric with upper plate structures indicates that the detachment gouge was remobilized either during or following slip on these upper plate structures. The remobilization of detachment gouge during or after upper plate faulting demonstrates that either the detachment slipped concurrently with slip along upper plate faults, or the detachment slipped both prior to and following upper plate fault slip.

3.8. Observations: Suspended upper plate material in gouge

In several localities (SMP A, Size 36) there are well-preserved fragments of upper plate material within the detachment gouge. These fragments range in size from ~1cm to ~30cm, and while in some localities the fragments are deformed (Fig. 6), in other localities the fragments appear to be undeformed. In some cases the fragments of upper

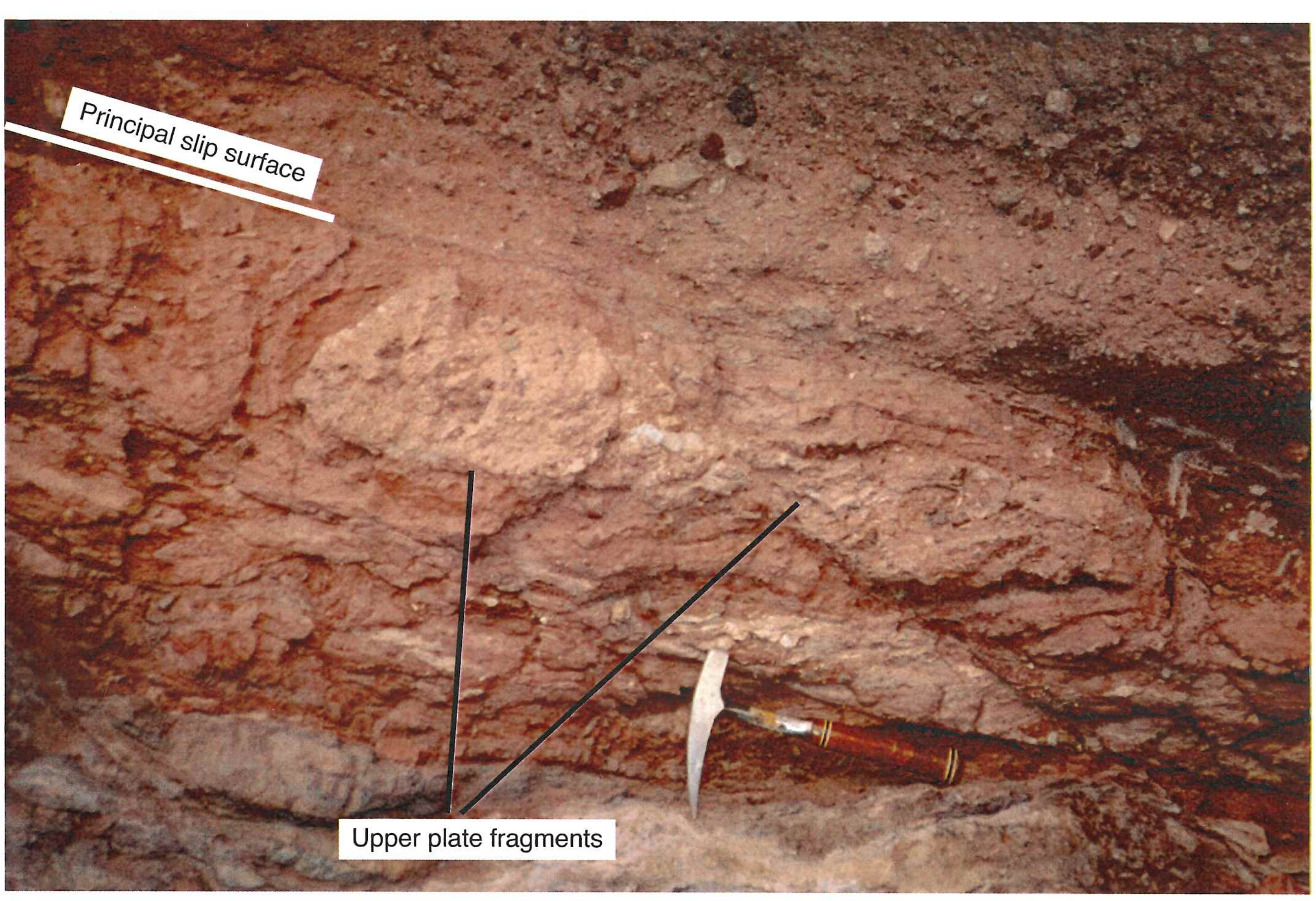


Figure 6. Upper plate fragments surrounded by flow-banded gouge below a planar principal slip surface, without upper plate faults nearby (at Size 36).

plate material are directly below, or adjacent to upper plate faults; in other cases the fragments of upper plate material suspended in the gouge are not near upper plate faults.

3.9. Discussion: Alternating slip based on suspended upper plate material in gouge

The process by which upper plate material is incorporated into the detachment gouge inherently involves the transfer of upper plate material below the principal slip surface of the detachment. The mechanisms that could accomplish this transfer of material are: A) faulting, either physically dropping material down in the hangingwall (normal fault) or in the footwall (reverse fault), or creating an avenue for material to travel down, B) a fracture, acting as an avenue for upper plate material to drop down, or C) soft sediment deformation, causing upper plate material to sink below the principal slip surface. Although each of these mechanisms may occur, faulting is probably the dominant process as there is clear evidence that this process occurred in several localities (Fig. 7), and the upper plate is riddled with normal faults, many of which offset the principal slip surface.

Once upper plate material has dropped below principal slip surface, the detachment fault must accommodate some slip in order to disengage this upper plate material and transport it downdip, suspended in the gouge. In localities where an upper plate fault is responsible for the movement of upper plate material, this process requires slip to alternate between upper plate faults and the detachment fault (Fig. 8). Introduction of upper plate material into the detachment gouge by alternating slip on upper plate faults

Figure 7. Upper plate material is dropped below the principal slip plane of the detachment fault along many planar normal faults (at Size 36).

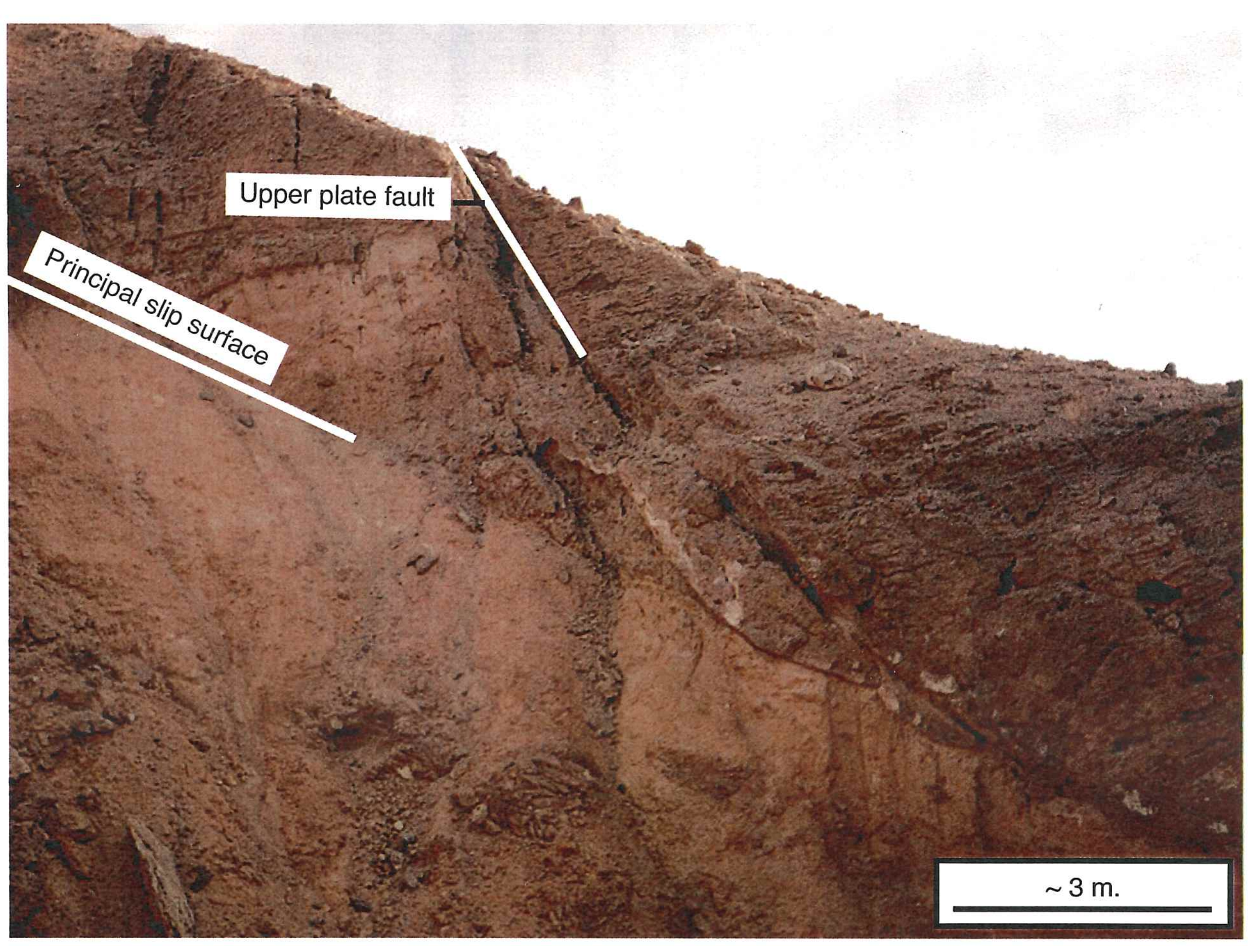


Figure 8. Upper plate fragments dragged down along upper plate faults, surrounded by flow-banded gouge, with an irregular principal slip surface (at SMP A).

and the detachment provides strong evidence that there is temporal alternation between slip on upper plate faults and slip along the detachment fault.

Evidence of the incorporation of upper plate material into the detachment gouge also provides insight into the geochemical evolution of the system. In the process of dragging coherent fragments of upper plate material into the gouge, some of the upper plate material is likely broken down by cataclasis, and assimilated into the gouge. The evidence of seemingly undeformed upper plate material in the gouge can therefore be used to predict that at least some of the detachment gouge will bear a geochemical signature of upper plate material. A detailed geochemical study of the detachment gouge would permit reasonable estimates of the volume of upper plate material that has been incorporated into the detachment. However, in order for such a measurement to be accurate it is important to estimate the amount of slip along the detachment to determine the distance that upper plate-derived material could have been transported. Without an effort to determine the volume of upper plate material that has been removed form the upper plate, estimates of extension the upper plate will not be reliable.

4. Kinematic development of the detachment

It has been demonstrated that upper plate faulting causes upper plate material to be incorporated into the detachment gouge. This transfer of upper plate material complicates extension estimates, and alters the geochemistry of the gouge. The above discussion confirms a first-order coupling between upper plate faults and slip on the principal slip surface of the detachment fault. Given this basic level of coupling, it is appropriate to consider the extent to which deformation in the upper plate is kinematically coupled with, and dependent upon the detachment below. The movement of upper plate material below the principal slip surface of the detachment creates an irregularity along an otherwise mostly planar principal slip surface. This section addresses the relationship of such irregularities on the principal slip surface to the spatial distribution of the upper plate faults.

4.1. Observations: Irregularities along the detachment

Many upper plate faults intersect the principal slip surface at irregularities along the principal slip surface (defined as any deviation from a planar geometry at a mesoscopic scale). These irregularities are in most cases marked by detachment gouge above the principal slip surface. Although some upper plate faults intersect the principal slip surface without an irregularity (where the principal slip surface appears to be planar), there are no irregularities along the principal slip surface which are clearly unassociated with any upper plate fault. In several cases where there is an irregularity along the principal slip surface for which there is no specifically associated upper plate fault, there is extensive faulting in the adjacent upper plate (Fig. 9).

4.2. How to generate an irregularity

In order to generate an irregularity along the principal slip surface, material must either be (1) moved down from above the principal slip surface to below this interface or (2) moved up from below the principal slip surface into the upper plate. The transfer of upper plate material below into the detachment gouge was discussed in section 3.9. The movement of material (gouge) from below the principal slip surface into the upper plate requires A) a fracture or fault in the upper plate (presumably this is more effective where multiple faults intersect the principal slip surface), or B) the injection of gouge up into the upper plate, with resulting compaction of the upper plate. Salt provides a compelling analog for the gouge in this process, as similar structures are observed in salt tectonics when buoyant salt intrudes overlying structures and forms salt diapirs (Vendeville and Jackson, 1992). It is also possible that an irregularity can be generated by slip on the principal slip surface alone, if the fabric of the gouge developed in such a way that it could act as a barrier to further slip.

According to Lister and Davis (1989), evolution of the principal slip surface of the detachment involves two processes: "incisement" wherein the lower plate material is incorporated above the principal slip surface and "excisement" during which upper plate material is incorporated below the principal slip surface (Fig. 10). The process of "excisement" describes the incorporation of upper plate material into the detachment

Figure 9. Highly irregular principal slip surface is characterized by remobilized gouge at a locality with extensive faulting in the adjacent upper plate (at Nemo Canyon).

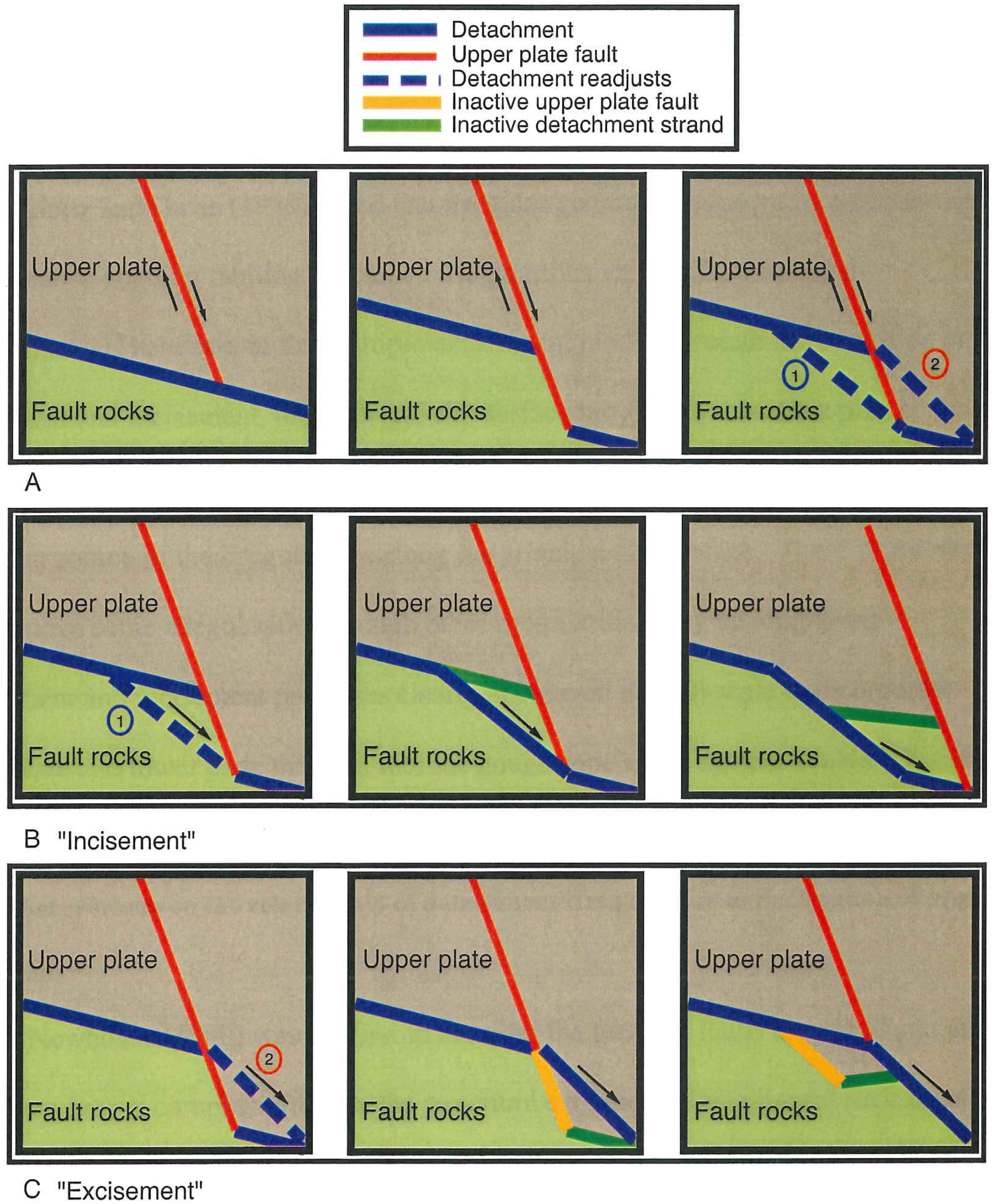


Figure 10. Illustration of incisement/excisement processes. A) An upper plate fault causes the detachment to reestablish a principal slip surface either (1) by cutting into the lower plate or (2) by cutting into the upper plate. B) Incisement occurs when the detachment readjusts via a new principal slip surface in the lower plate. Detachment gouge is stranded above the new principal slip surface and transported downdip in the upper plate. B) Excisement occurs when the detachment readjusts via a new principal slip surface in the upper plate. Upper plate material is incorporated into the gouge below the new principal slip surface.

gouge via the migration of principal slip surfaces. This idea is similar to their model of upper plate fault truncation by a young detachment, yet it is considered important on the scale of individual upper plate faults, not the scale of the whole detachment.

Lister and Davis (1989) noted that irregular geometries along the principal slip surface cause ongoing faulting to remove irregularities via "excisement" and "incisement". Therefore, in the multiple-detachment model, through the processes of excisement and incisement, the principal slip surface progresses towards a planar geometry. The cyclical nature of this model implies that upper plate faulting is the dominant source of the irregularities along the principal slip surface. These processes may remove some irregularities, though other irregularities may be long-lived. Excisement and incisement processes clearly operate on a small scale to incorporate upper plate and lower plate material into the gouge zone as the system evolves (Fig. 8).

4.3. Other workers on the relationship of detachment irregularities to the location of upper plate faults

Newhouse (1940) was the first to consider the fact that faults are not planar and as such, may have a complex effect on the structural evolution of an adjacent rock mass. He specifically conjectured that an irregular master fault would cause complicated geometries of deformation in the rock above. Bruhn and Schultz (1996) offered the following mechanical explanation for this development: bends, steps and jogs along the master fault cause local stress concentrations that can cause the nucleation of upper plate faults.

Ackermann and Schlische (1997) similarly noted that new faults probably nucleate at "random flaws within the rock volume." The implications of this suggestion are two-fold: that the location of faults may be largely determined by flaws (irregularities), and that the location of these irregularities may be random. Ackermann and Schlische (1997) also suggested that the only constraint on the location of the upper plate faults is that the younger faults do not nucleate in the crack shields of larger faults. Withjack et al., (1995) found that antithetic normal faults break above concave-upward bends along the principal slip surface and synthetic normal faults break above convex-upward bends of the principal slip surface. This correlation arises from the observation that upper plate faults seem to be concentrated where the principal slip surface is irregular, and more broadly that deformation patterns in the upper plate of a master (detachment) fault depend on the shape of the detachment fault itself. Withjack et al., (1995) also observed that when upper plate faults move past fault bends, they become inactive, and new faults nucleate at the fault bends to accommodate the strain. The nucleation of upper plate faults at irregularities along the principal slip surface requires that the faults break at the intersection with the principal slip surface and propagate upward, which provides some insight into the kinematic development of upper plate faults (Maldonado, 1990).

Strong coupling between the character of the detachment fault and patterns of upper plate fault geometry has important implications for the development of supradetachment basins. Patterns of upper plate deformation play a key role in the evolution of supradetachment basins (Friedmann and Burbank, 1995; Dorsey and Becker, 1995; Fowler et al., 1995.; Miller and John, 1999). Dorsey and Becker (1995) suggested that upper plate faulting exerts a primary control on the development of supradetachment basins. Miller and John (1999) took this idea further and proposed that the shape of the Chemhuevi-Sacramento detachment controlled the location and fill of supradetachment basins during extension. A better understanding of the extent to which the shape of detachment faults controls the location of upper plate structures is essential to studies of the nucleation and evolution of supradetachment basins.

4.4. Can this relationship be modeled?

The idea that the irregular character of the underlying principal slip surface of the detachment may exert an important control on the location and orientation of upper plate faults is inherently lost if the geometry of the detachment is approximated as planar. This has important implications for analog models that attempt to model detachment-systems using a planar principal slip surface. Specifically, the character of the principal slip surface fault may influence the location (and therefore spacing) of upper plate faults, and the likelihood of developing synthetic or antithetic faults. Since irregularities are randomly distributed, the location and facing direction of upper plate faults may not be predictable. Therefore, while an analog model of upper plate deformation above an irregular principal slip surface may be useful in terms of observing the kinematics of this interaction, such a model could not be used to predict the location, spacing, or facing direction of upper plate faults. Other aspects of the distribution and character of upper plate faults that are not controlled by random irregularities along the principal slip surface may be more predictable based on analog modeling.

4.5. Which came first: the "chicken" or the "egg"

A fundamental problem is the "chicken or egg" nature of the relationship between irregularities on the principal slip surface and associated upper plate faults. It can be demonstrated that there is a clear relationship between irregularities on the principal slip surface and upper plate faults; however it is unclear which came first. Do upper plate faults develop at irregularities along the principal slip surface or do upper plate faults create irregularities by allowing detachment gouge to breach the principal slip surface and intrude into the upper plate? It may be that there is not a simple answer to this question, and rather that there is a dynamic interplay between the development of upper plate faults and the generation of irregularities along the principal slip surface. The main point is that the irregularities on the principal slip surface are related to the upper plate faults, and this relationship demonstrates a strong kinematic coupling between the character of the principal slip surface of the detachment fault and the distribution of faults in the overlying upper plate.

5. Geometric Analysis

The above discussion has established on the basis of intersection geometries that upper plate deformation above the detachment faults in Death Valley was kinematically coupled with detachment slip. Given the strong evidence for first-order coupling, it is appropriate to proceed with an analysis of fault population systematics in an effort to learn more about the history of slip along the detachment. In order to analyze spatial variation in upper plate fault geometry with increasing distance downdip along the detachment fault, I designed a geometric analysis to project the upper plate faults onto an appropriate cross-section line for each of several localities. Trends in the upper plate fault population with distance downdip along the detachment were analyzed for the 4 localities for which spatial relationships between upper plate faults were measured in the field: (Natural Bridge Canyon, South of Natural Bridge, Size 36, Nemo Canyon) (Figs. 11-14). For each locality, the chosen cross-section line is parallel to the dipline of the detachment and within the plane of the detachment. Using fault orientation data measured in the field, I mathematically projected the upper plate faults onto a cross-section line for each locality by determining a point (Pi) along each upper plate fault where the fault intersects the cross-section line (Fig. 15).

5.1. Discussion of error in my analysis

My method of geometric analysis (Appendix A) is valuable in evaluating the trends in a population of upper plate faults downdip along the detachment, as the method reveals trends that are not readily apparent in other projections of the data. Figure 16

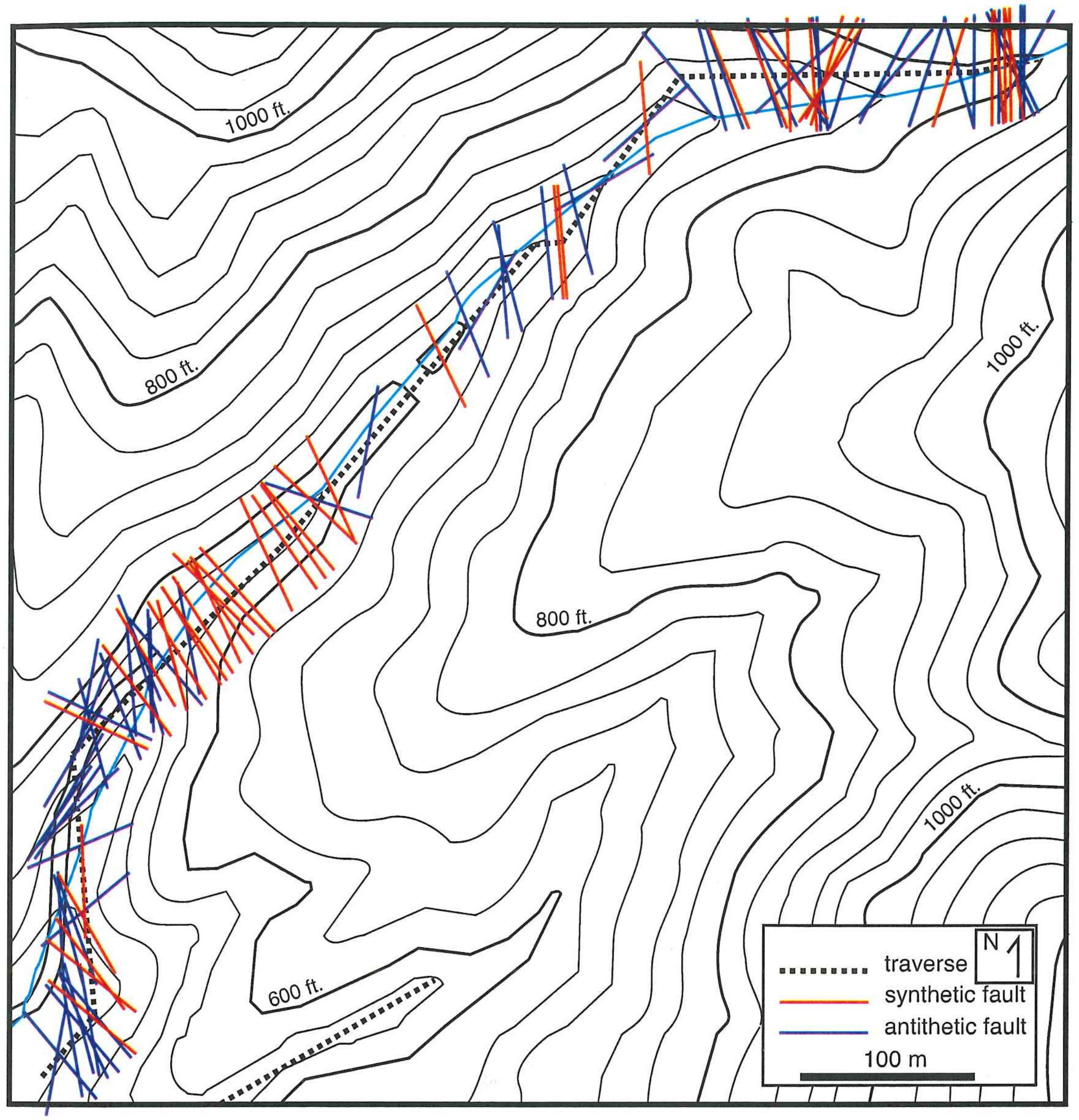


Figure 11. Topographic map of Natural Bridge shows the traverse and the locations where the faults were measured along the traverse. Strikes of faults are represented by line segments of arbitrary length; facing directions are differentiated by color. See Figure 1 for map location.

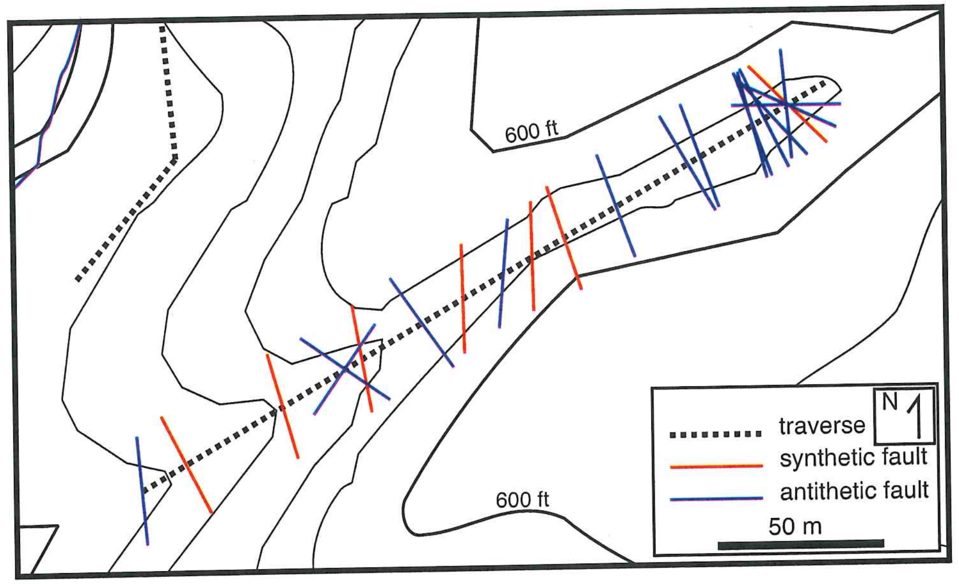


Figure 12.

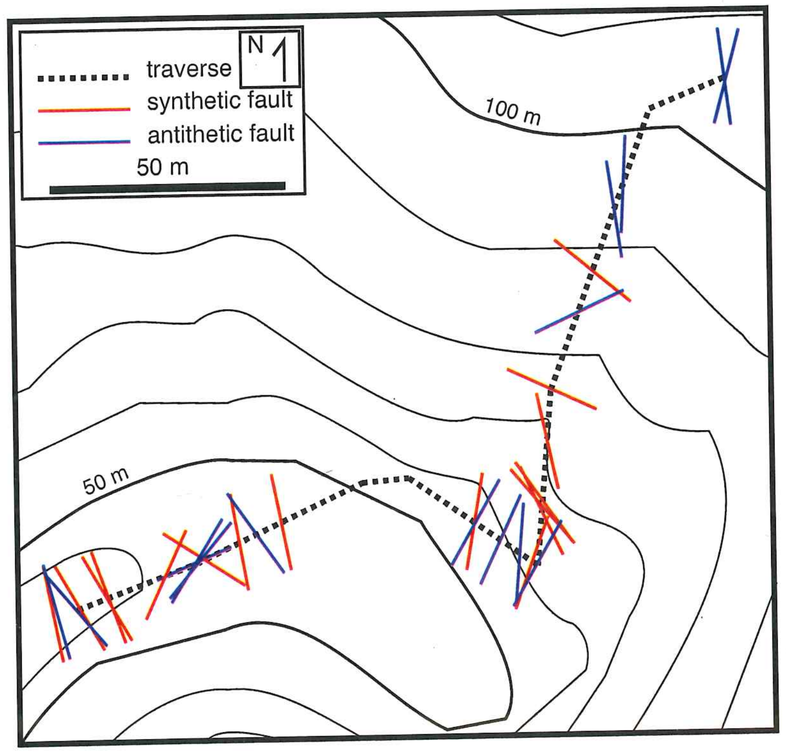


Figure 13.

Figures 12. and 13. Topographic maps of South of Natural Bridge (Fig. 12) and Size 36 (Fig. 13) show the traverses and the locations where the faults were measured along the traverses. Strikes of faults are represented by line segments of arbitrary length; facing directions are differentiated by color. See Figure 1 for map locations.

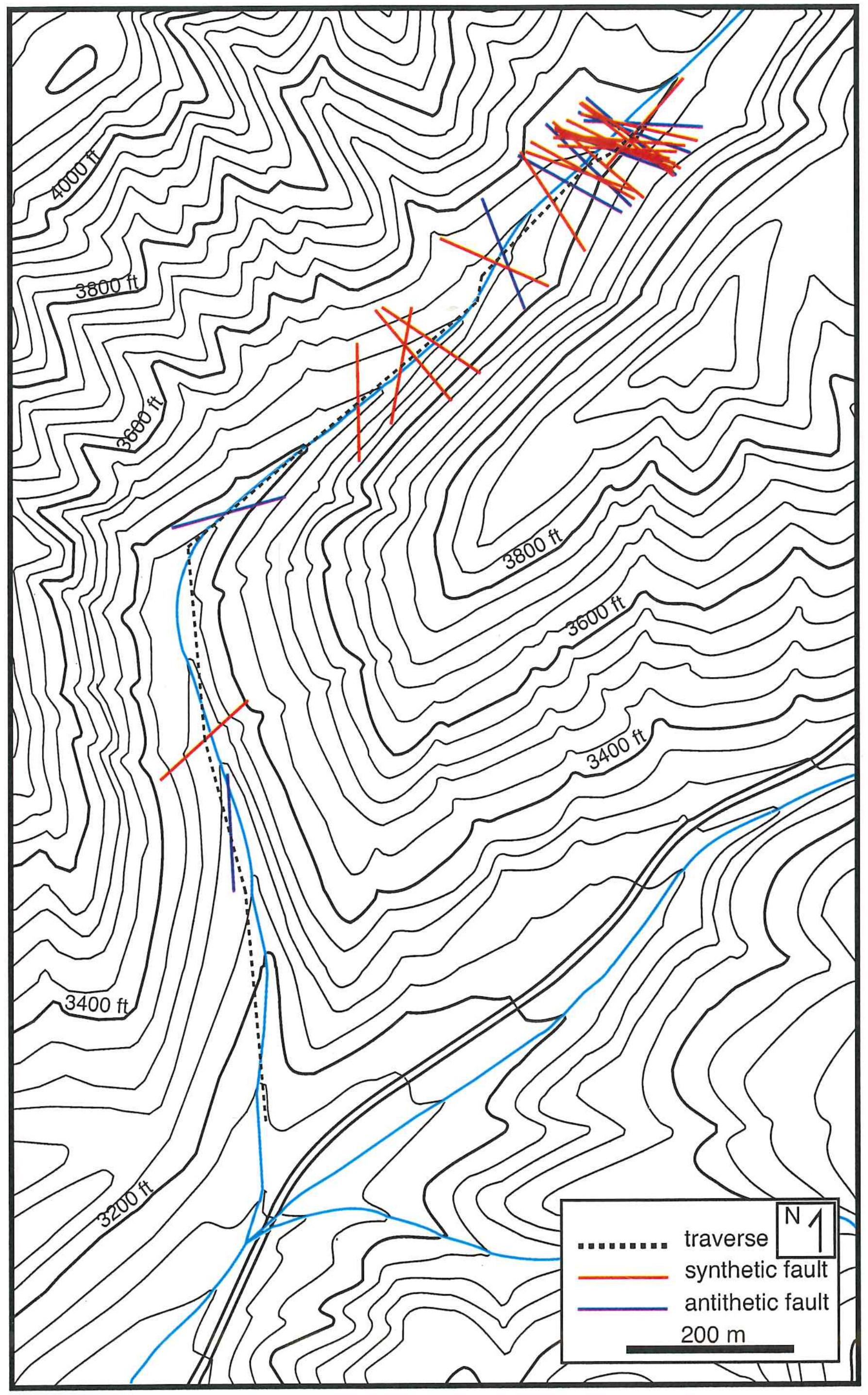


Figure 14. Topographic map of Nemo Canyon shows the traverse and the locations where the faults were measured along the traverse. Strikes of faults are represented by line segments of arbitrary length; facing directions are differentiated by color. See Figure 1 for map location.

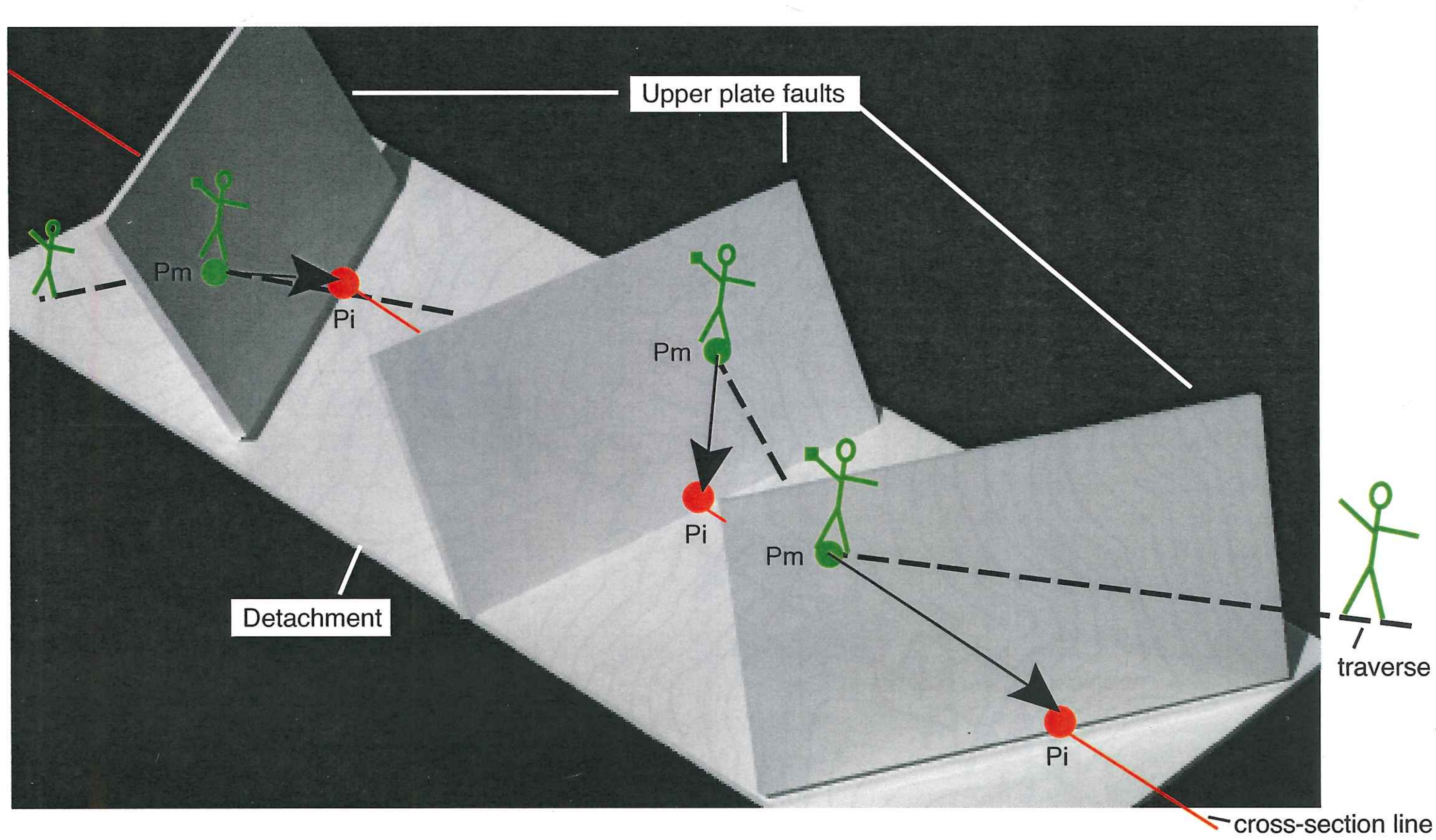


Figure 15. Three-dimensional diagrammatic representation of the geometry between upper plate faults and the detachment fault illustrating the geometrical projection technique. Pm (point of measurement) represents the points along the traverse where each upper plate fault intersects the traverse; at these locations the orientations of the upper plate faults were measured. The cross-section line is oriented parallel to a dipline along the detachment and located in an average position with regard to the location of the Pm points. Pi (point of intersection) represents the points where each upper plate fault intersects the cross-section line.

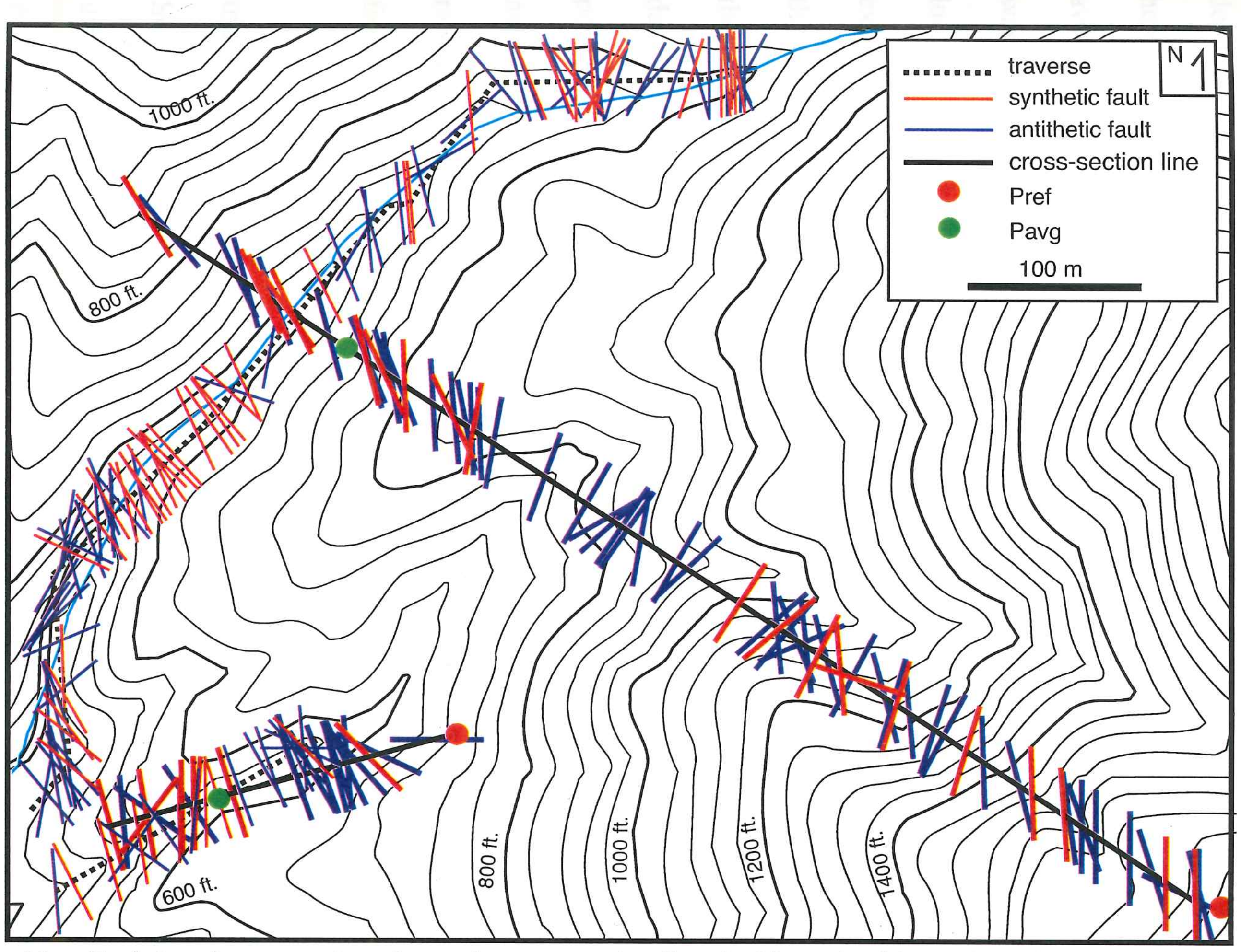


Figure 16. Fault locations as projected onto the cross-section lines for Natural Bridge and South of Natural Bridge, juxtaposed against upper plate fault localities as measured along traverses for each locality. For the Natural Bridge traverse, 1000 meters of the cross-section line are plotted, corresponding to the distance from 500 meters from the origin to 1500 meters from the origin (see trend plot). For the South of Natural Bridge traverse, ~300 meters of the cross-section line are plotted, corresponding to the distance from 10 meters from the origin to 310 meters from the origin (see trend plot).

illustrates the spatial relationship of the field traverses at Natural Bridge and South of Natural Bridge to the respective cross-section lines for each locality, which are oriented downdip along the detachment and lie within the plane of the detachment. It is important here to restate that the orientation of the cross-section lines were determined using an average of the detachment orientation measurements that were taken at the top of the wash, where the detachment daylights. It is possible that these measurements reflect local variation in the detachment orientation, and as such, it may be erroneous to extrapolate this detachment orientation over a large region, as it was necessary to do in this analysis in which the detachment is assumed to be planar. In subsequent sections of this paper I explore the relationship of the geometry of the upper plate faults to the detachment, challenging the assumption that the detachment is planar and considering the possibility of a segmented or a curved detachment. It will become clear that given the assumption of a planar detachment, the major conclusions that can be drawn from the relationship of the upper plate fault geometries to the detachment are largely independent from the orientation of the detachment.

The complex history of individual faults and fault arrays may be grossly underestimated when these structures are approximated as planar surfaces. Cowie and Scholz (1992) cautioned against this oversimplification, and remarked that faults are not discrete planes of shear but zones of brittle deformation that may be relicts from fault development. Peacock and Sanderson (1997) also documented that normal faults are not simple planar surfaces, but instead are typically highly segmented, with "relay ramps" connecting segments which overstep in map view and have the same dip direction and "antithetic transfer zones" defining the area between two normal faults that overstep in map view and have opposite dip directions. Also fault thickness may vary: Axen et al. (1999) reported a significant variation in the width and complexity of upper plate fault systems in the Sierra El Mayor, Baja California.

In the geometric analysis, in order to determine the points where the upper plate faults intersect the cross-section line along the detachment, it was necessary to assume that the faults have a constant strike and dip over a "projection distance", the distance between the points where I measured the fault (Pm) and the calculated points where individual upper plate faults intersect the cross-section line (Pi). Since each fault was projected over a different distance, the amount of uncertainty that is introduced by the geometrical projection is unique for each fault. To quantify the amount of error introduced by this assumption, I calculated the projection distance for each fault. The greater the projection distance, the more uncertainty was introduced into the calculation of the location of the point of intersection for that particular fault (Fig. 17).

The distance between Pm and Pi for an individual fault depends on many factors, including (1) the strike and dip of the fault, (2) the orientation of the traverse relative to the orientation of the cross-section line, (3) the distance from Pm to Pavg (the average coordinates for the Pm points for all faults along a traverse, through which the line of cross-section was projected), (4) the distance downdip along the upper plate fault from Pm to the detachment, and (5) the length of the traverse. The projection distances range from 18-1,369m for the upper plate faults at Natural Bridge, given a cross-section line length of 2,306m. For South of Natural Bridge, the projection distances range from 16-

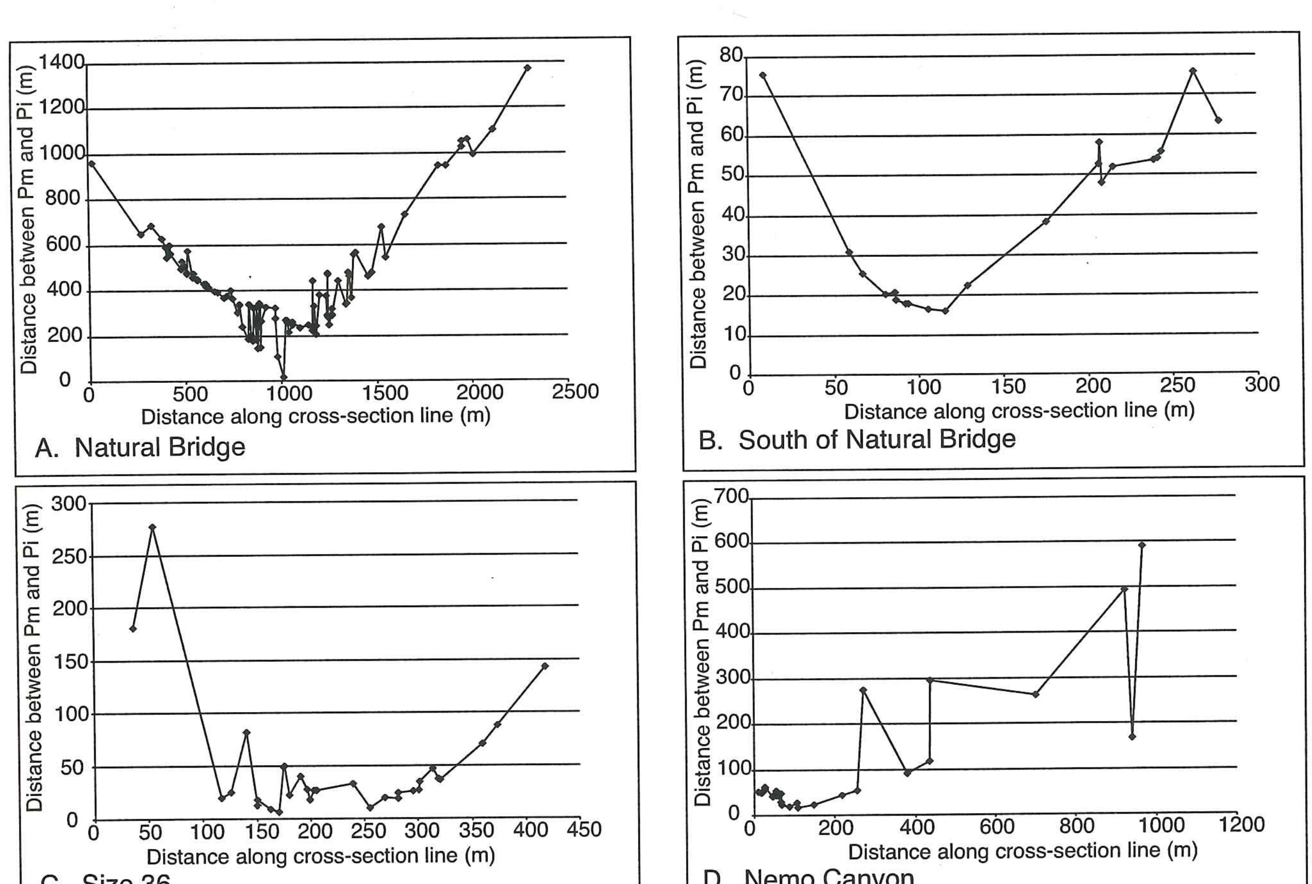


Figure 17. Plot of distance along cross-section line vs. distance between Pm and Pi for each fault at each locality. Plot illustrates the variation within the fault populations in the amount of error introduced by the geometrical projection of the faults onto the cross-section lines. The distance between Pm and Pi represents the distance over which the assumption of constant strike and dip was necessary for the projection of each individual fault onto the cross-section line, and functions as a quantification of potential error. (A) Natural Bridge (B) South of Natural Bridge (C) Size 36 (D) Nemo Canyon.

76m, with a cross-section length of 268m. For Size 36 the projection distances range from 6-277m over a cross-section length of 382m, for Nemo Canyon the projection distances range from 16-296m over a length of 429m. There is a clear correlation between the length of the traverse and the range of values for projection distance.

6. Fault population systematics

Field observations about upper plate faults, including their orientation (strike, dip, listricity, facing direction), character (sense of offset, amount of offset), and distribution (spacing, density) are discussed in this section. These patterns are compared to first-order patterns of upper plate fault geometries that have been produced in experimental work including analog and theoretical models. Fault population data are usually displayed using stereonet plots (Fig. 18), which are useful for analyzing the distribution of values for strike and dip. My geometrical analysis makes it possible to put this information into a spatial context, illustrating trends in these values and the distribution of these values with increasing distance downdip along the detachment. For each of my localities, stereonet plots will be considered. For those localities where it was possible to apply my geometrical analysis, plots of trends in the strike and dip of synthetic and antithetic faults with increasing distance downdip along the detachment will supplement the data (Fig. 19-22).

6.1. Upper plate fault orientation (strike, dip, listricity, facing direction): Observations and discussion

Facing direction: Conventions

The facing direction of a fault is typically described using the terms 'synthetic' or 'antithetic', relative to some reference frame (Stewart and Argent, 2000). In the simple case where the strike of an upper plate fault is parallel to the strike of the underlying detachment fault, it is sufficient to define a synthetic fault as one which dips in the same

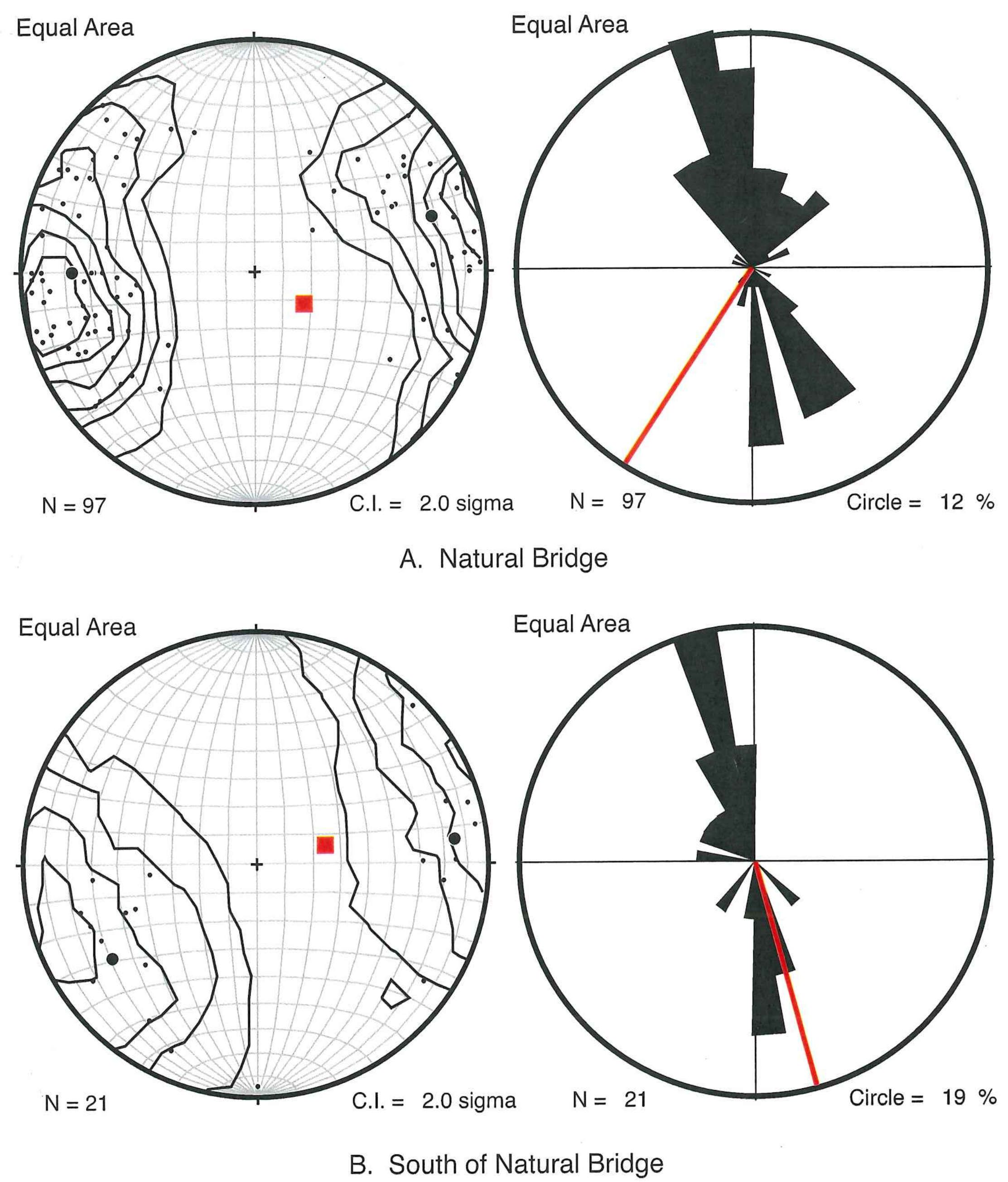
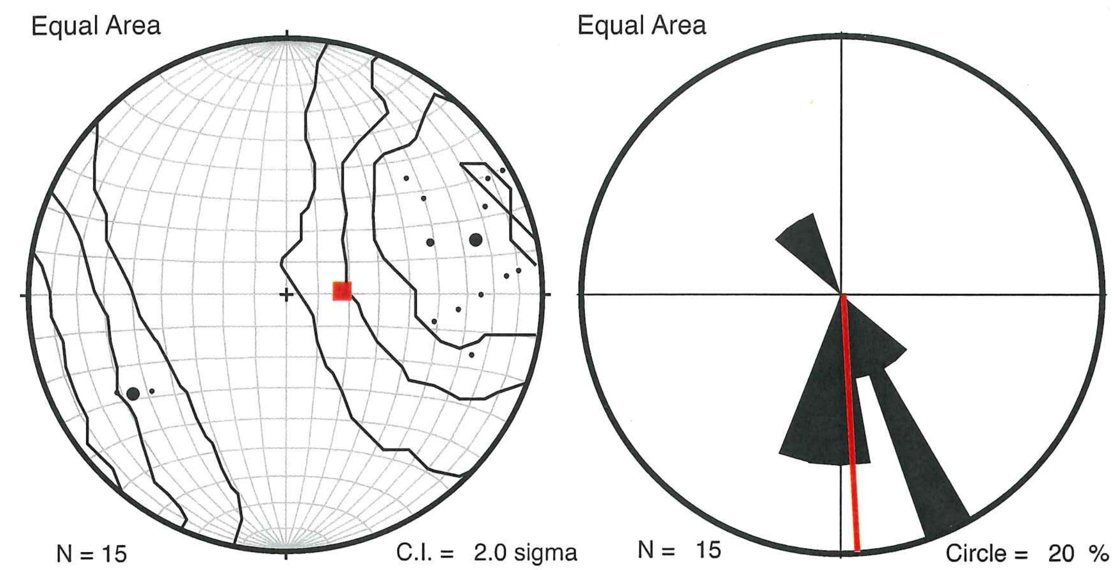
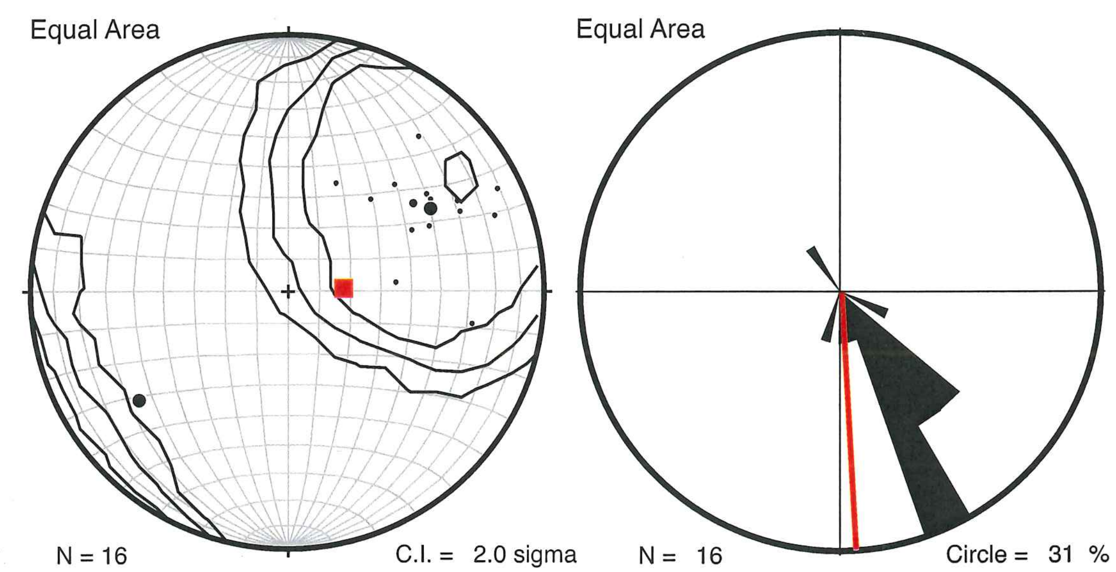


Figure 18. Stereonet plots showing (i) Kamb contour of poles to planes for all upper plate faults at each locality. Larger circles indicate average values for the synthetic and the antithetic faults; red square marks the orientation of the pole to the detachment. (ii) Rose diagrams of strike showing the distribution of strikes of fault planes for each locality; the strike of the detachment is shown in red.



C. SMP A



D. SMP B

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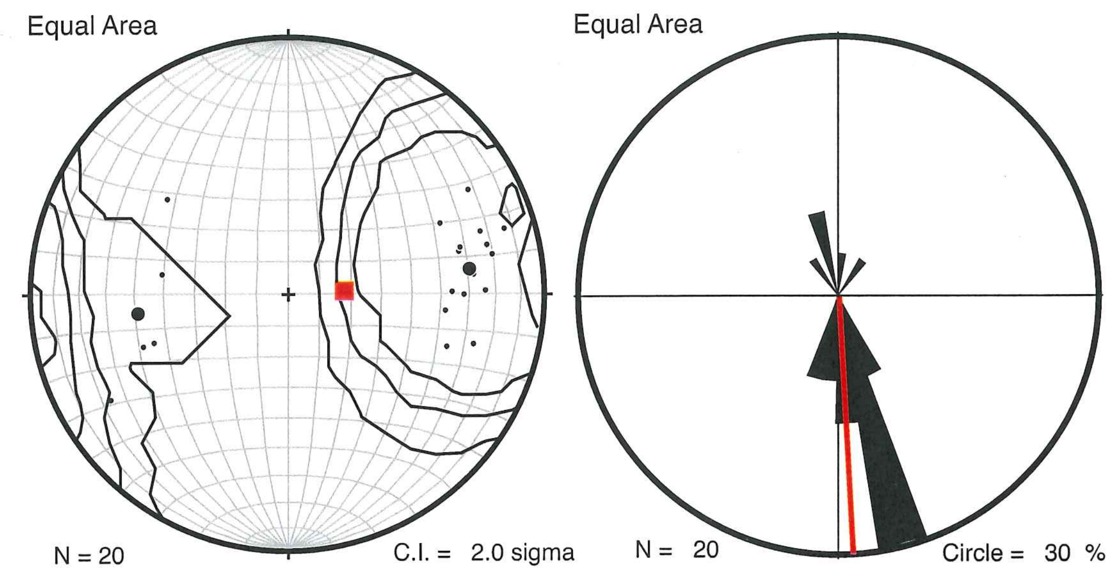
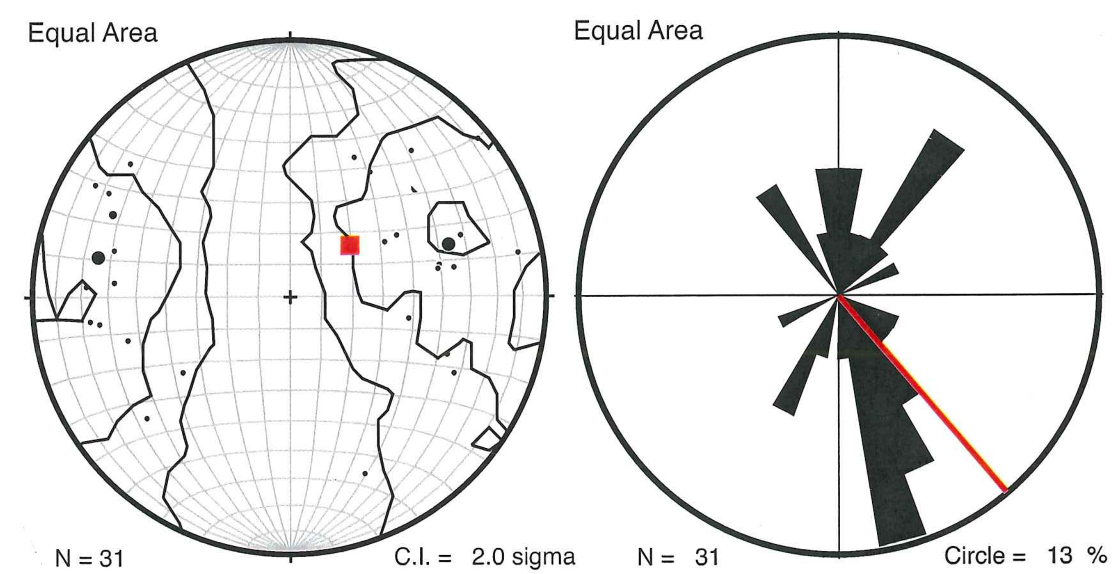
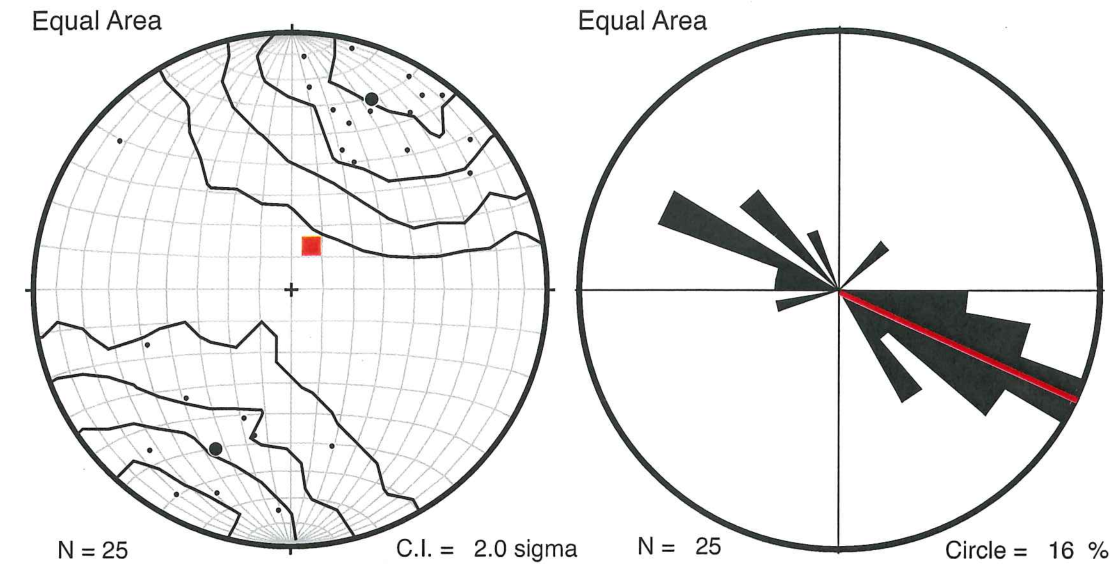


E. SMP C

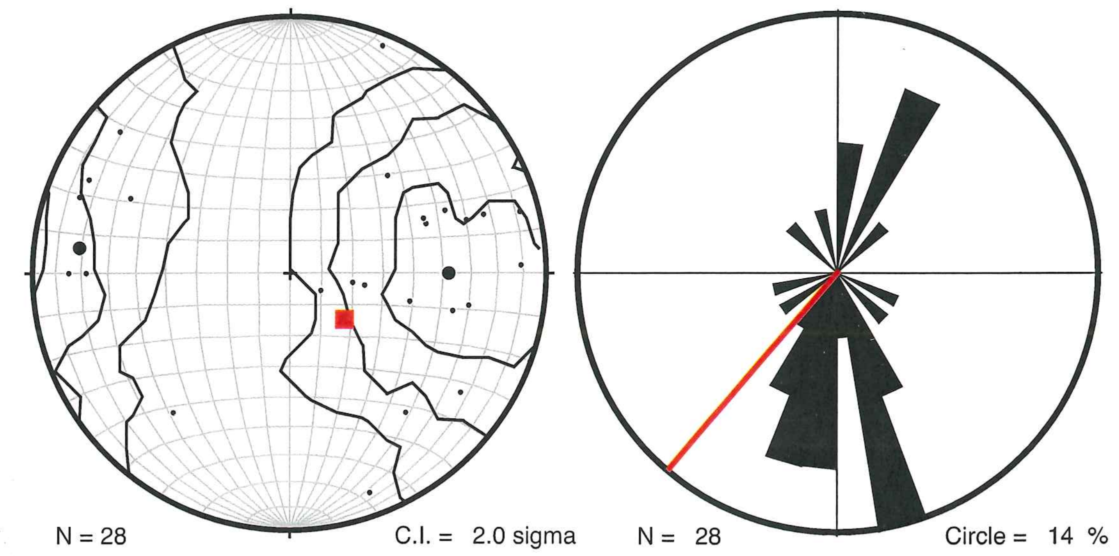


F. Size 36

Figure 18. con't.



G. Nemo Canyon



H. South of Emigrant Canyon

Figure 18. con't.

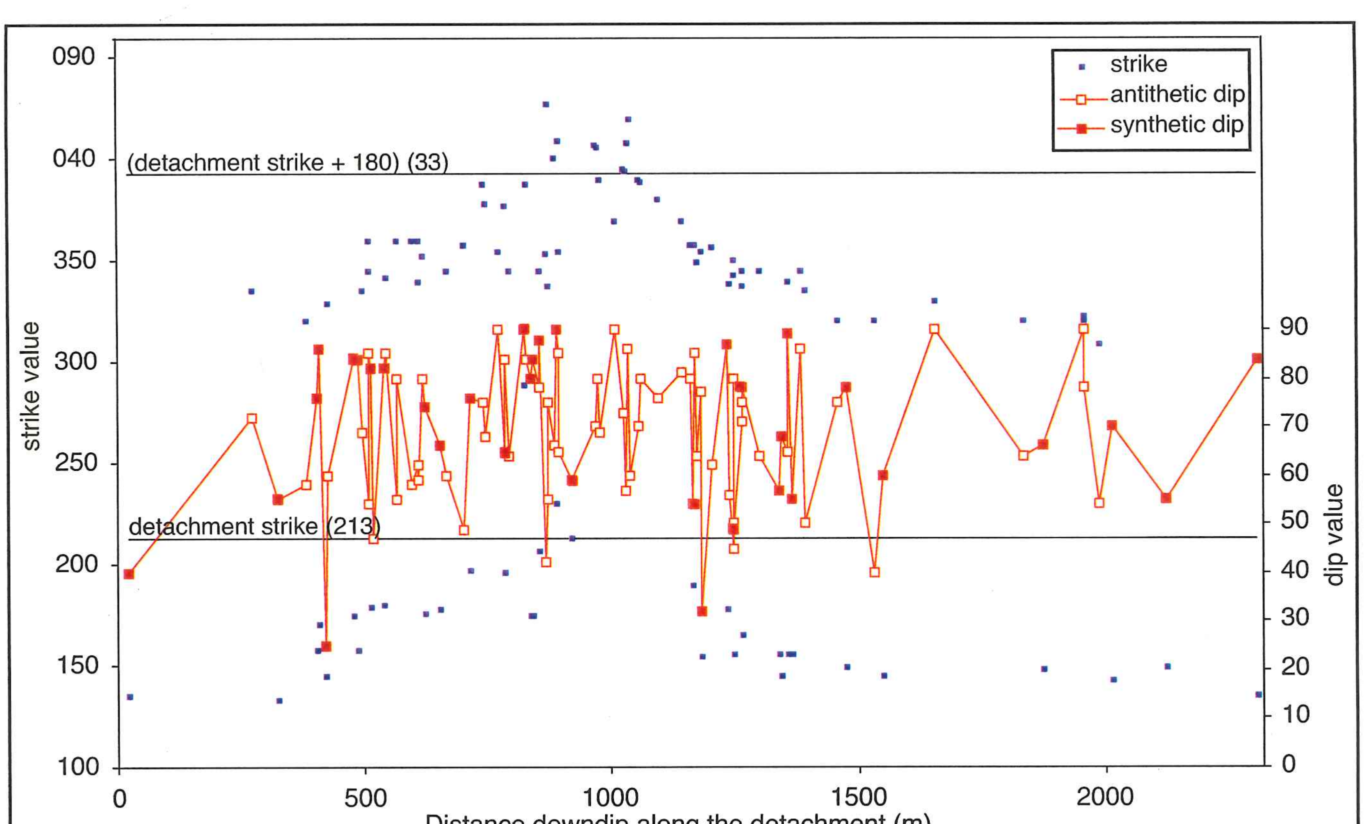


Figure 19. Trends in the strike and dip of antithetic and synthetic upper plate faults with increasing distance downdip along the detachment at Natural Bridge. Synthetic faults have strikes ranging from 133 to 288 degrees; antithetic faults have strikes ranging from 309-67 degrees. The strike values along the y-axis are organized such that the antithetic and the synthetic faults plot as two separate groups. Two reference lines show the strike of the detachment and the strike of an antithetic fault that is oriented parallel to the detachment (detachment strike + 180). The dip values for the faults are plotted directly above or below the strike value for each individual fault, depending on whether the fault is synthetic or antithetic. A line to illustrate the variation in the dip values downdip along the detachment connects the dip values.

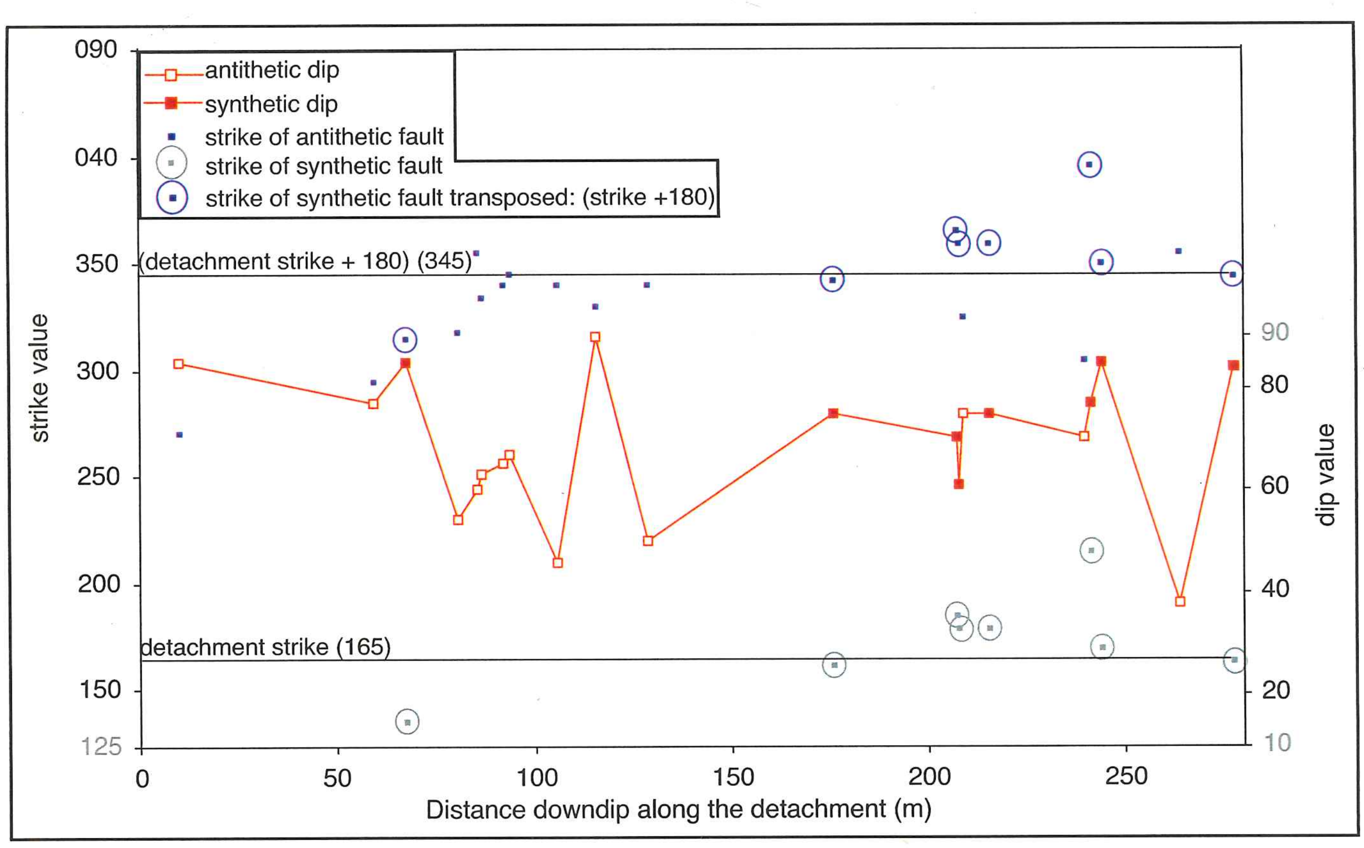


Figure 20. Trends in the strike and dip of antithetic and synthetic upper plate faults with increasing distance downdip along the detachment at South of Natural Bridge. Synthetic faults have strikes ranging from 135 to 215 degrees; these are plotted in light gray and circled. Strikes of synthetic faults are also converted to the parallel antithetic orientation by adding 180 to the strike value. These are plotted in blue and circled, in order to show trends in strike of the total fault population while preserving the distinction between the synthetic and antithetic faults in the population. Antithetic faults have strikes ranging from 270-355 degrees; the strike values along the y-axis are organized such that the antithetic and the synthetic faults plot as two separate groups. Two reference lines show the strike of the detachment and the strike of an antithetic fault that strikes parallel to the detachment (detachment strike + 180). The dip values for the faults are plotted directly above or below the strike value for each individual fault, depending on whether the fault is synthetic or antithetic. A line to illustrate the variation in the dip values downdip along the detachment connects the dip values.

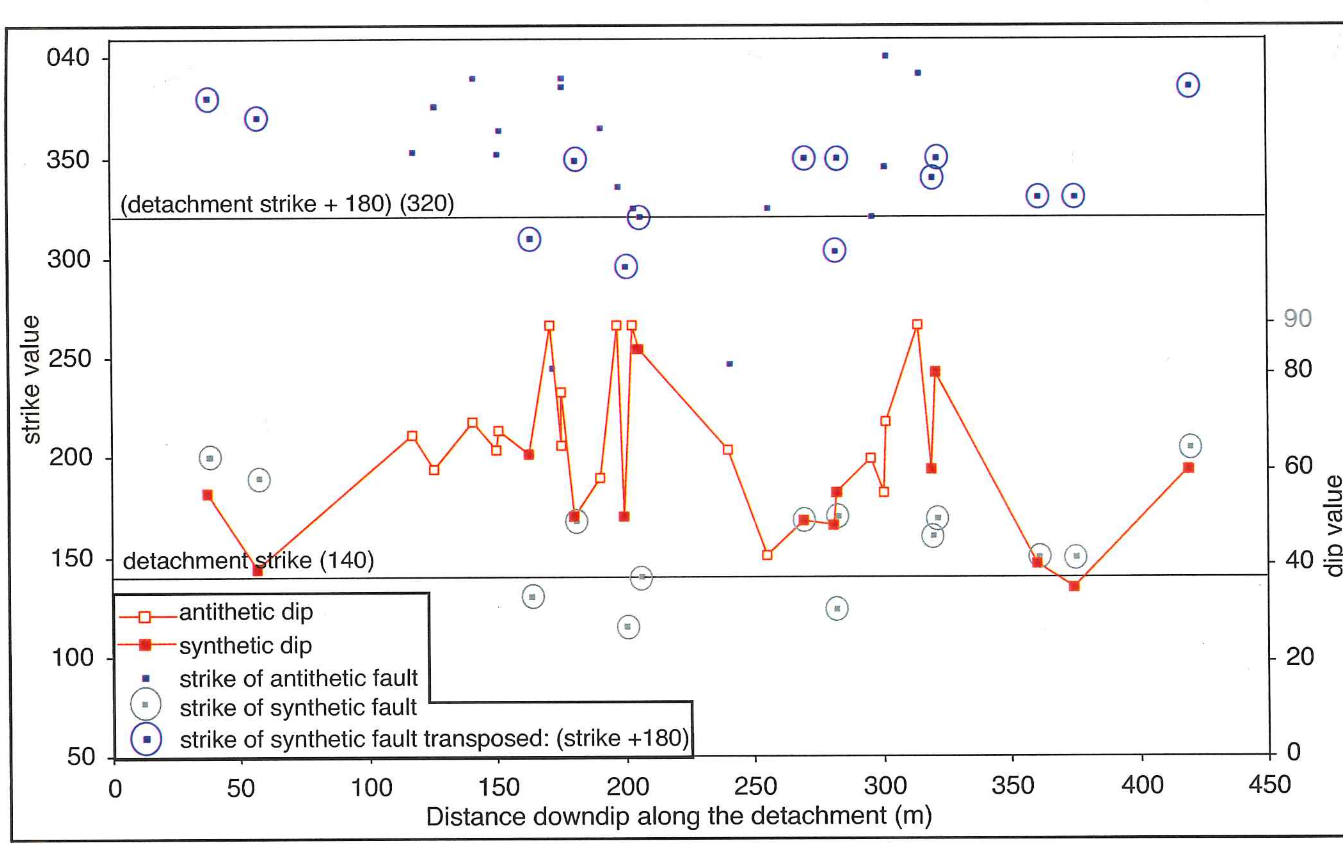


Figure 21. Trends in the strike and dip of antithetic and synthetic upper plate faults with increasing distance downdip along the detachment at Size 36. Synthetic faults have strikes ranging from 115 to 205 degrees; these are plotted in light gray and circled. Strikes of synthetic faults were also converted to the parallel antithetic orientation by adding 180 to the strike value. These are plotted in blue and circled, in order to show trends in strike of the total fault population while preserving the distinction between the synthetic and antithetic faults in the population. Antithetic faults have strikes ranging from 245-40 degrees; the strike values along the y-axis are organized such that the antithetic and the synthetic faults plot as two separate groups. Two reference lines show the strike of the detachment and the strike of an antithetic fault that strikes parallel to the detachment (detachment strike + 180). The dip values for the faults are plotted directly above or below the strike value for each individual fault, depending on whether the fault is synthetic or antithetic. A line to illustrate the variation in the dip values downdip along the detachment connects the dip values.

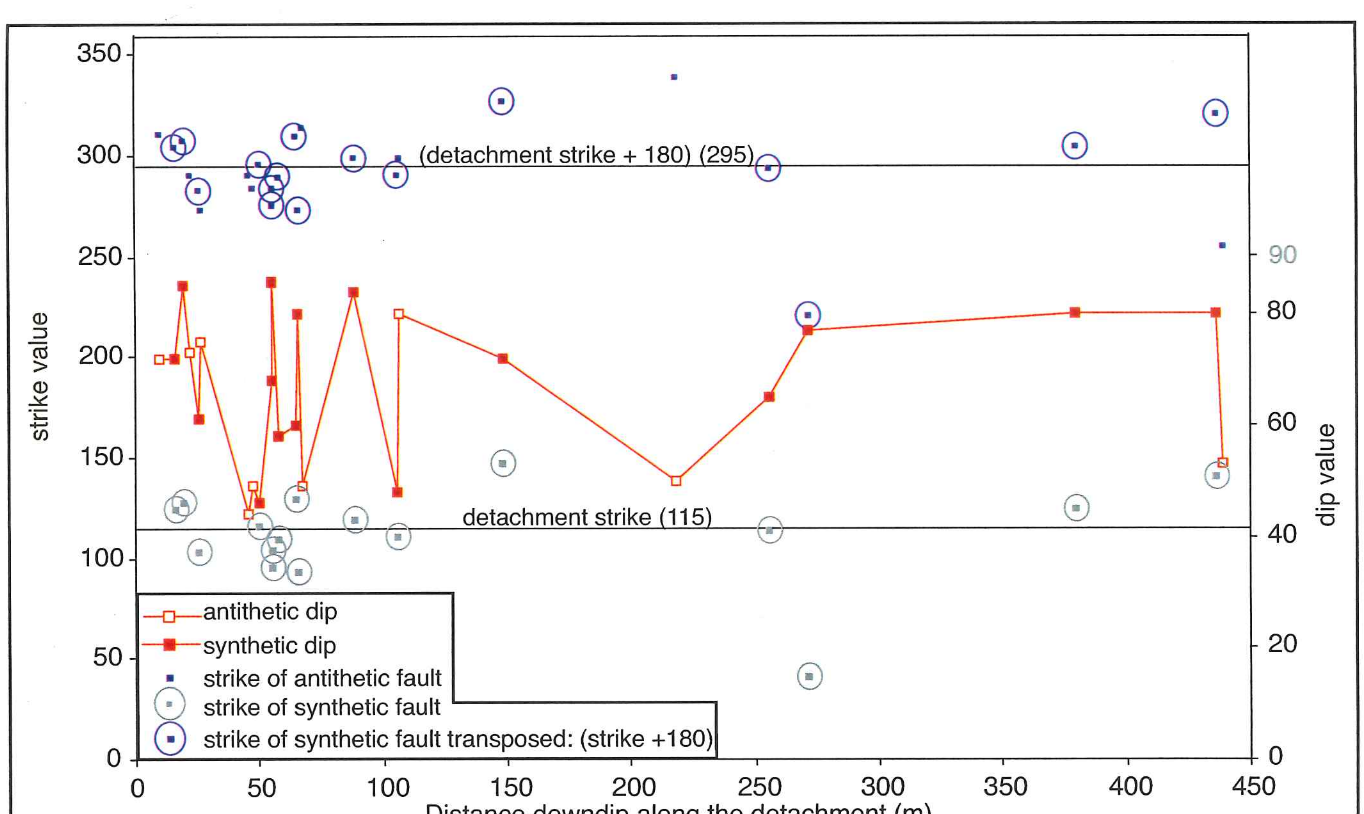


Figure 22. Trends in the strike and dip of antithetic and synthetic upper plate faults with increasing distance downdip along the detachment at Nemo Canyon. Synthetic faults have strikes ranging from 41 to 147 degrees; these are plotted in light gray and circled. Strikes of synthetic faults were also converted to the parallel antithetic orientation by adding 180 to the strike value. These are plotted in blue and circled, in order to show trends in strike of the total fault population while preserving the distinction between the synthetic and antithetic faults in the population. Antithetic faults have strikes ranging from 255-339 degrees; the strike values along the y-axis are organized such that the antithetic and the synthetic faults plot as two separate groups. Two reference lines show the strike of the detachment and the strike of an antithetic fault that strikes parallel to the detachment (detachment strike + 180). The dip values for the faults are plotted directly above or below the strike value for each individual fault, depending on whether the fault is synthetic or antithetic. A line to illustrate the variation in the dip values downdip along the detachment connects the dip values.

direction as the detachment; an antithetic fault dips in the opposite direction from the detachment (Axen, 1988). However, if the strike of an upper plate fault is not parallel to the strike of the detachment fault, it is necessary to define the distinction between a synthetic and an antithetic fault using a quantitative formulation. If the strike and dip of a fault is reported using the right-hand rule, given any strike of the detachment fault, there are 180 degrees of strike values that correspond to synthetic orientations and 180 degrees that correspond to antithetic orientations. In this study, synthetic upper plate fault orientations are defined as faults that strike within the range of +/- 90 degrees from the strike of the detachment; all other orientations are classified as antithetic.

Facing direction: Observations

Of the 97 upper plate faults measured at Natural Bridge, 35% of these faults are synthetic, 65% of them are antithetic (Table 1). At South of Natural Bridge Canyon, synthetic faults are also the minority in the population: 38% synthetic, 62% antithetic faults were measured. This ratio is in contrast with the relative proportion of synthetic faults measured in upper plate faults populations in other localities. The data for SMPA, SMP B and SMP C all include a majority of synthetic faults (87%, 94%, 75%, respectively). At size 36, there are 45% synthetic and 55% antithetic faults, comparable numbers of each. At Nemo Canyon there are 64% synthetic faults and at South of Emigrant Canyon, there are 68% synthetic faults.

The distribution of antithetic and synthetic faults downdip along the detachment at Natural Bridge is marked by a complete lack of synthetic faults from 918-1166m, but

Table 1. Summary of upper plate fault population data for all localities.

locality	total faults	% synthetic	% antithetic			
Natural Bridge	97	35	65			
South of Natural Bridge	21	38	62			
SMP A	15	87	13			
SMP B	16	94	6			
SMP C	20	75	25			
Size 36	31	45	55			
Nemo	25	64	36			
S. of Emigrant Canyon	28	68	32			
	SYNTHETIC FAULTS			ANTITHETIC FAULTS		
	min dip	**max dip**	**mean dip**	**min dip**	**max dip**	**mean dip**
Natural Bridge	25	89	70	40	89	69
South of Natural Bridge	61	85	77	38	89	65
SMP A	49	89	68	54	65	60
SMP B	35	80	55	61	61	61
SMP C	52	77	62	41	69	51
Size 36	35	85	55	42	89	69
Nemo	46	86	70	44	80	61
S. of Emigrant Canyon	11	89	55	58	89	74
	min strike	**max strike**	**range strike**	**min strike**	**max strike**	**range strike**
Natural Bridge	133	288	155	309	67	118
South of Natural Bridge	135	215	80	270	355	85
SMP A	135	198	63	324	330	6
SMP B	114	190	76	324	324	0
SMP C	150	198	48	329	38	69
Size 36	115	205	90	245	40	155
Nemo	41	147	106	255	339	84
S. of Emigrant Canyon	135	250	115	310	112	162
	mean offset			**mean offset**		
Natural Bridge	52			48		
South of Natural Bridge	75			17		
SMP A	N/A			N/A		
SMP B	N/A			N/A		
SMP C	5			4		
Size 36	173			26		
Nemo	32			34		
S. of Emigrant Canyon	271			12		

there are antithetic faults continuously over this distance (Fig. 19). At South of Natural Bridge, there is a lack of synthetic faults from 67-175m; the antithetic faults are continuous over this distance and the synthetic faults are concentrated over the distance from 175-277m (Fig. 20). At Size 36, there is a distinct lack of synthetic faults from 56-163m. There are more antithetic faults updip, whereas the synthetic faults seem to be more concentrated downdip (Fig. 21). There are no remarkable trends in the distribution of upper plate antithetic and synthetic faults downdip along the detachment at Nemo Canyon (Fig. 22).

Facing direction: Discussion

Compared with other published field studies of upper plate faults, the large proportion of antithetic faults in Natural Bridge and South of Natural Bridge Canyon may be unusual. Gross and Hillemeyer (1982) reported that there are significantly fewer antithetic than synthetic faults in the upper plate of the Whipple Mountain detachment, although they noted that this apparent paucity of antithetic faults could be because they exhibit less offset, or because they were rotated to synthetic orientations. Stewart and Argent (2000) compared the polarity of domino-style faults with and without a basal detachment, and conclude that in the presence of a detachment, the majority of the upper plate faults should be synthetic in origin, although they do not offer a mechanical explanation for this observation. Above the Altotiberina detachment in Central Italy, Boncio et al. (2000) reported that synthetic faults are concentrated updip, whereas there are more antithetic faults downdip. Withjack et al., (1995) found that in their clay model of brittle deformation above a master normal fault, antithetic normal faults nucleated above concave-upward bends along the surface of the master fault.

It is possible that the large number of antithetic faults at Natural Bridge and South of Natural Bridge reflect a concavity in the structure of the underlying detachment. Similarly, the zones at Natural Bridge, South of Natural Bridge and Size 36 where there are no synthetic faults may reflect a concave-upward bend in the detachment. Alternatively, the lack of synthetic faults may indicate the location of the downdip segment of a graben structure.

Strike: Observations

The minimum, maximum and range of strike values for synthetic and antithetic faults at each locality are summarized in Table 1. The range of strikes for each locality is variable, and the range of strikes of antithetic faults is not systematically less or greater than the range in synthetic faults. The range of strikes scales with the total number of faults measured for each locality.

The spatial trend in the strike for synthetic and antithetic faults at Natural Bridge can be fit with two best-fit lines, and the points that fall outside of these lines can be interpreted as part of two more trends (Fig. 23). One best-fit line records a steady clockwise rotation of the strikes of the synthetic and the antithetic faults from 324 to 1037m downdip from the origin. The slope of this line indicates that the amount of this rotation is approximately 0.15 degrees per meter. From 869m to ~1450m downdip, another best-fit line shows that the strikes steadily rotate counter-clockwise at a slope of

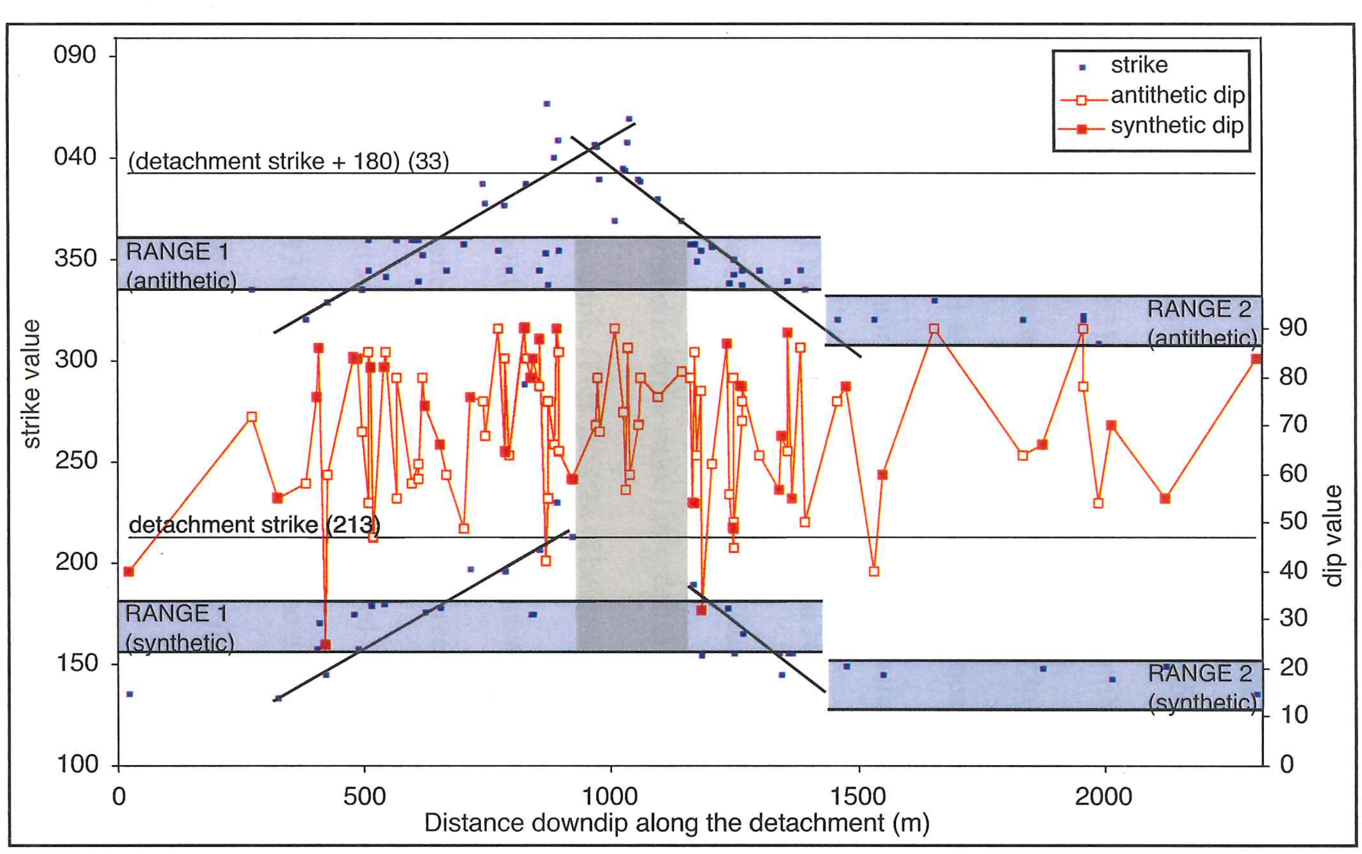


Figure 23. Interpretation of trends in the strike of upper plate faults with increasing distance downdip along the detachment at Natural Bridge. Black lines show a gradual clockwise rotation followed by a gradual counter-clockwise rotation of strike values in both antithetic and synthetic fault populations. The slopes of the lines that characterize the trends in the synthetic and antithetic faults are equivalent. Light blue ranges encompass most faults that fall outside of the black line trends. Range 1 for antithetic faults includes strike values that are 180 + the values in Range 1 for the synthetic faults; Range 2 for antithetic faults includes strike values that are 180 + the values in Range 1 for the synthetic faults. The light gray area highlights a distance downdip along the detachment over which there are no synthetic faults whatsoever, and no antithetic faults within Range 1.

approximately 0.195 degrees per meter. The points that fall outside of these two best-fit lines all lie neatly within two ranges of strike values. Range 1 contains strikes between 335 and 360 degrees (the antithetic faults) and between 155 and 180 degrees (the synthetic faults) and describes the strikes of the faults from 0 to ~1450m. Range 2 contains strikes between 310 and 335 degrees (the antithetic faults) and 130 and 155 degrees (the synthetic faults), and occurs from ~1450 to 2306m. A prominent void in the Range 1 occurs from 891 to 1176m; within this distance there are no faults with strikes that lie within Range 1, nor are there any synthetic faults.

For South of Natural Bridge, Size 36, and Nemo trend plots, the strikes of the synthetic faults were converted to the corresponding parallel antithetic strike values (by adding 180 to the synthetic strike value) in order to analyze variation in the strike of the fault population as a whole (Figs. 20-22). The trend in strike of upper plate faults along the detachment at South of Natural Bridge indicates a general clockwise rotation of antithetic and synthetic strikes in the downdip direction along the detachment. At Size 36, the synthetic and antithetic faults are clustered within Range 1, with values from 348-390 degrees, from 37 to 190m downdip along the detachment, and within Range 2, with values from 320-350 degrees, along the distance from 197 to 374m along the detachment (Fig. 24).

At Nemo Canyon, the data show a majority of the upper plate faults concentrated updip along the detachment. This distribution may reflect the fact that the updip faults were measured along one continuous exposure, whereas the remainder of the fault population were measured along a traverse with variation in the orientation of the

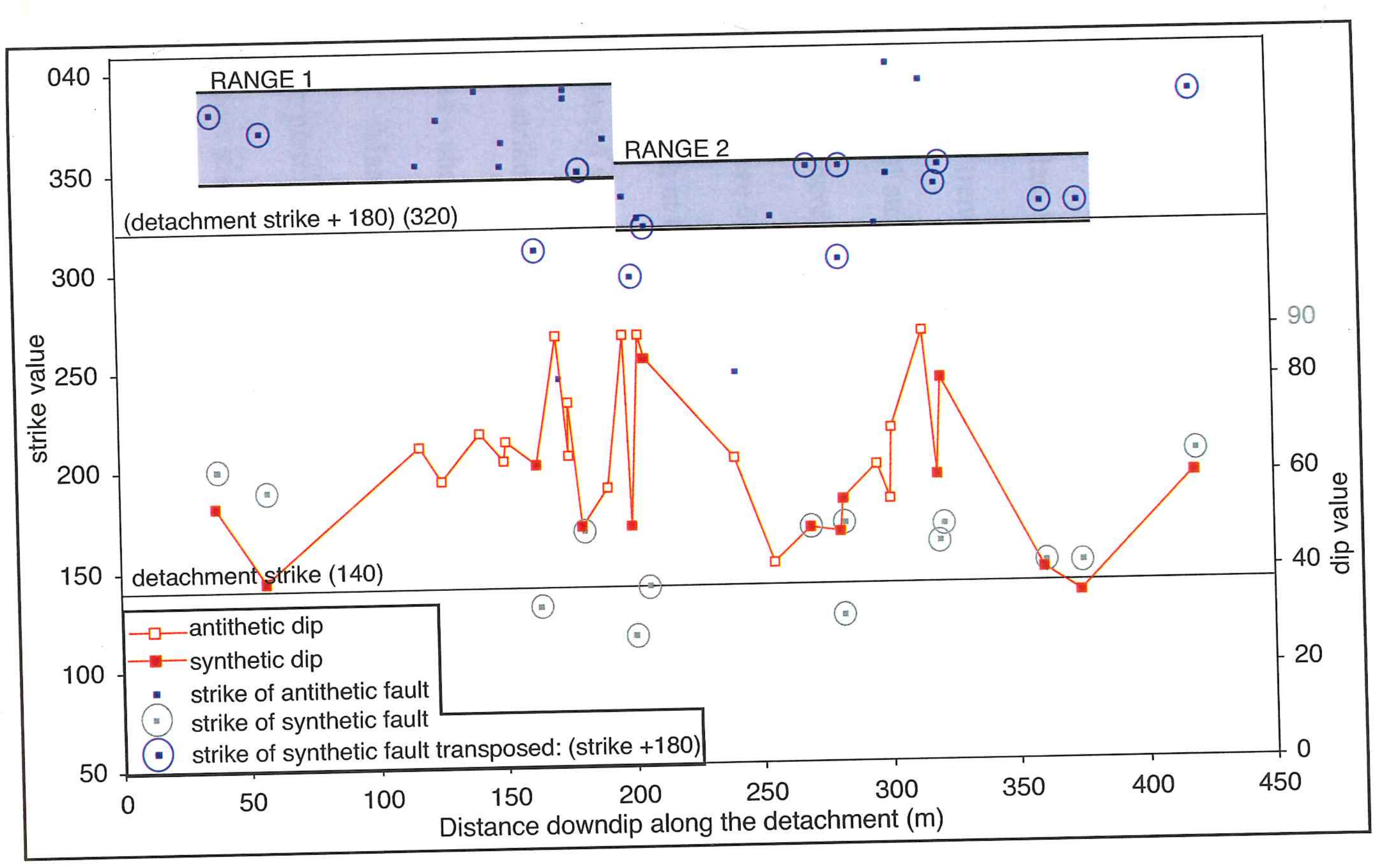


Figure 24. Interpretation of trends in the strike of upper plate faults with increasing distance downdip along the detachment at Size 36. Light blue ranges capture the variation in the clustering of the strike values with increasing distance downdip along the detachment.

exposure. The upper plate faults along the updip section are clustered in value within the range from 273-314 degrees, with no systematic variation.

Strike: Discussion

All four of the localities show some downdip variation in the range of strikes of the upper plate faults. Two different types of trends were interpreted from the trend data: clear linear trends which track a gradual rotation of strike, and ranges which demonstrate clustering of strikes over specific distances downdip along the detachment. For the two localities where linear variation is observed (Natural Bridge and South of Natural Bridge), there appears to be a clockwise rotation of strikes in the updip section along the detachment; at Natural Bridge this trend is complemented by a steady counter-clockwise rotation of strike in the downdip section. The lack of a meaningful linear downdip trend in the strikes at Size 36 and Nemo Canyon may reflect the fact the downdip section covers a shorter distance than the downdip section at Natural Bridge.

Many workers have reported significant variation in the strike of faults in the upper plate of detachment faults, (e.g. Hodges et al., 1990). However, most discussions of upper plate fault populations overlook this variation, because the systems are usually described two-dimensionally, using cross-sections along the detachment wherein all upper plate faults are assumed to strike parallel with the detachment fault. Indeed, analog models have demonstrated that purely orthogonal slip along a planar detachment will produce upper plate faults that are parallel or sub-parallel to the strike of the detachment (e.g. McClay and Ellis, 1987). Therefore, given the assumption that upper plate deformation was kinematically coupled with slip along the detachment, the observed variation in the strike of upper plate faults downdip along the detachment along the Black Mountain detachment may indicate that at least one of the following are true: slip along the detachment was not purely orthogonal, or the detachment is not planar. Analog experiments document a variation in the strike of upper plate faults developed above a master fault with a component of oblique slip. The relevance of this finding will be explored in detail in a section below.

Dip: Observations

The minimum, maximum and mean dip value for synthetic and antithetic faults at each locality is summarized in Table 1. The minimum dip values for the antithetic faults are mostly higher then the minimum dips for the synthetic faults, with the exceptions of South of Natural Bridge, SMP C, and Nemo Canyon. The average dip values for the synthetic faults are mostly higher than the average dip values for the antithetic faults, with the exceptions of SMP B, Size 36, and South of Emigrant Canyon. The mean dip of the synthetic and antithetic faults for each locality hovers around 60 degrees (Table 1).

There is no apparent trend in the dip values downdip along the detachment at Natural Bridge, South of Natural Bridge, Size 36, or Nemo Canyon. There is no apparent trend in the dip values of the antithetic faults or the synthetic faults. There is no systematic change in the variability of the dip values at any of these localities. There is no apparent correlation between dip value and strikes in any of these fault populations, nor is there any clear correlation between dip value and variation in fault density.

Dip: Discussion

Several workers have suggested that the variability of dips in the upper plate faults above a detachment fault reflects a shallowing of dips with increasing age due to rotation of the fault-bounded blocks as they move along a curved detachment or a rolling hinge (Holm et al., 1993; Wernicke et al., 1998). Gross and Hillemeyer (1982) found this correlation to be relevant in the Whipple Mts. Jackson and McKenzie (1983) noted that normal fault systems generally develop new generations of high-angle faults when the dip of the original faults has been reduced by rotation.

Other work has investigated the relationship between dip angle of upper plate faults and the obliquity of slip and variation in strain rates along the detachment. Tron and Brun (1991) documented an increase in fault dip with increasing obliquity of slip along the detachment. Friedmann and Burbank (1995) attributed a change in fault dip over time in the Death Valley area to a decrease in the strain rate along the detachment.

The mean dip of the synthetic and antithetic faults, approximately 60 degrees, is consistent with the interpretation that σ_1 was nearly vertical during upper plate fault development. These high-angle faults, which cut nearly horizontal bedding, show no evidence of having been rotated. There are no apparent downdip trends in the dip of the upper plate faults, providing further evidence that these faults have not been rotated, and their original dips are preserved. Therefore, the variation in dips is inconsistent with a rolling-hinge model, and the upper plate rocks have been transported downdip along the detachment dominantly by translation, with little if any rotation.

Listricity: Observations

Listric and planar faults are observed at all localities. Most listric faults are relatively planar until ~1m from the intersection with the principal slip surface of the detachment, at which point the dips become more shallow, yet there are also several faults that appear to be curved over a distance of several meters. There is no systematic change in the type of intersection of upper plate faults with the principal slip surface downdip along the detachment at any locality. It is important to note that the distances over which the intersection between the upper plate and the principal slip surface is exposed is very short compared with the distance of the traverses at each locality. There are generally more listric synthetic faults than listric antithetic faults in a given fault population.

Listricity: Discussion

The relative population of listric faults observed in the upper plate of other detachment faults is quite variable, and this variability may be due in part to the lack of a consensus as to how much curvature and what degree of curvature must be observed in order for the fault to be considered listric. Gross and Hillemeyer (1982) claimed that listric faults are not really observed in the Whipple Mts., in spite of the fact that models using listric faults are applied to the region in efforts to explain the rotation of upper plate fault blocks.

The development of listric faults in upper plate systems may be attributed to the variation in rheology with depth, namely at the interface between upper plate faults and the detachment gouge. Jackson and McKenzie (1983) suggested that distributed creep in the lower crust produces more fault rotation than brittle failure at shallow depths, and this distinction may be applicable to the difference between upper plate rocks and detachment gouge. This change in the material properties as the fault approaches the weak (gouge) layer may induce a local rotation of the stress field causing the upper plate fault to change dip. However, given this explanation, one might expect that all of the upper plate faults that sole into or end at the principal slip surface of the detachment would be curved, and that is not the case.

Another possibility is that listric upper plate faults are older once-planar faults that have been rotated to a shallower dip where the fault is adjacent to the detachment as a result of the displacement gradient associated with slip along the detachment. Gupta and Scholz (1996) described this as a form of reverse drag that may be a manifestation of the decrease in displacement away from the fault and may not be related to listric faulting. This explanation predicts that all planar upper plate faults that are postdated by some detachment slip will appear to be listric. Listric upper plate faults may also result from contemporaneous motion along the detachment and the upper plate fault or variation in the rate of slip along the detachment.

6.2. Upper plate fault character (sense of displacement, amount of displacement): Observations and discussion

Sense of displacement, amount of displacement: Observations

Information about the sense and amount of displacement along upper plate faults was determined by assessing the dip of the fault and the offset of bedding. The vast majority of the measured upper plate faults in all localities show normal sense-of-slip. For example, at Natural Bridge, 3 of 97 measured faults showed evidence of a reverse sense of slip. Very few of the measured upper plate faults had exposed striations or slickensides; of these faults, only one (at Natural Bridge) indicated a component of oblique slip.

The poor expression of bedding in the upper plate rocks complicated measurements of the magnitude of displacement; amount of displacement was measured with confidence for less than half of the upper plate faults at each locality. The average offset along upper plate synthetic and antithetic faults for each locality is summarized in Table 1. It is important to emphasize that these numbers reflect the average offset only for those faults for which offset was measured, not for the total fault population. The synthetic faults generally have a higher mean offset at all localities except for Nemo Canyon, for which the mean offset is nearly the same for synthetic and antithetic faults. Trends in amount of offset along upper plate faults with increasing distance downdip along the detachment were not considered due to the limited number of faults for which displacement was measured.

Sense of displacement, amount of displacement: Discussion

Other work has shown dip-slip faults to be dominant in upper plate fault populations. Gross and Hillemeyer (1982) reported only two strike-slip faults in upper plate fault populations in the Whipple Mountains. The amount of displacement on measured upper plate faults is quite variable. It is important to recognize that the magnitude of displacement may vary along the length of a given fault. Several studies have demonstrated that displacement along normal faults is usually greatest in the middle and dies out at the fault tips (Cowie and Scholz, 1992; Schlische et al., 1996; Walsh and Watterson, 1988). Due to limits imposed by the exposure of upper plate faults, my measurements of displacement were made at varying positions along the fault, which introduces some inconsistency into the measurements.

Several clay analog models have generated significantly more displacement along synthetic faults than antithetic faults (Withjack et al., 1995; Rahe et al., 1998). Based on the limited amount of information about magnitudes of fault displacement that could be measured in the field, the distribution of upper plate fault displacement in Death Valley appears to be consistent with these predictions.

A more detailed and thorough analysis of the distribution of displacement in the upper plate fault population may reveal important information about the location and development of future supradetachment basins. The upper plate above the Black Mountain detachment in Death Valley is a young system composed of young/poorly consolidated sediments and riddled with faults that accommodate relatively small displacements; however this system may represent the incipient stages of development of major upper plate faults. Upper plate faults that preferentially accommodate a significant amount of the extension may evolve into bounding faults for supradetachment basins. The upper plate of the late Tertiary Emigrant detachment-system provides an example of one such fault, a major high-angle normal fault called the Towne Pass fault that bounds the Nova Basin, a large depositional basin (Hodges et al., 1989).

6.3. Upper plate fault distribution

Location and spacing of upper plate faults: Observations

At South of Natural Bridge there are two ~20m sections with a high density of faults (Fig. 25). The first, from 80-100m, includes 5 faults, all of which are antithetic. The second, from 200-220m includes 4 faults, 3 of which are synthetic. At Natural Bridge, Size 36 and Nemo Canyon, the sections downdip along the detachment with high fault densities are characterized by nearly equal numbers of synthetic and antithetic faults. At Natural Bridge and Size 36, fault distribution is bimodal, with two broad regions of high fault density. At Nemo Canyon there is only one area that hosts a high number of upper plate faults. Field observations of intersection geometries reveal that high densities of upper plate faults occur adjacent to zones where the intersection with the principal slip surface of the detachment is more complex.

Location and spacing of upper plate faults: Discussion

The apparent clustering of upper plate faults at each locality may arise from an artifact referred to as data censoring (Pickering et al.,1995; Ackermann et al., 2001), wherein at extreme updip and downdip limits of the traverse, where measurements were more sparse, faults that intersect the detachment along the cross-section line but are exposed beyond the limits of the traverses are not represented. However, if the

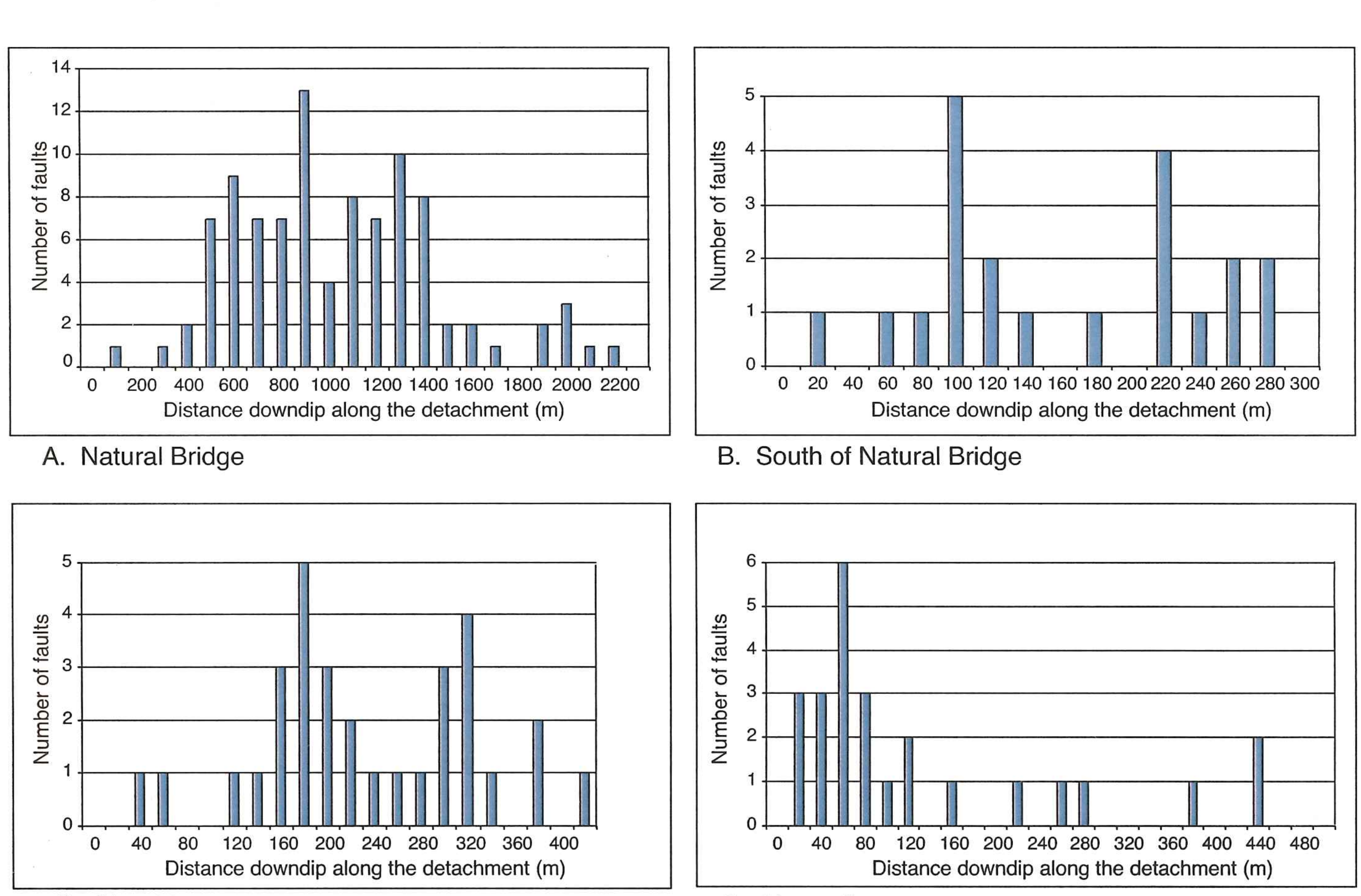


Figure 25. Histograms showing distribution of upper plate faults downdip along the detachment for each locality. A) Natural Bridge, bins are 100 meters B) South of Natural Bridge, bins are 10 meters C) Size 36, bins are 20 meters D) Nemo Canyon, bins are 20 meters.

distribution of faults is entirely obscured by this artifact, one would expect a Gaussian or "normal" distribution, with the majority of upper plate faults in the middle of the section and the density decreasing steadily towards both ends of the section. Instead, at Natural Bridge, South of Natural Bridge and Size 36, the distribution of faults downdip along the detachments follow bimodal distributions. The highest density of faults is not in the middle of the section; rather there is a zone with a lower density of faults in the middle of the section.

This deviation from a Gaussian distribution suggests that the distribution of faults reflects some real patterns in fault density downdip along the detachment; these patterns are not entirely obscured by sampling artifacts. The low density of faults in the middle of these sections suggests that there is a larger structure nearby accommodating most of the strain. Ackermann and Schlische (1997) found that "stress-reduction shadows" are localized around large faults causing a void in the physical distribution of brittle structures around large faults. Clifton et al. (2000) observed that in sandbox analog models, small faults are more abundant in the zone where faults of opposing dips meet. They suggest that this fault density develops because when the tips of faults with opposing dips meet, the faults lock, and new faults nucleate to accommodate the strain. Therefore the high-density zones downdip along the detachment may form near the junction of a synthetic and an antithetic fault.

Clifton et al. (2000) also found that mean fault spacing in upper plate fault populations varies as a function of the obliquity of slip along the detachment. They demonstrated that with increasing obliquity, mean fault spacing decreases. They attributed this increase in fault density to the decrease in the size of the stress-reduction shadows; the models with more oblique slip were characterized by a greater degree of fault segmentation, and the shorter fault segments have smaller stress-reduction shadows. Clifton et al. (2000) also documented that the spacing between the faults becomes more regular with increasing obliquity, as the obliquity of slip directly affects the extent to which fault linkage or fault nucleation dominates the system. The spacing of upper plate faults above a detachment fault might also be predetermined by inherited structure/weakness, and/or be determined by irregularities on the principal slip surface of the detachment, as discussed in section 4.

7. Does upper plate deformation record a history of oblique and orthogonal slip on the detachment fault?

Several workers have used analog models to explore the relationship between the obliquity of slip along the detachment fault and the strike of faults that develop in the upper plate (Withjack and Jamison, 1986; Smith and Durney, 1992; Tron and Brun, 1991; Keep and McClay, 1997; Clifton et al., 2000). The variation in the strikes of upper plate faults is the single most pronounced difference between models of orthogonal and oblique extension (Clifton et al., 2000). Patterns of upper plate deformation generated by different angles of oblique slip on a detachment fault are well established and there is excellent agreement among different experiments conducted using different materials (e.g. sand, silicone: Tron and Brun, 1991; clay: Withjack and Jamison, 1986).

In models involving orthogonal slip, the strikes of upper plate faults are approximately perpendicular to the slip vector along the detachment; this is not the case in models of oblique detachment slip. The angle of obliquity is commonly described in terms of α, which is defined as the angle between the strike of the detachment fault and the slip direction (α =90 connotes orthogonal slip, and decreasing values of α correspond to increasing obliquity, α =0 represents strike-slip motion). Clifton et al. (2000) demonstrated that for systems where α =75, the predominant upper plate fault strike among the longest faults is 18 degrees from the strike of the detachment fault (the azimuths of small faults were found to span the range of the population for all values of α). For systems where α =60 and α =45, the predominant upper plate fault strike is 23 degrees from the strike of the detachment fault. For systems where α =30, there are two dominant upper plate fault strikes at 28 and 62 degrees from the strike of the detachment fault. There are also two dominant upper plate fault strikes for systems where $\alpha = 15$, which are oriented 28 and 62 degrees from the strike of the detachment fault. Clifton et al. (2000) also found a steady increase in the range of azimuths with increasing obliquity on the detachment (decreasing values of α). These patterns correlate closely with results from other experiments.

7.1. Relevant observations in Death Valley

Both orthogonal and oblique striations on principal slip surfaces of the detachment faults are clearly exposed in several localities in Death Valley and have been previously documented in the literature (Miller, 1999). This observation, supplemented by the pronounced variation in the strikes of the upper plate faults, strongly suggests that slip on the detachment fault may have been oblique at some time. It is possible that the observed variation in the strike of the upper plate faults directly reflects the obliquity of slip along the detachment at the time when the respective upper plate faults failed. If so, the measured orientation of the detachment at Natural Bridge (213, 21NW) indicates that the slip along the detachment was orthogonal at the time of failure of the upper plate faults which are located from approximately 850 to 1050m from the origin along the detachment (Fig. 19).

Significantly, if the measured orientation of the detachment (taken where the detachment daylights) only reflects local variation in the detachment orientation, the record still indicates a history of both oblique and orthogonal slip. The variation in the strike of the upper plate faults provides evidence that there must have been oblique slip. Given the constraint that the detachment dips generally westward, the fact that the strikes of the synthetic upper plate faults range with regular distribution from 135 to 230 degrees, and the strikes of the antithetic upper plate faults range with regular distribution from 309 to 60 degrees suggests that slip was orthogonal at some time.

Using measurements of striations and mesoscopic folds and faults, Miller (1999) identified two distinct slip directions, one orthogonal and one oblique, top-to-the-northwest, and correlated these sets of distinct slip directions with two distinct slip events. Miller (1999) suggested that the oblique slip event was tectonically-driven as evidenced by fault rocks in the lower plate which consist of gouge, cataclasite and breccia and are clearly tectonically derived. After tectonic slip ceased, Miller argued that the slip surfaces were subsequently reactivated by gravitational slip; this hypothesis is based largely on the presence of large landslide deposits on the Badwater turtleback. Miller assumed that the orthogonal slip event was the gravitationally-driven event, and on the basis of overprinting relationships between the two sets of sense-of-shear indicators, Miller suggested that the gravitationally-driven event occurred after the tectonic event.

Based on my geometric analysis of a large number of upper plate faults, it emerges that it is not possible to identify two distinct families of strikes at any of the three localities above the Black Mountain detachment or at Nemo Canyon above the Emigrant detachment. Assuming a correlation between the variation in the strikes of upper plate faults and the obliquity of slip along the detachment, the gradual rotation of the strikes of the upper plate faults ("linear trends") reflects a gradual change in the direction of slip on the detachment fault.

The ranges that demonstrate clustering of strikes over specific distances downdip along the detachment may reflect the fact that the detachment may have slipped in one oblique orientation for a long period of time, and the orientation of the structures which developed during that time were preserved during subsequent slip in a different direction. Alternatively, the ranges may reflect the latest stage of slip along the detachment, overprinting older structures with different orientations. This hypothesis could be tested using field observations of structural relationships between faults with strikes within the range and other faults in the population.

Very few of the strikes of the upper plate faults are consistent with orthogonal slip along the detachment. The general lack of upper plate faults that strike parallel to the strike of the detachment suggests that there was not an orthogonal slip event that was distinct temporally or by slip mechanism (ex: gravitationally-driven vs. tectonically-driven slip). The landslide deposits that Miller (1999) described may have resulted from gravitationally-driven slip, yet this probably does not reflect a major change in the mechanism of overall slip along the detachment, but rather isolated gravitational slides. It is likely that there are many slip surfaces which have developed as the result of gravitationally-driven slides, and others which initiated as rooted faults but later became tectonically inactive, and eventually accommodated gravitational slip. However, the presence of landslide deposits is probably unrelated to the overall mechanism of slip on the detachment, which was likely tectonically-driven throughout the life of the detachment.

7.2. Problems with the direct correlation

It is possible that the direction of slip along the detachment varies locally. If the strike of upper plate faults reflects locally oblique slip on the detachment, then the variation in strikes with distance downdip along the detachment may reflect the different slip histories of different sections of the detachment fault, yielding no information about the slip history of the detachment as a whole. It is also possible that the preserved striations may not record the latest slip event, as locally older slip events may be preserved during younger events.

Several analog models of extension above a detachment fault have examined the effects of multi-stage slip on the evolution of the overlying fault geometries. In these experiments, the faults that are preserved during the first stage strongly control fault development during the second stage (Boninie et al., 1997; Keep and McClay, 1997). Keep and McClay (1997) also found that later stages of slip cause the reorientation of earlier structures. These experiments demonstrate that multi-stage slip along the detachment fault causes a complex evolution of kinematically coupled structures in the upper plate; current upper plate fault orientations may not represent the orientation of faults at the time of initial failure. However, the current variation in upper plate fault strikes suggests that the youngest slip events have not entirely overprinted old structures. If that were the case, the trend of the upper plate faults would be more uniform.

It is not possible to make conclusions about different generations of faults based on the comparison between field observations and geometries generated in analog experiments. Current fault populations may only reflect the most recent of many stages in the evolutionary development of the detachment-system. Different generations of upper plate faults may have failed in kinematically distinct events. For example, upper plate deformation associated with tectonic slip on the detachment could be overprinted by upper plate deformation driven by gravitational instability. Although the current strike of individual faults may not directly reflect the direction of slip on the detachment at the time of nucleation of that fault, the variation in strikes suggests that the direction of detachment slip has varied temporally.

8. Curved or segmented detachment

The variation in strikes of the upper plate faults may also reflect a detachment surface that deviates from planar (is curved or segmented). The detachment faults clearly have a first-order curvature (termed "turtlebacks" by Curry, 1938), which are likely the result of thermal warping (Livaccari, 1993). However, there may also be a second-order curvature or segmentation of the detachment (Burchfiel et al., 1995).

Figure 26 shows a schematic curve based roughly on the data for the Natural Bridge locality which is intended to represent a curved detachment determined by orienting the strikes in the upper plate everywhere perpendicular to the dipline of the detachment. If the variation in strike is indeed reflective of a change in the orientation of the detachment, the continuous strike variation at Natural Bridge (as determined by the geometric analysis that assumes a planar detachment) may indicate a continuous deviation from uniformity in the orientation of the detachment. The gradual change in the orientation of the detachment suggests a curved (not segmented) detachment. However, the more erratic variation in strike at the other localities may reflect a more segmented detachment.

Oblique slip along the detachment fault and a non-planar detachment fault both emerge as viable hypotheses to explain the observed variation in the strike of upper plate faults downdip along the detachment. It is likely that the slip direction along the detachment varied through time, and it is also likely that the detachment is not perfectly planar. These two hypotheses may be related, as a non-planar detachment could give rise to local variations in the direction of slip.

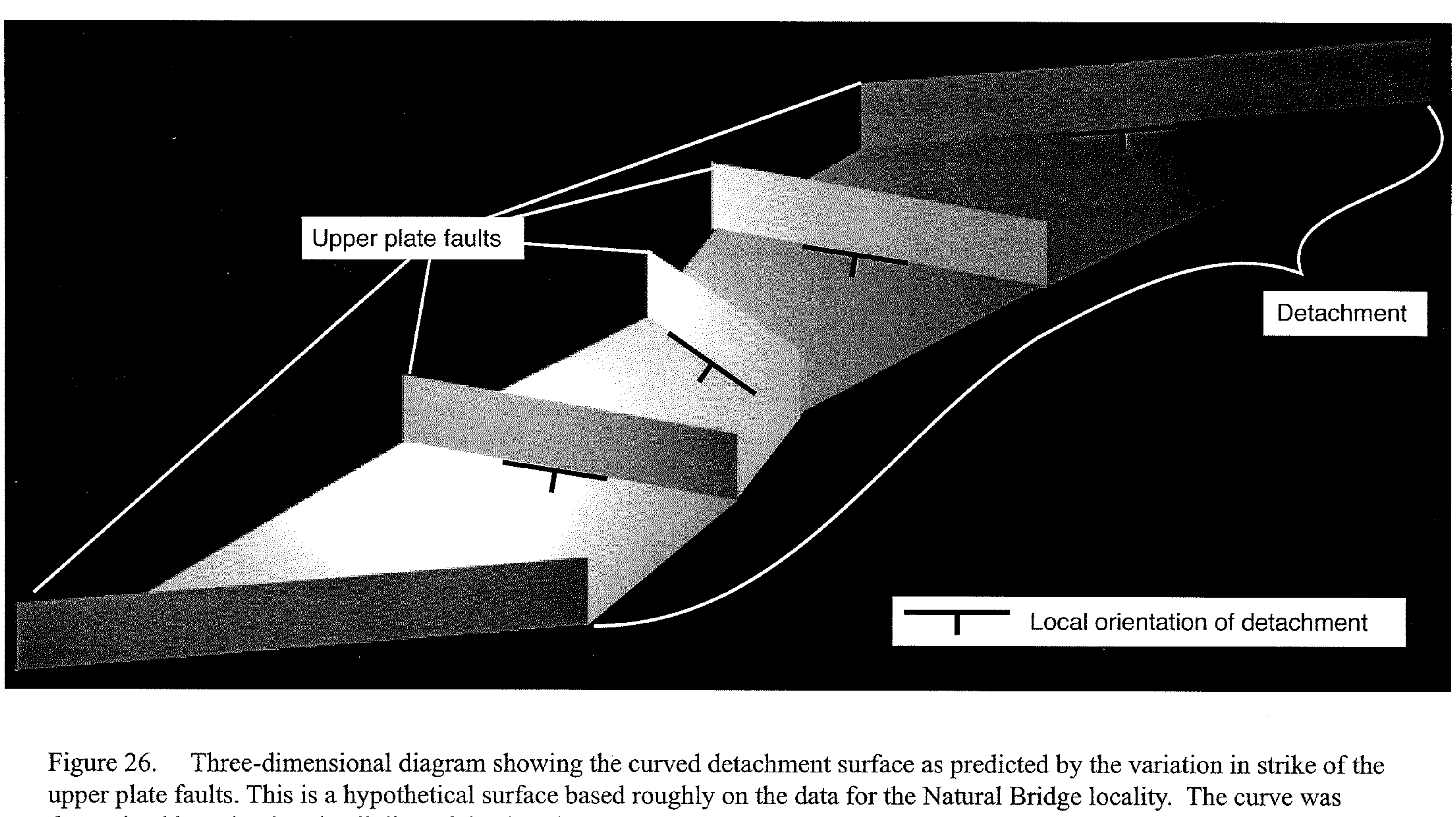


Figure 26. Three-dimensional diagram showing the curved detachment surface as predicted by the variation in strike of the upper plate faults. This is a hypothetical surface based roughly on the data for the Natural Bridge locality. The curve was determined by orienting the dipline of the detachment everywhere perpendicular to the strike of the upper plate faults.

On the basis of field data alone, it may not be possible to determine whether the obliquity of slip along the detachment or the irregular shape of the detachment exerts a stronger influence on the kinematics of faulting in the upper plate. Furthermore, field observations may not be sufficient to resolve the question of whether local variation in the direction of slip on the detachment is primarily caused by slip along an irregular detachment. However, these hypotheses may be independently tested using analog models of oblique slip along a non-planar detachment and seismological data to investigate the geometry of the detachment.

9. Low-angle slip along detachment faults

Despite compelling geologic and seismic reflection evidence (Sorel, 2000; Miller and John, 1999; Axen et al., 1999), active low-angle normal faulting remains controversial due to two problems: the lack of seismological evidence for slip on normal faults dipping <20 degrees (Jackson and White, 1989), and the incompatibility of normal slip on low-angle faults with classic Andersonian fault-mechanics theory (Anderson, 1951). Several workers have theorized that major low-angle normal faults originated as high-angle faults, but were flattened to a gentle dip due to flexure and uplift of the footwall caused by upper plate unloading (Holm et al., 1993; Buck, 1988; Jackson and White, 1989; Hamilton, 1988; Wernicke, 1992; Buck, 1988; Wernicke and Axen, 1998). Bradshaw and Zoback (1988) propose that low-angle normal faults may form because of a rotation of the maximum principal stress away from vertical with depth caused by a significant contrast in viscosity between two adjacent strata. Another prominent hypothesis invoked to explain the possible rotation of the stress field in order to facilitate low-angle normal faulting is that high pore fluid pressure in the detachment fault makes it weak, and this weakness may cause modification of the stress field within the fault zone (Axen, 1992; Axen and Selverstone, 1994). Some workers find this explanation problematic due to the very presence of upper plate faults and fractures, which could allow fluids to escape and thereby prevent overpressuring (Buck, 1988; Reynolds and Lister, 1987; Axen, 1992).

This study has shown that high-angle upper plate faults that are consistent with a vertical σ_1 cut sub-horizontal bedding. This relationship suggests that the faults have not rotated, nor did the upper plate rotate prior to upper plate fault development. This provides strong evidence that the detachment fault slipped in its low-angle orientation and that the upper plate faults failed in the same stress field, and have not been rotated from their initial dip orientations.

10. Seismic slip in detachment-systems

Because focal mechanisms from low-angle normal faults are rare, some workers suggest that they accommodate slip by aseismic creep (e.g. Wernicke, 1995). Abers (1991) is frequently cited as an exception, as he submits strong evidence of an earthquake on low-angle normal fault. However, Abers was careful to note that due to the ambiguity of the choice of a fault plane, the data do not conclusively demonstrate that slip on a low-angle normal fault occurred, but allow it as a possibility. There are other examples of seismically active low-angle normal faults in the literature, particularly in the Aegean, though these are controversial (e.g. Sorel, 2000). Abers (1991) suggested that low-angle normal faults are scarce in the earthquake data because there may be few regions where metamorphic core complexes are actively forming today. Another hypothesis is that low-angle normal faults may be seismic with long recurrence intervals (Wernicke, 1995).

Several studies have examined the idea that seismic slip within detachment-systems may be limited to slip along antithetic faults in the upper plate (Jackson and McKenzie, 1983; Bruhn and Schultz, 1996). Ofoegbu and Ferrill (1998) considered the idea that rapid (seismic?) slip on high-angle faults in the upper plate causes rapid strain accumulation in the fault block. As a result, shear stress increases on the detachment, gradually releases elastic strain and produces slip (aseismic?) on the low-angle fault segment. On the basis of seismologic data from central Italy, Boncio et al. (2000) found that earthquakes are concentrated within the upper plate and along the detachment, the data revealed only scattered and little seismicity in the footwall. They determined that

11. Conclusions

1. There has been temporal alternation between slip on upper plate faults and slip along the detachment fault; this interpretation is based on (A) the diversity of intersection geometries between upper plate faults and the principal slip surface of the detachment fault, (B) the reactivation of detachment gouge into an orientation that is parallel/sub-parallel to upper plate structures, and (C) the incorporation of fragments of upper plate material into the detachment gouge.
2. First-order coupling between upper plate fault kinematics and detachment slip is demonstrated by (A) temporal alternation between slip on upper plate faults and the detachment fault, (B) the incorporation of upper plate material into the detachment gouge, and (C) the remobilization of detachment gouge around upper plate faults.
3. Upper plate faults nucleate at irregularities along the principal slip surface of the detachment; upper plate fault slip also produces irregularities along the principal slip surface. This relationship demonstrates a strong kinematic coupling between the character of the principal slip surface of the detachment fault and the distribution of faults in the overlying upper plate. The variation in the shape of the principal slip surface may control the location (and therefore spacing) of upper plate faults, and the likelihood of developing synthetic or antithetic faults.
4. Evidence that upper plate faults are kinematically coupled with detachment slip provides the basis for further exploration of the degree to which the kinematics of upper plate faulting is controlled by properties of and slip along the detachment fault. Because the system is kinematically coupled, it is appropriate to make inferences

about the history of detachment slip based on a comparison between patterns of upper plate faults observed in the field and patterns generated in analog experiments.

5. Since irregularities are randomly distributed, the location and facing direction of upper plate faults may not be predictable. Therefore, analog models of upper plate deformation above an irregular principal slip surface can not be used to predict the location, spacing, or facing direction of upper plate faults. However, analog models may be used to predict those features of the distribution and character of upper plate faults that are not controlled by random irregularities along the principal slip surface.
6. In order to analyze spatial variation in upper plate fault geometry with increasing distance downdip along the detachment fault, I present a geometric analysis (Appendix A) that is used to project the upper plate faults onto an appropriate cross-section line that is oriented downdip along the detachment fault. This projection facilitates a direct comparison between field data of upper plate fault geometries and patterns generated in analog models. The projection of field data onto a cross-section line downdip along the detachment reveals trends that are not apparent either in the field exposure of upper plate faults, or in other projections of the data.
7. The mean dip of the synthetic and antithetic faults for each locality is approximately 60 degrees; these high-angle upper plate faults that are consistent with a vertical σ_1 cut sub-horizontal bedding. This relationship is consistent with the interpretation that σ_1 was nearly vertical during upper plate fault development, and the faults have not been rotated, nor was the upper plate rotated prior to upper plate fault development. The variation in dips is therefore inconsistent with the rolling-hinge model, as the

upper plate rocks have been translated downdip along the detachment with little if any rotation. Given the hypothesis that slip on upper plate faults was kinematically coupled with detachment slip, the evidence that the upper plate faults have not been rotated from their original dip suggests that the detachment fault slipped in its current low-angle orientation.

8. The variation in strike of upper plate faults follows clear linear trends that track a gradual rotation of strike; there is also evidence for a clustering of strikes over specific distances downdip along the detachment.
9. The observed variation in the strike of upper plate faults downdip along the Black Mountain detachment suggests that slip along the detachment was not purely orthogonal, and/or the detachment is not planar. Both of these hypotheses are viable explanations for the observed variation in the strike of upper plate faults downdip along the detachment. These hypotheses may be related, as variations in the character of the detachment may cause local variations in slip direction.
10. Assuming a correlation between the variation in the strikes of upper plate faults and the obliquity of slip along the detachment, the linear trends in the strikes of the upper plate faults suggest that there was a gradual change in the direction of slip along the detachment fault. The significant variation in the strikes of upper plate faults does not support the hypothesis that there were two distinct slip events along the detachment.
11. If the variation in strike reflects a change in the orientation of the detachment, the continuous strike variation at Natural Bridge may indicate a curved (not segmented)

detachment. However, the more erratic variation in strike at the other localities may reflect a more segmented detachment.

12. Detachment-systems may accommodate seismic slip; a seismic event could be triggered by slip on an antithetic fault in the upper plate. Evidence presented in this study that the kinematics of slip on upper plate faults is coupled with slip on the detachment confirms the plausibility of the hypothesis that detachment slip can be triggered by slip on upper plate faults.
13. A critical problem with the analysis of the upper plate fault data in this study is that it is difficult to separate the faults into chronologically distinct sets in order to differentiate between successive stages of kinematic development. Future field work should examine the structural relationships between upper plate faults with different strike orientations.

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APPENDIX A

Analytical method

1. I adopted a 3-D coordinate system which is commonly used in earth science applications: the positive x-axis points in the North direction, the positive-y axis points in the East direction and the positive z-axis points vertically down, into the ground. For consistency within this coordinate system, I subtracted the measured z values (elevation in meters) from an arbitrary number such that the values for elevation increase with lower elevation. The only constraint on this (above mentioned) arbitrary number was that it be large enough such that the z-coordinate of the points of intersection of the upper plate faults with a chosen line downdip along the detachment (later referred to as the cross-section line) would be greater than 0 so that distances between these points along this line could be measured with reference to the point along that line where z=0.

2. The generalized equation for a plane passing through a point (X_o,Y_o,Z_o) and perpendicular to the nonzero vector Ai+Bj+Ck is given by

$$A(X-X_o)+B(Y-Y_o)+C(Z-Z_o)=0$$ **equation 1.**

I redefined each upper plate fault in terms of the point where I measured the fault $Pm=(X_o,Y_o,Z_o)$ and a nonzero vector normal to the plane

$$Vn=Ai+Bj+Ck$$ **equation 2.**

where A,B,C were calculated from the geological measurements as follows:

A=sin(dip)*sin(strike)

B=-sin(dip)*cos(strike) **equation 3a-c.**

C=cos(dip)

As a result, each upper plate fault could be described by equation 1, rearranged as

$AX+BY+CZ=AX_o+BY_o+Cz_o$ **equation 4.**

(where $AX_o+BY_o+CZ_o$ is a scalar quantity.)

3. For each locality, I found a point on the detachment (Pavg)=(Xavg,Yavg,Zavg) that represents an average position relative to the position of the points where I measured the upper plate faults along my traverse (Pm). Xavg was determined by calculating the average of the X-coordinates of the measured points (Pm), Yavg was determined by calculating the average of the Y-coordinates of these points (Pm), and Zavg is the unique value for Z for the (X,Y) coordinate pair (Xavg, Yavg) that lies within the plane of the detachment. Zavg was calculated by defining the detachment plane using the steps outlined in #2, plugging Xavg and Yavg into the equation for a plane (equation 4) and then solving for Z ($Z=(AX_o+BY_o+Cz_o-AX-BY)/C$)

4. Using Pavg on the detachment, I defined a cross-section line parallel to the dip line of the detachment, within the plane of the detachment and passing through the point Pavg. Pavg was calculated for this purpose in order to determine a cross-section line within the plane of the detachment as close as possible to the location of the line of traverse in order to minimize error and assumptions about constant strike and dip with distance. The generalized parametric equations for a line passing through a point (Xavg,Yavg,Zavg) and parallel to the nonzero vector ai+bj+ck are given by

X=Xavg+at

Y=Yavg+bt **equation 5a-c.**

Z=Zavg+ct

I determined the nonzero vector parallel to the dip line vector of the detachment

Vn=ai+bj+ck **equation 6.**

using values for a,b,c which were calculated from the geological measurements as follows:

a=-cos(dip)*sin(strike)

b=-cos(dip)*cos(strike) **equation 7a-c.**

c=sin(dip)

5. Finally, for each upper plate fault, I determined the point of intersection Pi=(x,y,z) where the plane of the upper plate fault intersects the cross-section line along the detachment by first plugging equations 5a-c into equation 4 to solve for unique value t:

$t=AX_o+BY_o+CZ_o-AXavg-BYavg-CZavg/Aa+Bb+Cc$ **equation 8.**

then plugging the value for t back into equation 5 to find (x,y,z).

6. I then characterized the spatial distribution of the points of intersection of the upper plate faults along the cross-section line in terms of distances between each point and a reference point (Pref)=(Xref,Yref,Zref) along that line where Zref=0. Xref and Yref were found by plugging Z=0 into equation 5c and solving for t, then plugging the value for t into equations 5a, 5b. The distance from Pi(x,y,z) to Pref(Xref, Yref, Zref) was calculated using the equation for the distance between two points in 3-dimensional space

d(Pi, Pref)=sqrt((X-Xref)^2+(Y-Yref)^2+(Z-Zref)^2) **equation 9.**

The result of this method is the spatial distribution of upper plate faults along a cross section line downdip along the detachment, relative to a reference point.