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Concentration of shearing deformation related to changes in strike of monoclinal fold axes: the Waterpocket monocline, Utah

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Abstract

Detailed field investigation of the Waterpocket monocline within the Utah portion of the Colorado Plateau reveals a strong correlation between abrupt changes in the trend of the monoclinal fold axis and enhanced fault development within the Navajo Sandstone. Faults within the bends of the fold axis range in scale from individual deformation bands to large, complex fault zones visible on 1:40,000 scale aerial photographs. Slip vectors on faults within the bends examined range from nearly pure strike-slip to subequal amounts of strike-slip and dip-slip offset. The spatial density and size of individual faults decrease rapidly away from the fold axis bends. We interpret the abrupt variations in fold axis orientations to result from segmentation of the basement faults underlying the monocline or similarly oriented bends in the basement faults. In this regard, the structures observed within the Navajo Sandstone are transfer structures developed above relay zones of the basement fault segments. The exact nature of the deformation at a given bend depends upon the geometry and kinematic history of the fault segments at depth. Variations in the proportion of strike-slip and dip-slip offset on these faults suggest that variables such as the orientation of the bend with respect to the direction of maximum compressive stress during the Laramide and details of the geometry of adjacent basement fault segments may form important controls on the nature and distribution of secondary structures in the folded strata. The results of this study highlight the need to consider along-strike variations in fold geometry in addition to considering the effects of cross-sectional fold shape when assessing fold-related fracturing.

Keywords: Monocline; Waterpocket fold; Faults; Fractures; Basement fault; Fold axis orientation

1. Introduction

Fracture patterns associated with folds have usually been studied by relating fracture type (i.e. opening mode or shearing mode) and orientation to the trend of the fold axis or local bedding strike (Price, 1959; Stearns, 1968; Ameen, 1988). An additional focus of fold-related fracturing investigations has been the relationship between fracture distribution and cross-sectional changes in fold curvature (Jamison and Stearns, 1982; Mollema, 1994). Such studies have led to the development of generalized models of fold-related fracturing which have provided a useful context for interpreting fractures found in naturally occurring folds (e.g. Hancock, 1985). However, such generalized models are not always capable of addressing the marked variation of fracture patterns often observed in natural folds. For example, recent work in the Salt Valley anticline within Arches National Park, Utah has demonstrated a highly complex fracturing history that has resulted in dramatic spatial variation of joint patterns within this anticline (Zhao and Johnson, 1992; Cruikshank and Aydin, 1995). Similarly, Lorenz and Laubach (1994) reported notable along-strike variations in fracture orientation and spacing within the Frontier Sandstone exposed along the Hogsback monocline of Wyoming. These studies demonstrate the complex nature of fracturing within folds and highlight the necessity of improving predictive models of fracturing within folded settings.

The present study considers aspects of heterogeneous fracture development exposed within the Waterpocket monocline, a Laramide-age fold within the Colorado Plateau physiographic province. The excellent exposures and relative accessibility of this fold provides the opportunity to examine variations in deformation for significant distances along strike. Our data demonstrate a strong correlation between abrupt changes in fold strike upon the concentration of faults within the Jurassic Navajo Sandstone. We begin by presenting aerial photograph interpretations and field data collected at the monocline. Subsequently, we synthesize these observations into a

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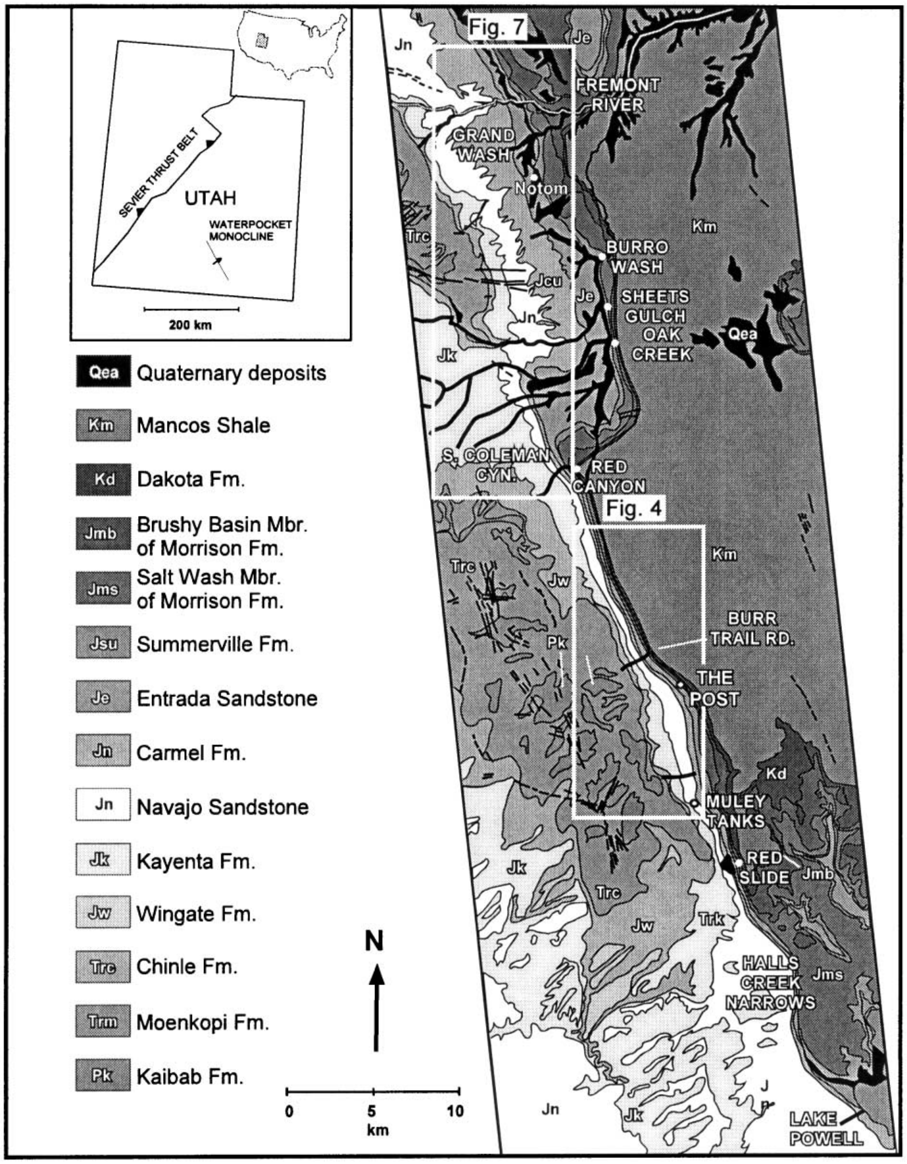

Fig. 1. Simplified geologic map of the Waterpocket monocline. Boxed areas show locations of Figs. 3 and 6. Inset shows regional location of monocline. Adapted from Hintze et al. (1964).

mechanically-based conceptual model that should provide a useful framework for interpreting certain fault patterns in other folds.

1.1. Definitions

We follow the terminology of Aydin and Johnson (1978) and Zhao and Johnson (1992) to describe structures exposed within the Navajo Sandstone. Within porous sandstones such as the Navajo Sandstone, shearing strain is accommodated through the formation of individual *deformation bands* that coalesce into *zones of deformation bands*. Increased shearing leads to the eventual development of a *slip surface* at the margin of the zone. Individual deformation bands may accommodate a few millimeters to several centimeters of slip, zones of deformation bands rarely accommodate more than several decimeters of shearing, and slip surfaces accommodate slip on the order of several meters (Aydin and Johnson, 1978). For the purposes of this paper, the term *fault* will be applied to zones of deformation bands exhibiting a slip surface. The term *fault zone* will refer to the concentration of many faults into an approximately tabular zone that may extend for up to several hundred meters along strike. Within the Navajo Sandstone exposed along the Waterpocket monocline, fault zones are commonly several meters wide and contain hundreds of individual faults. The term *joint* will refer to fractures that initially formed as opening mode features. Joints may be found individually or concentrated into clusters, or *joint zones*. We use the term *jointed fault* or *jointed deformation* *band* to refer to structures that initially formed in shear and subsequently experienced opening mode deformation along their margins. The term *faulted joint* refers to structures that initially formed in opening mode and subsequently accommodated shearing deformation (Zhao and Johnson, 1992). Similarly, faulted joint zones are complex joint zones subjected to shearing.

2. Geologic setting

2.1. Regional overview

Colorado Plateau monoclines have variously been interpreted to result from passive drape folding over basement faults undergoing vertical motions (e.g. Stearns, 1968) or to result from predominantly horizontal compression and thrust reactivation of basement faults during the Laramide orogeny (Baker, 1935; Kelley, 1955; Reches, 1978). Alternately, Yin (1994) proposed a model in which monoclines are interpreted as parasitic folds accompanying regional upwarping of the Colorado Plateau. Investigations within the Grand Canyon confirm the role of basement fault reactivation in the development of some monoclines (Huntoon and Sears, 1975; Reches, 1978; Huntoon, 1993). Davis (1978) mapped the traces of monoclines on the Colorado Plateau and interpreted the observed regular pattern of monoclines to reflect a consistently spaced network of fracture zones within the Precambrian basement.

Fission track data demonstrate that uplift of the Colorado Plateau monoclines began ~75 Ma and involved the erosional unroofing of between 1.3–4.5 km of sedimentary strata in the Grand Canyon region (Dumitru et al., 1994).

2.2. Waterpocket monocline

The Waterpocket monocline is located in southern Utah, in the Colorado Plateau physiographic province (Fig. 1, inset). A generalized stratigraphic column of southern Utah shows the major formations exposed in the fold (Fig. 2). Due to its high resistance to erosion and great thickness, the Navajo Sandstone dominates the exposures on the steep eastern limbs of the monocline. This study therefore focuses upon deformation within the Navajo Sandstone.

Early workers assigned the length of the Waterpocket monocline to extend for a total distance of about 160 km, from the Colorado River in the south to Thousand Lake Mountain in the north (e.g. Smith et al., 1963). These authors noted the existence of the southeastern terminus of the NW-trending Teasdale anticline near the vicinity of Oak Creek. Recent workers have interpreted the Teasdale anticline (or Miner's Mountain Uplift) to *replace* the Waterpocket monocline to the north of Oak Creek (Bump et al., 1997; Davis, 1999). In this interpretation, the gentle eastward dips of strata north of Oak Creek are an expression of the backlimb of the SW-vergent Miner's Mountain Uplift.

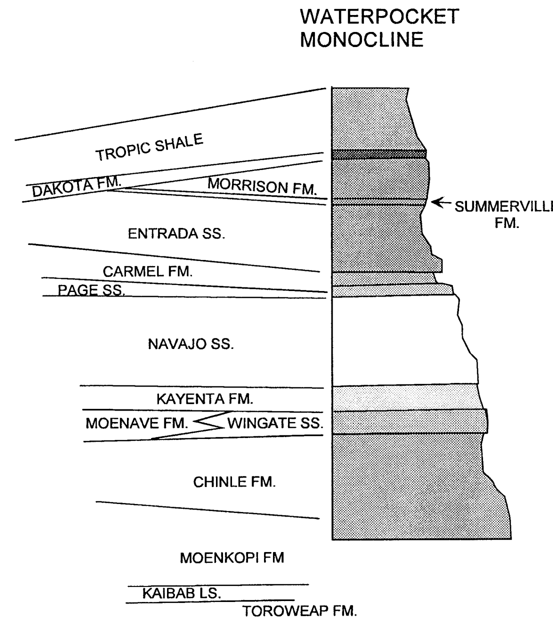

Fig. 2. Simplified stratigraphy of southern Utah. Adapted from Doelling et al. (1989).

South of Oak Creek, the Waterpocket monocline is coincident with the steep eastern limb of the Circle Cliffs Uplift, which is approximately 110 km long and 32 km wide (Kelley and Clinton, 1960). Structural relief between the Circle Cliffs Uplift and the adjacent Henry Basin ranges from 1000 to 2500 m (Kelley and Clinton, 1960). In most places, the Waterpocket monocline trends at an azimuth of about 340° (Fig. 1). Bedding dips are generally moderate, dipping east to northeast between 10 and 35° (Smith et al., 1963). Locally, bedding dips may exceed 70° (Kelley and Clinton, 1960). At several localities along the fold, bedding strikes abruptly deviate from the average orientation of 340°. These changes in strike occur along relatively short (usually less than 6 km) bends that connect two offset (clockwise or counterclockwise) segments of the fold that share similar strikes.

Kelley and Clinton (1960) utilized aerial photographs to map fracture patterns within the Colorado Plateau. They noted the predominance of fractures oblique to the axis of the Waterpocket monocline, with some regions characterized by fractures oriented parallel to the fold axis. Anderson and Barnhard (1986) inverted fault slip data collected between Cottonwood Wash and Capitol Wash and determined the direction of maximum compression during the formation of the fold in the Laramide to be at an azimuth of 068°. Davis et al. (2000) presented results of detailed mapping of conjugate strike-slip faults in the vicinity of Sheets Gulch, and postulated that these faults accommodate steep-axis bending strains induced by the shift in the monocline trace near Sheets Gulch resulting from the interaction of two blind thrust faults, one underlying the Circle Cliffs Uplift, and another coring the NW-trending Miner's Mountain Uplift.

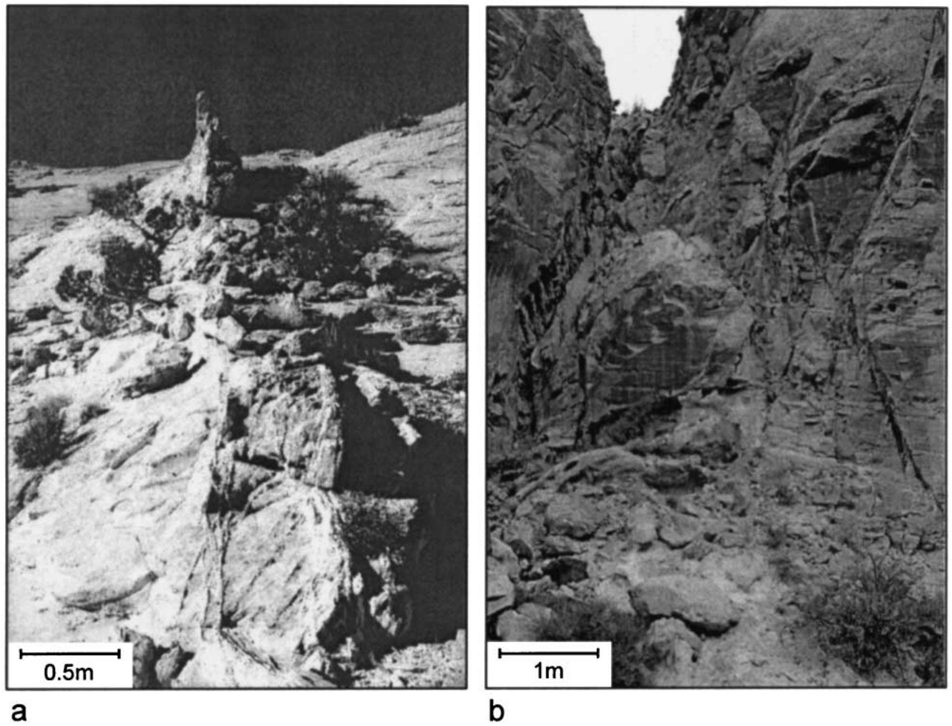

Fig. 3. Photographs of deformation band fault (a) and sheared joint zone (b), from the Waterpocket monocline. Note that whereas the deformation band fault forms a positive relief feature, the sheared joint zone erodes to form a negative relief feature. Scales shown are approximate.

3. Structural data

3.1. Methodology

The mapping strategy employed in this study consisted of interpretation of 1:40,000 scale black and white aerial photographs. These airphoto interpretations were confirmed and supplemented with field mapping using enlarged aerial photographs (1:20,000) as a base. Several detailed maps were prepared using ground-based photographs.

The final maps were constructed by digitally scanning the interpretations and linking the map segments with graphics software. Photographic distortion was reduced by using only the central part of each aerial photograph where angular distortion of the image is minimal.

Structures mapped within the Navajo Sandstone are mainly faults, joints, and joint zones. Joints and joint zones are typically expressed in airphotos as deep gullies that are commonly vegetated. In contrast, faults within the Navajo Sandstone almost always form erosionally resistant ridges (Fig. 3). The strong contrast in erosional morphology of these two types of structure is readily apparent in the three-dimensional perspective provided by stereoscopic viewing of the aerial photographs and provides the basis for differentiating faults and joints in areas that are inaccessible in the field due to rugged topography.

Although faults and joints may be easily distinguished from each other by their contrasting erosional characteristics, the aerial photograph traces of hybrid structures such as faulted joints and jointed faults strongly resemble joint zones. Thus, the classification of joint zones, faulted joints, and jointed faults can only be made through observation of these structures in the field. It should also be noted that only those structures large enough to show up distinctly at the scale of the aerial photographs are shown in the maps we present, meaning that the maps include most faults and joint zones, but not small deformation bands and individual joints.

3.2. Fault patterns along the Waterpocket monocline

Whereas the average trend of the Waterpocket monocline is about 340°, at several localities along its length the fold axis abruptly changes strike. Major strike changes, or 'bends' of the monocline axis, occur at (from north to south) Oak Creek, The Post, Muley Tanks, Halls Creek Narrows, and near the northwestern end of Halls Bay on Lake Powell (Fig. 1). We present data from the bends at The Post, Oak Creek, and Muley Tanks to ascertain the effects of rapid strike changes upon fault distribution and geometry within the folded Navajo Sandstone.

The magnitude and sense of lateral offset of the fold axis varies among these three localities. At The Post, two NNW-trending segments are offset in a counterclockwise sense by 1.5 km. North of Oak Creek, the monocline axis abruptly shifts 3 km to the east in a clockwise sense, then regains its typical NNW strike. Near Muley Tanks, another prominent

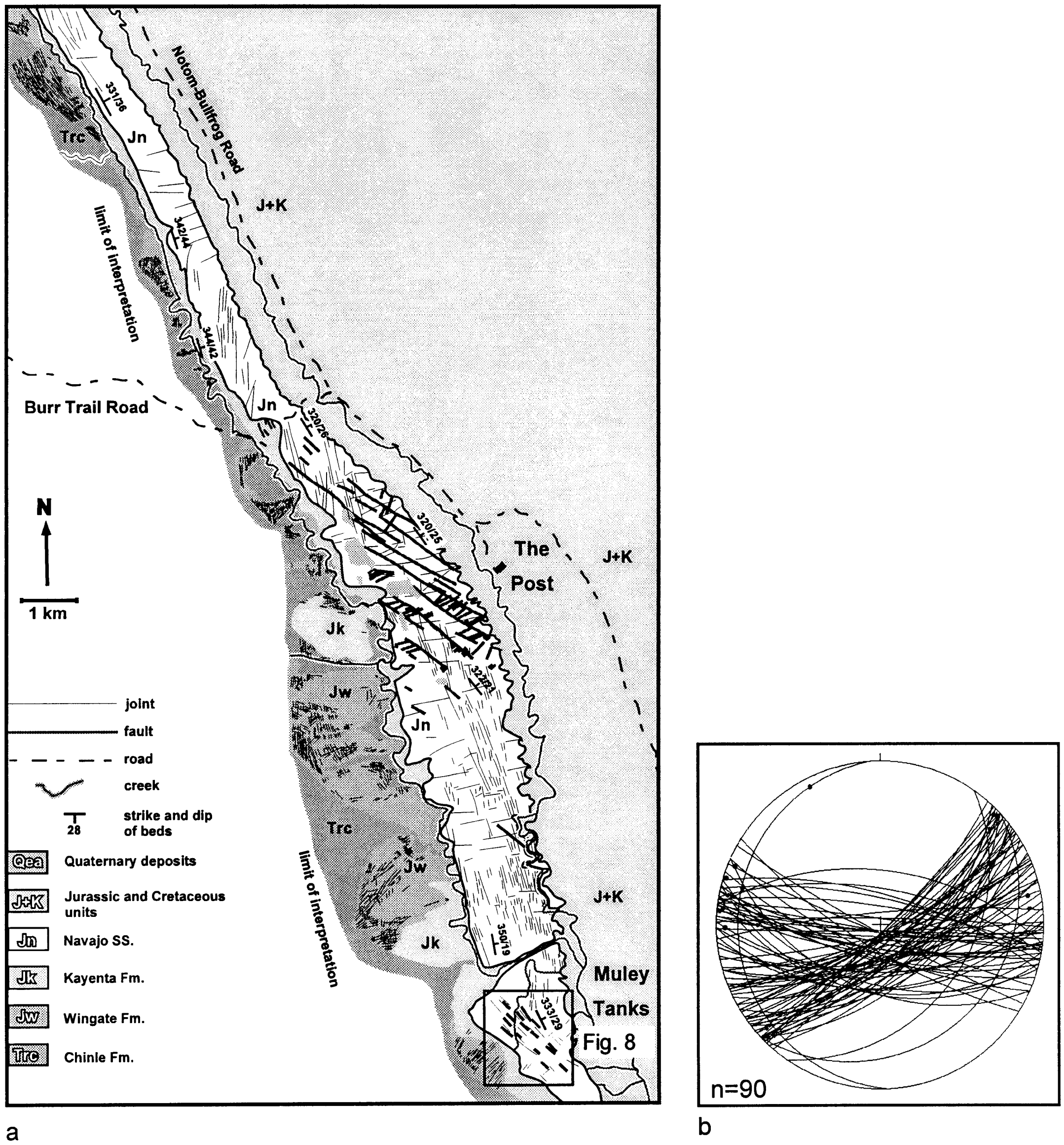

Fig. 4. (a) Airphoto interpretation of the region near The Post, Waterpocket monocline. Note concentration of faults within bent portion of monocline. Boxed area shows location of Fig. 8. Location shown in Fig. 1. (b) Stereographic projections of deformation bands and faults and slickenlines (dots) measured at this location.

counterclockwise bend in the monocline offsets two fold segments by 1.8 km.

3.2.1. The Post

A map of the region near The Post is presented in Fig. 4. Within this bend, beds of the Navajo Sandstone have an average strike of about 320°, and dip about 25° to the NE. In contrast, beds of the Navajo Sandstone south of the bend are oriented at 350°, 19° and north of the bend they are oriented at about 344°, 42°. Thus, the bend in the monoclinal axis represents a counterclockwise rotation of bedding strike by about 25° from the adjoining fold segments. Fig. 4 shows several structures of differing orientation within the Navajo Sandstone at this bend. Field investigations confirm that the numerous faint lines shown in Fig. 4 oriented approximately parallel and perpendicular to the fold are joints and joint zones, whereas the heavier lines correspond to faults and fault zones. This region is pervaded by shear-related structures that range in scale from individual deformation bands to large fault zones. In contrast, adjacent parts of the fold characterized by uniform strike exhibit irregular faulting of small slip magnitude.

Examination of the architecture of the long, NW trending fault zones in the field reveals that they consist of sub-parallel, right stepping segments. Each fault zone segment is composed of many individual faults having an average strike of 099°, which are arrayed along an azimuth of 305° (Fig. 5). Faults within this 099° set consistently exhibit left-lateral offset. Measurements of slickenline rakes on this fault set average 10° to either the NW or SE, indicating

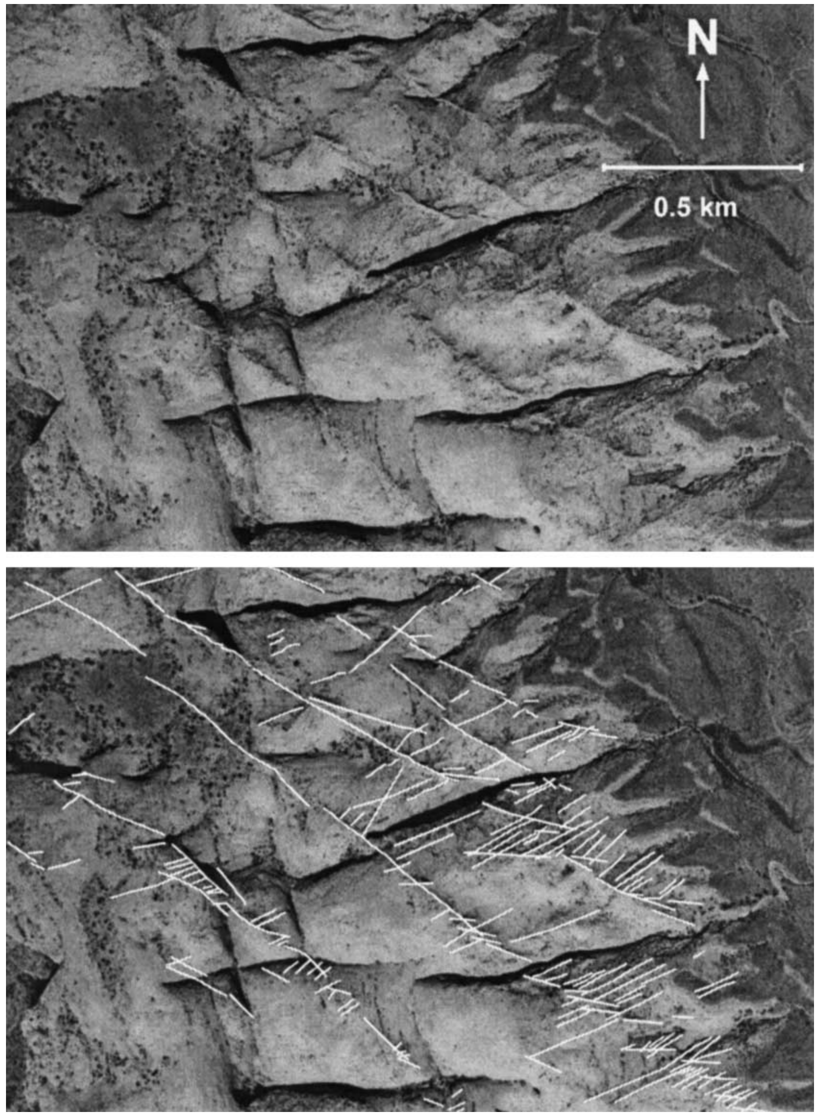

Fig. 5. Airphoto of southern portion of the bend at The Post (top). Lower photo shows interpreted fault traces. Note alignment of faults along northwest-trending zones.

minor components of dip-slip offset. Another fault set visible in Fig. 5 has an average strike of 057°. Observations of offset bedding features indicate that slip along this fault set is right-lateral. Slickenlines measured on these faults have an average rake of 6° either to the NE or SW and demonstrate that the dominant right-lateral motion was accompanied by minor dip-slip offset. These faults also are concentrated along and near the large fault zones shown in Fig. 5. However, in many cases, larger members of this right-lateral fault set extend for several tens of meters and may in some cases connect two adjacent NW-trending fault zones. Most members of the 099° and 057° fault sets have dips greater than 70°. The low rake of slickenlines on both fault sets indicates that primarily strike-slip motion occurred along these faults, with only minor amounts of dip-slip offset. Mutual offsetting relationships between members of the 057° and 099° fault sets indicate that the two sets evolved coevally.

The internal structure of the large fault zones can be quite complex; however, a smaller fault zone (Fig. 6) shows the basic structural pattern, which resembles those reported by other workers (Cruikshank et al., 1991; Johnson, 1995; Davis, 1999; Davis et al., 2000). In general, the fault zone architecture consists of two subparallel overlapping fault segments that bound a region pervaded by a second set of faults inclined to the overlapping segments. As slip accumulates on the overlapping faults, the initially simple relationships between the bounding faults and the internal faults develops into a very complex network of mutually crosscutting faults of both sets.

Direct measurement of cumulative slip along the large fault zones is difficult to estimate due to the lack of

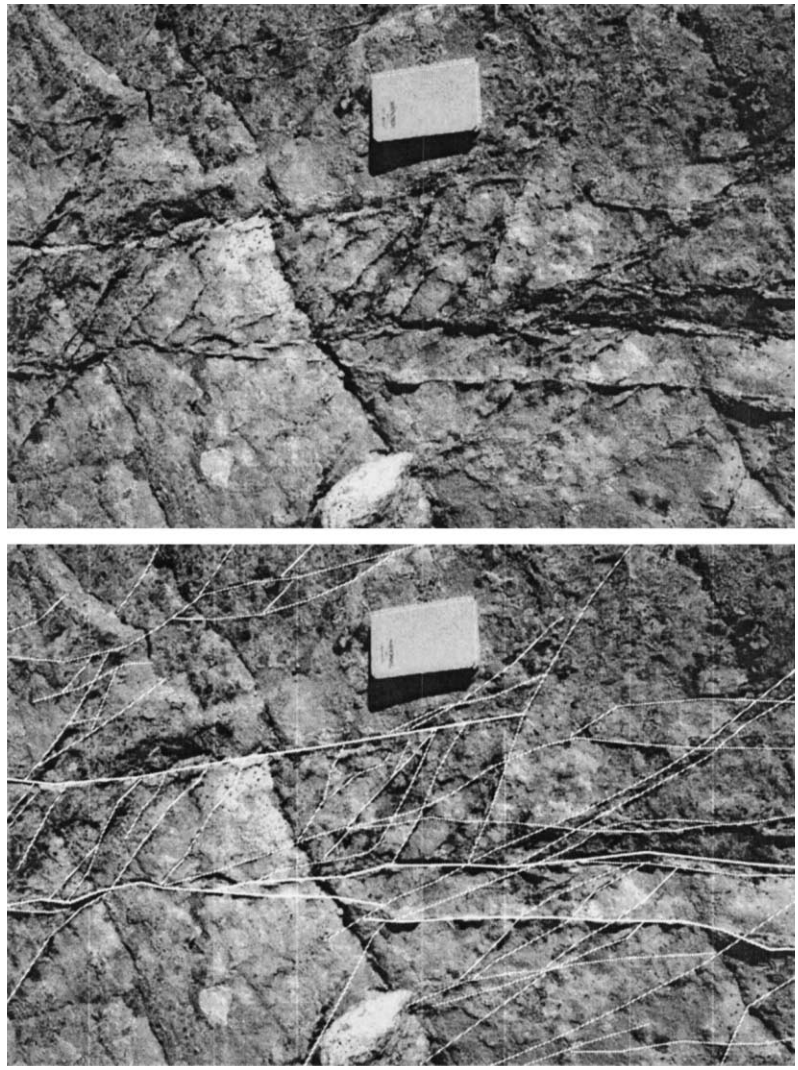

Fig. 6. Photo of overlapping faults within the Navajo Sandstone (top). Lower image shows highlighted fault traces. Note concentration of faults with different trend within overlapping region.

distinctive marker beds within the Navajo Sandstone and the steep topography created by the erosionally resistant fault zones and the surrounding Navajo Sandstone. However, it is possible to measure the offsets across the individual faults within and adjacent to the large fault zones. Slip along individual faults often ranges between approximately 10 and 40 cm. As each large fault zone is composed of tens to hundreds of smaller faults, the large fault zones probably accommodate strike-slip offsets on the order of several meters.

3.2.2. Oak Creek

A clockwise bend in the monocline axis occurs near Oak Creek (Figs. 1 and 7). Bedding attitudes within the Navajo Sandstone exposed along Oak Creek Canyon average 036°, 14°. In contrast, beds of the Navajo Sandstone in the fold segment south of the bend average 341°, 36° and immediately north of the bend average 353°, 8°. This is the most significant bend in the axis of the Waterpocket monocline, representing a change in strike of the fold axis of about 45° and an approximately 3 km eastward shift of the monoclinal axis. This is perhaps the most complex of the three bends examined, and may represent the intersection of two uplifts, rather than a simple offset of a monocline axis (Bump et al., 1997; Davis, 1999).

A map of the region surrounding the bend at Oak Creek (Fig. 7) demonstrates the high concentration of faulting in the region of the offset. Fault density declines with increasing distance from the sharp bend in the fold axis. Examination of faults in canyons perpendicular to the strike of the fold reveals that they have similar orientations and senses of slip to those observed at The Post; i.e. a set with an average strike of 060° that exhibits predominantly right-lateral slip, and a set striking at 280° having left-lateral offset. Members of both fault sets have dips ranging from about 70° to nearly vertical. Observation of offsets on these faults indicates that strike slip motions predominated, accompanied by only minor components of dip-slip offset.

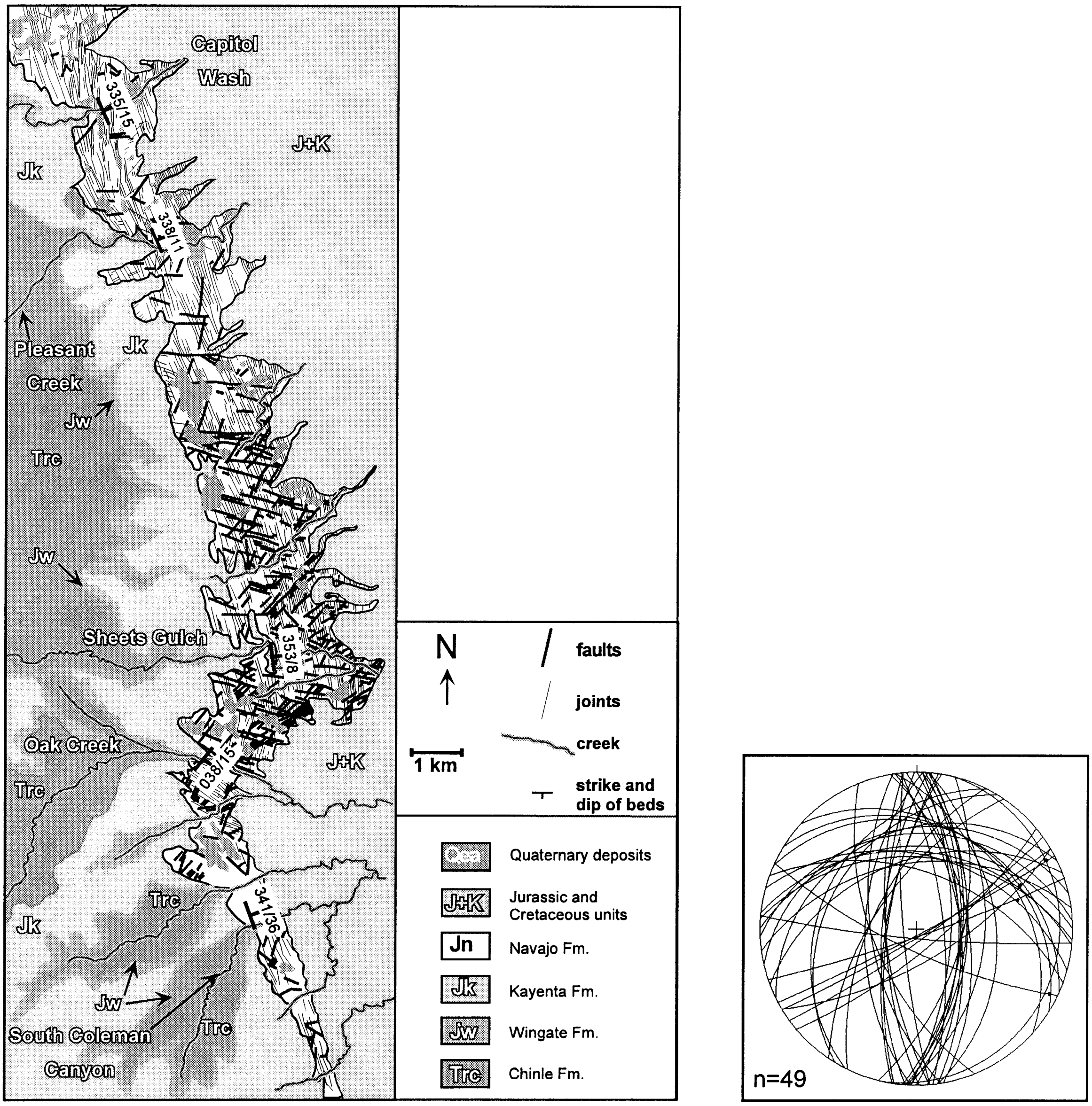

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Fig. 7. (a) Airphoto interpretation of the Oak Creek area, showing fault zones and joint zones. Location shown in Fig. 1. (b) Stereographic projections of deformation bands and faults and slickenlines (dots) measured at this location.

Where measured, slickenlines were observed to rake very shallowly. Mutual crosscutting relationships indicate that these faults formed simultaneously, in agreement with observations at The Post.

Examination of the Navajo Sandstone exposed within South Coleman Canyon (3 km south of Oak Creek) confirms the absence of faults belonging to either the 060° or 280° fault sets. All faulting observed in this canyon was related to bedding plane slip. This result is consistent with, and confirms our analysis of, aerial photographs, which shows a rapid decrease in the occurrence of faults of the 060° and 280° sets south of Oak Creek.

Observations within Sheets Gulch divulge the presence of a third set of faults in this area. This fault set strikes approximately north and dips steeply. Individual members of this fault set exhibit up to several centimeters of normal slip. Steeply raking slickenlines indicate that these faults primarily accommodated dip-slip motion. These faults frequently serve as the nucleation sites for later-formed joint zones, which also strike approximately parallel to the monocline axis. These joint zones commonly display evidence of slip, indicated by small-scale offsets of bedding laminae and the presence of secondary joints that indicate a normal sense of shear along the earlier joints. Delineation of these faults on the aerial photograph interpretation in Fig. 7 is precluded by their thin width and/or subsequent involvement in jointing deformation, which imparts a similar erosional morphology to that characteristic of joint zones.

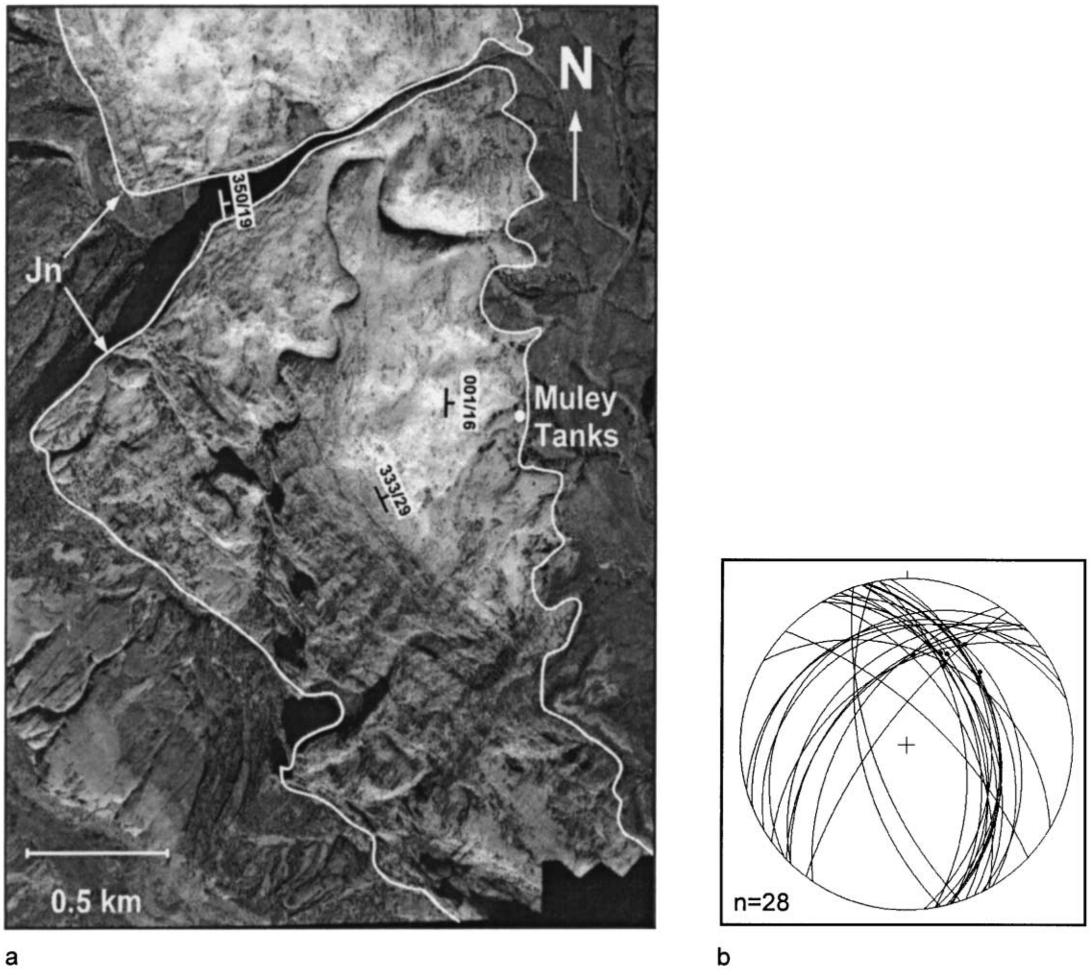

Fig. 8. (a) Airphoto of the Muley Tanks region. Note the difference in deformation between the northern and southern parts of the photograph. WNW -trending lineations in the SW extent of exposed Navajo Sandstone are joint zones and oblique-slip faults. (b) Stereographic projections of deformation bands and faults and slickenlines (dots) measured at this location.

3.2.3. Muley Tanks

A third bend in the Waterpocket monocline occurs south of The Post, near Muley Tanks (Fig. 1). Here, the monoclinal axis is shifted approximately 1.8 km to the west in a counterclockwise bend. This locality provides an opportunity to compare the deformation patterns within the Navajo Sandstone across the transition zone between a region characteristic of straight segments of the monocline and an area dominated by deformation related to a bend in the fold axis. In contrast to the bends at The Post and Oak Creek, the Navajo Sandstone exposed within this bend is not characterized by a diffuse zone of conjugate faulting. Instead, faulting is concentrated in a narrow belt within the Navajo Sandstone (Fig. 4, boxed area; Fig. 8) corresponding to an area of rapidly changing dips. This deformation primarily consists of joint zones and east-dipping oblique-slip faults. Both types of structure are oriented subparallel to the strike of bedding within the bend.

The easternmost outcrops of Navajo Sandstone at Muley Tanks consist of a large expanse of relatively undeformed sandstone that has an average bedding attitude of 001°, 16°. Within this mass of rock, deformation primarily consists of steeply dipping joint zones striking approximately 170° and deformation bands localized along slipped dune boundaries (Fig. 8).

This part of the Muley Tanks area thus reflects the southern continuation of the deformation style characteristic of the fold segment south of the bend at The Post (Fig. 4). Progressing westward, bedding strikes gradually rotate counterclockwise and dips increase such that bedding attitudes adjacent to the zone of jointing and faulting averages 333°, 29°. Faults measured in this area have an average orientation of 341°, 51° and exhibit normal displacements ranging from a few centimeters to about one meter. The average slickenline orientations of these faults measures 58° to the NW, indicating that the predominantly normal slip on these faults was accompanied by a lesser component of left-lateral motion. Examination of aerial photographs reveals that this belt of faulting and jointing deformation persists for several kilometers to the south.

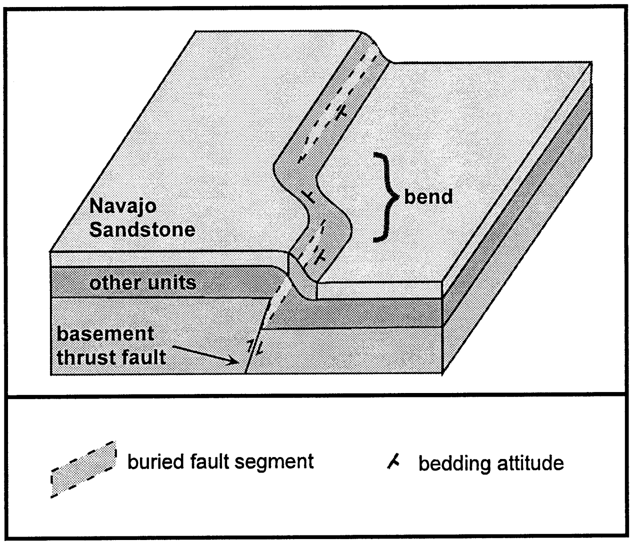

Fig. 9. Conceptual model of monocline axis bends related to a stepping basement fault geometry.

Thereafter, the fold resumes a more northerly trend and lacks the intense deformation characteristic of the bend.

4. Discussion

The structural maps and airphoto interpretations presented from the Waterpocket monocline demonstrate the spatial correlation between the density of deformation band faulting within the Navajo Formation and abrupt changes in strike, or bends, of the monoclinal axis (Figs. 4, 7 and 8). Three well-exposed bends within the Waterpocket monocline exhibit enhanced faulting in the vicinity of the bends. The bends at The Post and Oak Creek are characterized by faults with strongly lateral slip vectors, whereas the bend at Muley Tanks contains faults with a significant normal slip component and a subsidiary component of left-lateral slip.

Observations of other monoclines together with modeling results demonstrates that bends in fold traces may result from a stepping basement fault geometry (Shamir and Eyal, 1995). We thus interpret the observed sinuosity of the shape of the Waterpocket monocline to result from variations in the geometry of the underlying basement fault system. Bends in the fold axis are interpreted to result from steps in the segmented basement fault system, as shown schematically in Fig. 9.

Within the bends examined at the Waterpocket monocline, secondary fault sets oriented oblique to the overall orientation of the fold axis form dense networks in the Navajo Sandstone. This faulting may in some cases extend for several kilometers into the adjacent segments of the fold; however, there is a distinct reduction in fault density with increasing distance from the bends. Examination of aerial photographs reveals that straight segments of the folds far from bends lack well-developed deformation band fault sets of similar orientation and development to those found within the bends. Field investigation of these straight parts of the fold verifies that deformation is dominated by joint zones, faulted joints, and bedding plane faults.

Variations in the patterns of secondary faulting within the Navajo Sandstone at the bends examined in this study most likely result from differences in the geometry of the

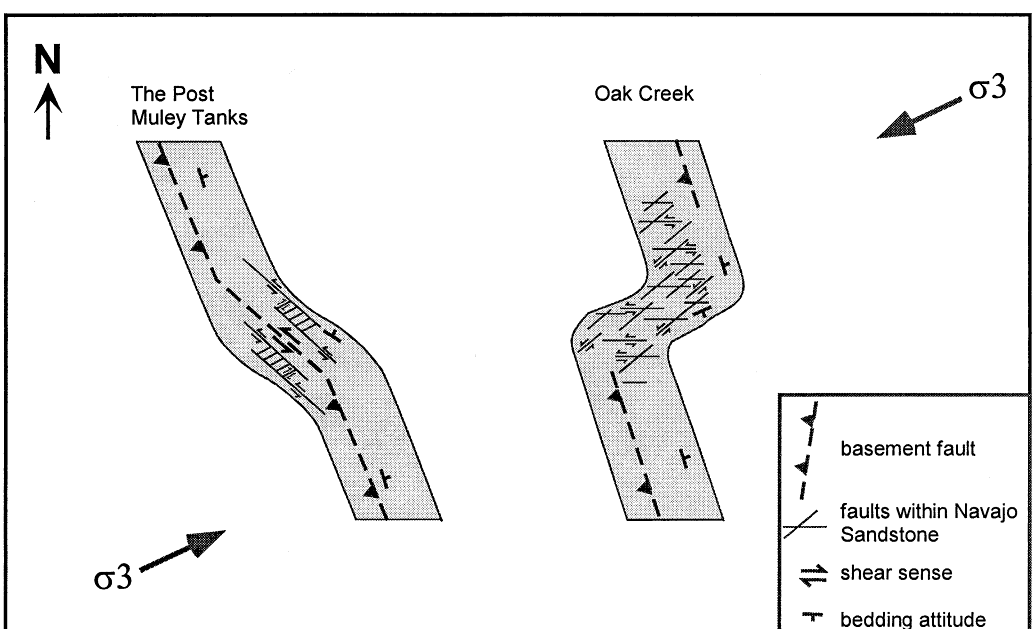

Fig. 10. Generalized diagrams of bends in monocline axes, showing configuration of inferred basement fault segments and the observed kinematics of faults within the Navajo Sandstone. Arrows show the interpreted direction of the maximum compression ($\sigma 3$) during the Laramide, oriented at an azimuth of 065°.

basement fault system underlying the monocline at each of these bends. Simplified representations of the two basic patterns of faulting related to bends in the monocline axis encountered in this study are shown in Fig. 10, which includes our interpretation of the basement fault geometry associated with each pattern.

Faulting deformation at The Post is dominated by a series of large fault zones that trend at an orientation of 305°, subparallel to the strike of bedding within the bend, which averages 320° (Figs. 4 and 5). These fault zones contain many individual left-lateral strike-slip faults that strike at an average orientation of 099°. A set of right-lateral strike-slip faults with an average strike of 057° is also present at The Post; however, members of this fault set are observed to have less offset than the 099° set.

The greater development of NW-trending fault zones as compared with the NE-trending faults also present at The Post (Figs. 4 and 5) may indicate the presence of a NW-trending basement fault that links the major basement fault segments north and south of the bend. Straight segments of the Waterpocket monocline are oriented approximately normal to the inferred Laramide maximum compression direction of 065° (Reches, 1978; Anderson and Barnhard, 1986). Therefore, basement faults underlying straight segments of the Waterpocket monocline are likely to have experienced primarily reverse motion. Subject to the same stress field, NW-trending basement fault segments would have resolved upon them a component of left-lateral slip in addition to the reverse component. The enhanced development of NW-trending fault zones at The Post may thus reflect the influence of a basement fault segment that links the basement faults north and south of the bend and experienced left-lateral slip.

The orientation of faulting concentrated near the bend at Muley Tanks also strikes subparallel to bedding within the bend. Well-developed faults have an average strike of about 337° and dip 50° to the NE; the beds near the zone of deformation at the bend near Muley Tanks strike at about 333° and dip 29° to the NE. Slickenlines measured on these faults indicate that they accommodated a greater component of normal slip than left-lateral strike slip. Faults and deformation bands of small offset have an average strike of 228° and dip 46° to the NW. The increased component of normal slip on these faults is likely the result of increased extensional stresses resulting from a relatively rapid change of bedding dip at this location as compared with The Post and Oak Creek.

The bend at Oak Creek exhibits two prominent fault sets within the folded Navajo Sandstone, both of which show similar offset magnitudes (Figs. 7 and 10). One set strikes about 060° and exhibits right-lateral offset; the other strikes at about 280° and exhibits left-lateral offset. The two fault sets appear to be subequally developed, in contrast to the bend at The Post where left-lateral faults are better developed than right-lateral faults. A third fault set is not represented in Fig. 7, because of its orientation subparallel to the major joint set in this area. Fieldwork shows that this fault set is oriented N–S and consistently exhibits normal slip with only a minor lateral slip component.

There is a strong asymmetry of fault distribution north and south of the bend at Oak Creek (Fig. 7). To the south of Oak Creek, the fault sets extend for only a short distance; to the north there is a large area pervaded by faults of both sets. Farther north, there is a distinct lack of faults belonging to either set.

The bend at Oak Creek is perhaps the most complex of the three examined in this study. Recent workers have attributed the faulting deformation at this site to the interference between two uplifts rather than a bend within a single monocline (Bump et al., 1997; Davis, 1999). In this interpretation, the Circle Cliffs Uplift/Waterpocket monocline to the south is replaced by the SW-vergent Miner's Mountain Uplift to the north, and the observed eastward dip of strata north of Oak Creek represents the gently sloping backlimb of the Miner's Mountain Uplift. This interpretation may help explain the very large area of faulting observed at this locality as compared with the bends at The Post and Muley Tanks.

4.1. Comparison with mechanical modeling results

4.1.1. Relationship between monoclinal fold shape and basement fault geometry

Shamir and Eyal (1995) modeled the elastic strain field above dislocation planes embedded in a homogeneous elastic half-space in order to simulate the interactions between adjacent monoclines observed in Israel. The geometries of reverse fault segments in the subsurface were inferred from map traces of monoclines and imposed model displacements were scaled relative to the observed structural relief on each of the monoclines. The upper tips of the model faults were set at 1 km depth. The results of this study suggest that basement fault segmentation is responsible for the variations in monoclinal axis trends as observed in regional maps. Specific factors shown to have important effects on monoclinal fold shape include the amount of overlap and separation of adjacent basement fault segments, as well as along-strike and down-dip-slip gradients.

The results of this study support our interpretation that the sinuous map traces of the Waterpocket monocline result from segmentation of the basement fault systems that underlie them. The geometry of the basement fault system is difficult to estimate in the absence of subsurface data and remains uncertain. If our inferences concerning basement fault geometry as illustrated in Fig. 10 are reasonable, then it is possible to interpret the concentrated faulting at bends in monoclines as transfer structures at fault relays.

4.1.2. Generation of secondary structures within overstep regions between faults

If the bends of the monoclinal axes at the Waterpocket

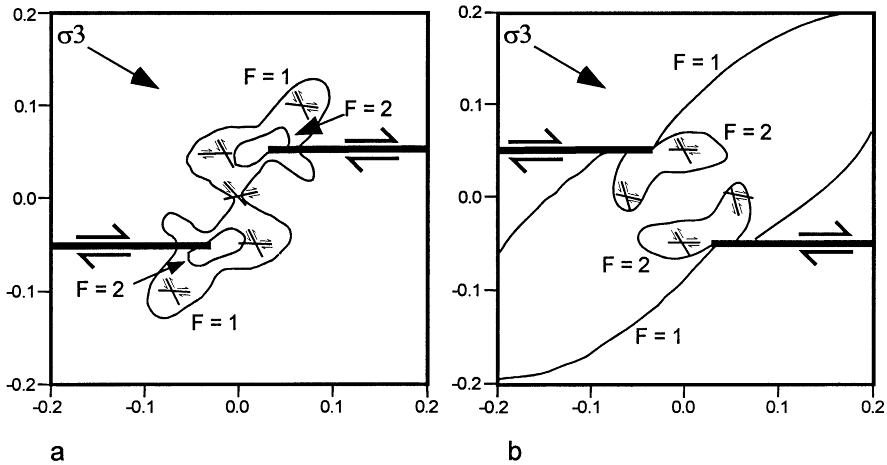

Fig. 11. Shear failure tendency (*F*) contoured for the case of: (a) left-stepping cracks, and (b) right-stepping cracks subjected to right-lateral shearing. Shear failure is expected in regions where $F > 1$. After Segall and Pollard (1980).

monocline results from a segmented and stepping basement fault geometry, then it follows that the presence of secondary faulting localized within these bends may result from mechanical interaction among the underlying basement fault segments. Segall and Pollard (1980) presented a two-dimensional model of échelon cracks subjected to lateral shearing and investigated various mechanical consequences of the interaction between such cracks. Of particular interest in the context of the present study is the concentration of shearing stresses in the vicinity of stepping, échelon cracks (Fig. 11). In the diagram, contours of a Coulomb shear failure condition are shown as applied to a granitic rock containing two échelon cracks subjected to right-lateral shearing. For the case of a left-stepping pair of cracks subjected to right-lateral shear (i.e. a compressional step; Fig. 11a), shear failure is predicted to be strongly localized in the immediate vicinity of the crack tips and to favor the formation of faults with a reverse component of shear. The enhancement of shear failure due to crack interaction rapidly decreases away from the crack tips. In contrast, for a right-stepping pair of cracks undergoing right-lateral shear (Fig. 11b), interaction between adjacent cracks enhances the likelihood of shear failure in a very broad region surrounding the crack tips. Stresses in this extensional step would be expected to favor the formation of faults with a normal component of slip. In both cases, the importance of the interaction between adjacent discontinuities in enhancing the formation of secondary structures in the region of the step is clear.

We interpret the enhanced faulting observed at bends in the axis of the Waterpocket monocline to result from similar interactions between adjacent basement fault segments coring the monoclines. In this respect, the bends are similar to relay zones and the faulting characteristic of the bends are analogous to relay structures. Although the relationships shown in Fig. 11 are derived from a two-dimensional analysis of strike-slip discontinuities, we expect that the importance of mechanical interaction between adjacent shear discontinuities is also relevant to the case of flexure of strata above buried basement fault segments. Other factors (e.g. the dips of adjacent fault segments, depths to the upper fault tips for each fault segment, linkage structures connecting fault segments) are also likely to affect the deformation observed within the folded layers.

5. Conclusions

Our study demonstrates a strong correlation between rapid changes in fold strike and increases in deformation band fault density within the Waterpocket monocline of the Colorado Plateau. We interpret these abrupt changes in strike of the fold axis, or bends, to result from segmentation of the fault system underlying the monocline, or similarly oriented bends within a single basement fault. This configuration is similar to relay or transfer structures associated with segmented faults. The nature of the secondary faults at the relay structures is interpreted to reflect variations in the geometry and kinematics of the main fault segments. We propose several possible arrangements of basement fault geometries that may account for the deformation observed at the bends within the Waterpocket monocline. In some cases, the dominant fault set within a bend is aligned subparallel to the orientation of the bend, suggesting that an obliquely oriented basement fault segment may underlie the bends and link the basement fault segments north and south of the bend. At other bends, fault sets of differing orientations are broadly distributed and subequally developed. Although the details of fault distribution and kinematics vary, our data suggest that local stress perturbations related to bends in fold axes may provide a mechanism for the formation of certain fault sets of limited along-strike extent within folds.

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