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Center for Nuclear Waste Regulatory Analyses

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April 29, 1997
Contract No. NRC-02-93-005
Account No. 20-5708-471

U.S. Nuclear Regulatory Commission
ATTN: Shirley L. Fortuna
Office of Nuclear Material Safety and Safeguards
Two White Flint North
Mail Stop 8 A23
Washington, DC 20555

Dear Mrs. Fortuna:

The purpose of this letter is to transmit the enclosed manuscript, "Extensional Layer-Parallel Shear and Normal Faulting" (IM 20-5708-471-722). The manuscript documents the occurrence of bedding parallel deformation in a system of normal faults near the Gold Ace Mine on the southwest flank of Bare Mountain. Slip tendency analysis indicates that as slip occurs on listric faults, the faults are rotated to lower dips, causing them to become increasing less likely to slip. However, because the bedding is rotated to a higher angle of dip, bedding-parallel shear becomes more likely. We plan to submit this manuscript for publication in the Journal of Structural Geology.

If you have any questions please contact Dr. David Ferrill at (210) 522-6082 or me at (210) 522-5252.

Sincerely,

Budhi Sagar
Technical Director

/adm

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Extensional layer-parallel shear and normal faulting

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Abstract-An extensional fault system in Bare Mountain, Nevada, contains abundant evidence of layer-parallel shear deformation contemporaneous with faulting. Layer-parallel shear is manifest by deformation of pre-existing fabrics such as teeth on bedding-parallel stylolites and shape fabrics in fossiliferous and oolitic limestone that all indicate shear in the down-dip direction, perpendicular to fault-bedding intersections. Cleavage at a low angle to bedding has the same vergence, indicating development and/or modification during shear parallel to bedding with a down-dip sense. Localized layer-parallel shear along discrete bedding planes has locally offset normal faults, and shear distributed within layers has reoriented block-bounding normal faults. These observations of internal deformation within fault blocks indicate that layer-parallel shear contributes to fault block deformation. In simple rigid-block models of extension accommodated by normal faults above a low-angle detachment or décollement zone, extension causes faults to rotate to progressively lower dips, while originally horizontal beds rotate to steeper dips. These rotations reorient faults away from originally optimum conditions for slip

into orientations of a lower slip tendency, whereas bedding rotates to steeper dips with progressively higher slip tendency. The occurrence of layer-parallel shear depends on the presence of weak strata or mechanical anisotropy within fault blocks. The timing or amount of rotation before the initiation of layer-parallel shear is dependent on the frictional resistance to sliding or resistance to shearing within layering in fault blocks. Offset or deflection of block-bounding normal faults may cause faults to lock as extension increases. Alternatively, bedding and faults may become simultaneously active, progressively lowering dips of faults and bedding until neither is well oriented for slip, at which point new faults will be required to accomplish additional extension. At Bare Mountain, early extension within the fault system was accomplished by fault slip and associated block rotation. Continued extension was accomplished by slip along bedding within fault blocks.

INTRODUCTION

Extensional imbricate fault systems consisting of several nearly parallel normal faults ("domino" or "bookshelf" faulting) are relatively common in regions of extensional deformation. Examples include unlithified sedimentary strata in the Gulf of Mexico (Diegel *et al.*, 1995), sedimentary strata in the North Sea (Rouby *et al.*, 1996), and sedimentary and volcanic strata in the Basin and Range Province (Anderson, 1971; Wernicke and Burchfiel, 1982; Maldonado, 1990). The linkage of displacement in these systems is either by faults merging downward into a low-angle detachment, or by transfer of fault displacement downward into a thick décollement zone (Fig. 1; Brun and Choukroune, 1983). Typically, faults in extensional imbricate systems are assumed to form with steep dips (around 60°) representing optimal failure orientations in a normal faulting stress regime. It is commonly assumed that fault blocks rotate rigidly with negligible internal deformation (e.g., Wernicke and Burchfiel, 1982).

Other deformation mechanisms assumed to operate in extensional settings are vertical simple shear and oblique simple shear (e.g., Dula, 1990; Groshong, 1990), which assume constant thickness parallel to the shear direction, and layer-parallel shear, which assumes constant bed length and thickness (Ferrill and Morris, in press). Vertical and oblique simple shear algorithms are the most widely used in cross-section construction and restoration, although

Higgs *et al.* (1991) recognized evidence of layer-parallel simple shear associated with natural extensional faulting.

In this paper, we study an imbricate fault system exposed in profile in Bare Mountain, Nevada, in the western Basin and Range. Fault blocks in this system display a variety of structures indicating internal deformation by layer-parallel shear with a top-towards-the-fault, down-dip sense of shear during faulting. We use slip tendency analysis (Morris *et al.*, 1996) to interpret the sequence of deformation during fault displacement and find that slip tendency analysis can account for the structural style observed at Bare Mountain. Based on field observations and geometrical considerations, we describe five characteristics of layer-parallel shear in extensional fault systems: (1) Extensional layer-parallel shear is characterized by a down-dip sense of shear, opposite to that observed in contractional structures; (2) Extensional layer-parallel shear is non-uniformly distributed and weak layers or layer boundaries tend to concentrate shear strain, like layer-parallel shear in compressional settings (e.g., Ferrill and Dunne, 1989); (3) Increasing extension and steepening of stratal dips in extensional fault blocks tends to increase down-dip shear relative to slip on faults; (4) Increasing extension may rotate faults and fault blocks into orientations that are more favorable for layer-parallel shear and less favorable for fault slip; (5) Extensional layer-parallel shear rotates layering in fault blocks to lower dips.

EFFECTS OF STRESS FIELD ON PROGRESSIVE DEFORMATION

Early models of imbricate normal faulting treated fault blocks as rigid bodies that progressively rotate during deformation (Wernicke and Burchfiel, 1982). Initially, layering may be horizontal and faults steeply dipping. In a typical normal faulting stress regime, where the maximum principal compressive stress (σ_1) is vertical, the resolved normal stress (σ_n) on horizontal bedding is equal to σ_1, and resolved shear stress (τ) is zero. Therefore, initial slip tendency (τ/σ_n) for horizontal bedding is zero. In contrast, high angle normal faults have large resolved shear stress and small resolved normal stress. Therefore, slip tendency of high angle normal faults is initially at or near the maximum possible slip tendency in the stress field.

As fault blocks rotate with progressive extension, bedding rotates to steeper dips and faults rotate to gentler dips. Therefore, slip tendency for bedding increases and slip tendency for faults decreases with increasing extension and block rotation. If the frictional resistance to sliding (μ) was equal on faults and bedding, then slip on bedding would be expected to accommodate extension as bedding rotated to dip more steeply than faults. For example, if we assume that faults initiate at 60° in horizontal strata, frictional resistance to sliding is equal for bedding and faults, and initially fault blocks rotate rigidly, then slip tendency would be equal for faults and bedding when faults and bedding both dip at 30° (Fig. 2). As extension continues, slip on the normal faults rotates faults to lower dips, and down-dip slip on bedding rotates bedding to lower dips within fault blocks. At large extensions, neither faults nor bedding are likely to be appropriately oriented for slip, at which time new faults may form to accommodate additional extension (Ramsay and Huber, 1987).

The actual occurrence of slip on a fault or bedding horizon depends on frictional resistance to sliding and cohesion on the surface, and any complications such as intersections of surfaces that might cause locking. In some cases, resistance to sliding on bedding or shear within layers may be lower than frictional resistance to sliding on faults, because of presence of weak horizons or layers that slip or plastically deform easily. Therefore, weak horizons and layers may slip or shear at relatively low slip tendency.

EXTENSIONAL FAULTING AT BARE MOUNTAIN, NEVADA

Bare Mountain is an uplifted block of Precambrian and Paleozoic strata exposed in southwestern Nevada (Fig. 3). The block is bounded on the east by the Bare Mountain fault, a steep east dipping normal fault that has been active since the Middle Miocene (e.g., Ferrill *et al.*, 1996; 1997). Bare Mountain is also in the footwall of the Fluorspar Canyon/Bullfrog Hills Detachment system that was also active during the Middle Miocene (Maldonado, 1990). Lateral variations of stratigraphic age and metamorphism of exposed strata, and pre-Middle Miocene (Oligocene?) structures exposed in the central part of Bare Mountain indicate a northeastward plunge for major structural elements of the range. Consequently the steep southwestern flank of the mountain now exposes a profile nearly perpendicular to the plunge of the range. This profile reveals a pre-Middle Miocene extensional fault system consisting of presently east-dipping normal faults (Fig. 4), which we interpret as an original southeast dipping fault system that was subsequently rotated to its present orientation during later Tertiary northeast tilting of the Bare Mountain block. Of these normal faults, the Gold Ace Mine fault has the largest displacement with nearly 3 km of offset. An outcrop of the hanging wall of the Gold Ace Mine fault exposes a meso-scale extensional imbricate fault system (Fig. 4) consisting of east-dipping normal faults that offset north-dipping Cambrian limestones and dolomites. Bedding-fault intersections plunge northeast. Faults are approximately 10 to 100 m apart with displacements of 5 to 75 m.

Strata in the Gold Ace Mine exposure are dominantly Papoose Lake Member of the Bonanza King Formation and consist of white to dark gray limestone and dolomite with sparse intercalated yellowish-orange silty and sandy beds (Monsen *et al.*, 1992). The lowermost part of the outcrop exposes the basal contact of the Bonanza King Formation, and medium-gray limestone of the upper part of the Carrara Formation. High-amplitude bedding-parallel stylolites are common within fault blocks and frequently exhibit layer-parallel shear with a down-dip sense (top toward the underlying fault). Other indicators of layer-parallel shear within the fault blocks include layer-oblique cleavage (in argillaceous limestones) and thin localized slip surfaces (at bed boundaries) that offset pre-existing structures (Fig. 5a). Shear is not evenly distributed throughout the stratigraphic sequence, but is localized within certain zones such as contacts between relatively stiff sandy or silty beds and weaker limestone beds (e.g. Fig. 5b). Some sheared layers and slipped bedding horizons clearly deflect or offset block-bounding normal faults (Fig. 5b), indicating that layer-parallel shear post-dates slip on at least some of the normal faults. In thin section, these slip surfaces are recognized as anastomosing systems of discrete slip surfaces that bound lenticular zones of wall rock material. Sandy and silty beds appear in thin section to be nearly undeformed, whereas limestones are nearly completely recrystallized and commonly define a penetrative grain-scale shape fabric oblique to bedding that verges in the down-dip direction. Similarly, fossiliferous and oolitic limestone beds are seen in thin sections to be nearly completely recrystallized, and in hand sample display a shape fabric consistent with a down-dip shear sense. Spaced cleavage at a low angle ($<45°$) to bedding, in rare thin argillaceous limestone beds, also verges in the down-dip direction, which suggests pressure solution during down-dip layer-parallel shear. Here, we evaluate the described pattern of fault slip and internal deformation in the context of the stress field and resolved stresses on faults and bedding during fault system development. Material yield strength, frictional resistance to sliding, and juxtaposition of layers across faults control layer-parallel shear in extensional imbricate fault systems.

SLIP TENDENCY ANALYSIS OF FAULTS AT BARE MOUNTAIN

The Gold Ace Mine exposure (shown in Fig. 4) was mapped using a plane table and alidade to provide detailed geometric constraints for the fault system. Fault and bedding orientations were collected throughout the mapped area and were used to define the plunge of the fault/bedding intersection at the exposure (Fig. 4b). A plunge-perpendicular cross section was then generated by projecting all structural data onto a plane normal to the fault-bedding intersection line (Fig. 6). In this cross section, faults dip 20° to 65° to the southeast, and bedding dips 15° to 65° to the northwest. We consider this cross section to represent the fault system geometry at the end of its period of activity and prior to the northeast tilting of the Bare Mountain block.

The *pattern* of relative slip tendency is sensitive to orientations and relative magnitudes of the principal stresses that define the stress tensor, and less sensitive to the actual magnitudes of the principal stresses. Here we have no detailed constraints on the stress field during faulting. For the analysis, we assume that the paleo-stress magnitudes in which the fault system developed were analogous to the contemporary normal faulting stress field in the region (discussed by Morris *et al.*, 1996), and that the faults originated striking parallel to the intermediate principal stress, which is typical of normal faulting stress regimes. We expect this stress field to realistically model the *pattern* of slip tendency in the fault system, which is the primary focus of this analysis.

The analysis indicates that slip tendency for both faults and bedding was near maximum in parts of the fault system late in its development (Fig. 6). This is consistent with the mesostructural relationships which show layer-parallel shear deformation synchronous and subsequent to normal faulting. Thus, this fault system evolved to a point where bedding was appropriately oriented to accommodate a component of the slip and/or shear required for continued extension. However, the variation of fault and bedding dips in the exposure produces considerable variation in slip tendency, suggesting that layer-parallel shear might be expected only in certain fault blocks or parts of fault blocks where slip tendency was highest. Instead, we find evidence of layer parallel shear in virtually all fault blocks, even where modeled slip tendency on bedding is low to moderate, which indicates that bedding was relatively weak and underwent shear even at low to moderate slip tendency.

DISCUSSION

The role of fault block rigid rotation versus block deformation by layer-parallel shear is largely governed by material properties of fault block strata. Isotropic strong fault blocks are likely to rigidly rotate without internal deformation, whereas isotropic weak fault blocks with a penetrative bedding fabric are more likely to deform uniformly by layer-parallel shear (Fig. 7). For layer-parallel shear to occur within an anisotropic stratigraphic sequence cut by an imbricate normal fault system, two conditions must be met. Slip tendency on layering must overcome frictional resistance to sliding and or yield strength, and relatively weak layers (those poised for slip or shear) must align across faults with similarly poised layers so that slip can be transferred across faults (Fig. 5b, Fig. 7). Such localized displacement is expected to offset or deflect faults, which in either case will tend to increase resistance to sliding on faults, or cause faults to lock. For a more isotropic sequence of weak strata, shear within the sequence will lower the dip of the host faults, thereby decreasing slip tendency. Extensional layer-parallel shear also decreases bedding cutoff angles and increases down-dip fault length. In contrast, a strong stratigraphic sequence, or one lacking a strong layering anisotropy and irregular, welded layer contacts and generally weak faults (compared with layer yield strength and frictional resistance to sliding), will result in steeply tilted layers resting on a low angle detachment.

Layer-parallel shear at the Gold Ace Mine exposure at Bare Mountain, Nevada, is non-uniformly distributed. Shear is dependent on lithology and the juxtaposition of layers across faults. Competency contrasts at layer boundaries, such as between sandy or silty carbonate beds and limestone, localized slip along discrete surfaces at bed boundaries. Limestone beds accommodated layer-parallel shear by grain scale ductile flow which deformed primary sedimentary fabrics and early compactional stylolites. Argillaceous limestone beds accomplished shear by grain scale ductile flow and some component of pressure solution which developed cleavage at low angles to bedding. Evidence of layer parallel shear in beds that have relatively low modeled slip tendency suggests that beds are relatively weak and, therefore, slip or shear easily (at a low slip tendency). Also, late bedding parallel shear may have initiated under conditions of higher slip tendency on bedding (at steeper dip) and layer-parallel shear lowered bedding dip during progressive deformation.

CONCLUSIONS

Models of extensional faulting that include significant mechanical contrast within fault blocks predict down-dip shear in rotated normal fault blocks, especially late during progressive deformation. Down-dip shear may be mechanically preferred over fault displacement in highly extended imbricate fault systems. Field observations from Bare Mountain, Nevada, indicate that down-dip layer-parallel shear was an important mechanism of fault block deformation during extensional faulting that may have caused faults to lock.

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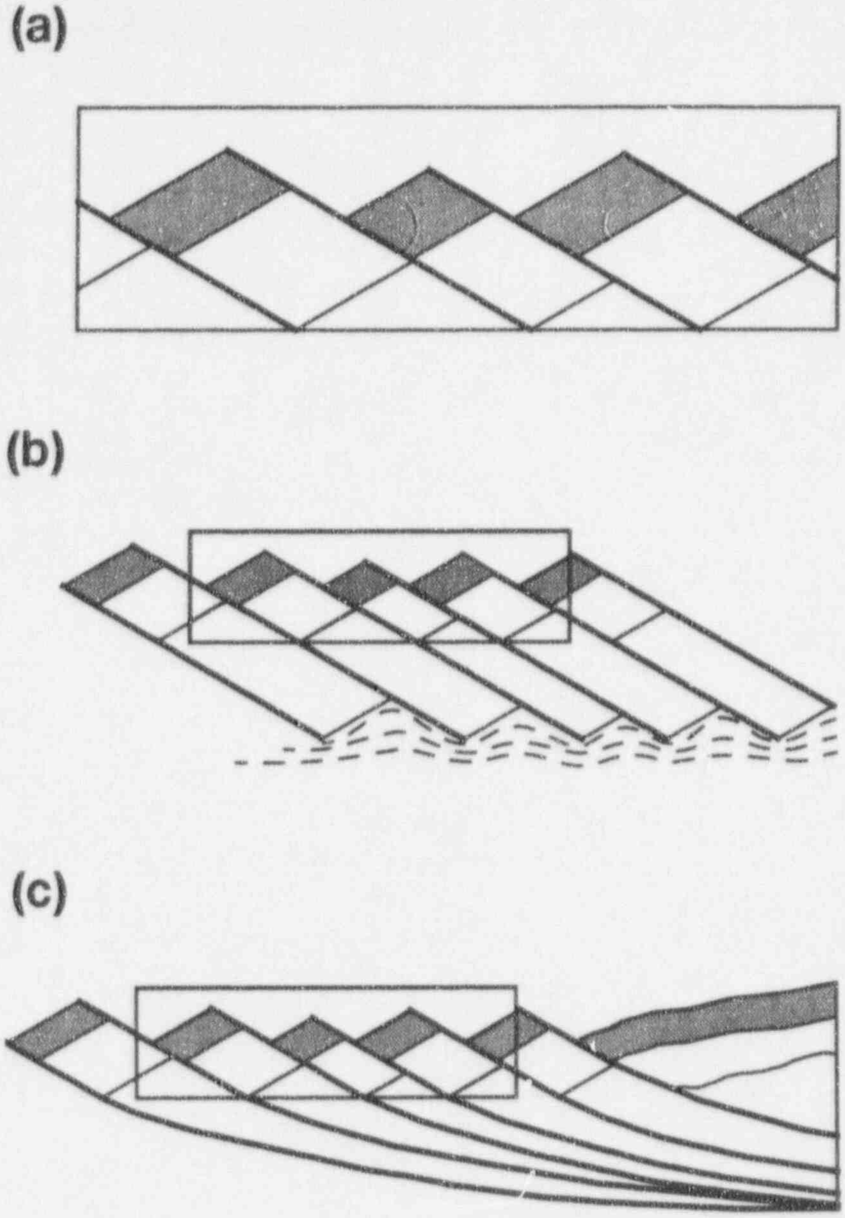
LIST OF FIGURES

Fig. 6. Slip tendency analysis of cross section of fault system from Bare Mountain Nevada. The modeled stress field ratios are σ_1 = 90 (vertical): σ_2 = 65 (north-south): σ_3 = 25 (east-west), are after Morris et al. (1996). Note that slip tendency of faults and bedding are both locally high in the modeled stress field.

Fig. 7. Schematic model for imbricate fault system evolution in isotropic strong, isotropic weak, and anisotropic strata. Layer-parallel shear in an anisotropic stratigraphic sequence cut by an imbricate normal fault system requires slip tendency on layering in excess of frictional resistance to sliding, and juxtaposition of relatively weak layers (those poised for slip or shear) across faults. Localized shear along bedding is likely to offset faults and cause faults to lock. Isotropic strong strata lack planar layering fabric and, therefore, extension is likely to be dominated by fault slip and rigid block rotation which progressively steepens bedding and reduces fault dips. Extensional fault blocks of weak isotropic strata are more likely to initially deform by layer-parallel shear which tends to reduce bedding dips while fault slip tends to reduce fault dips.



Ferrill et al Figure 1

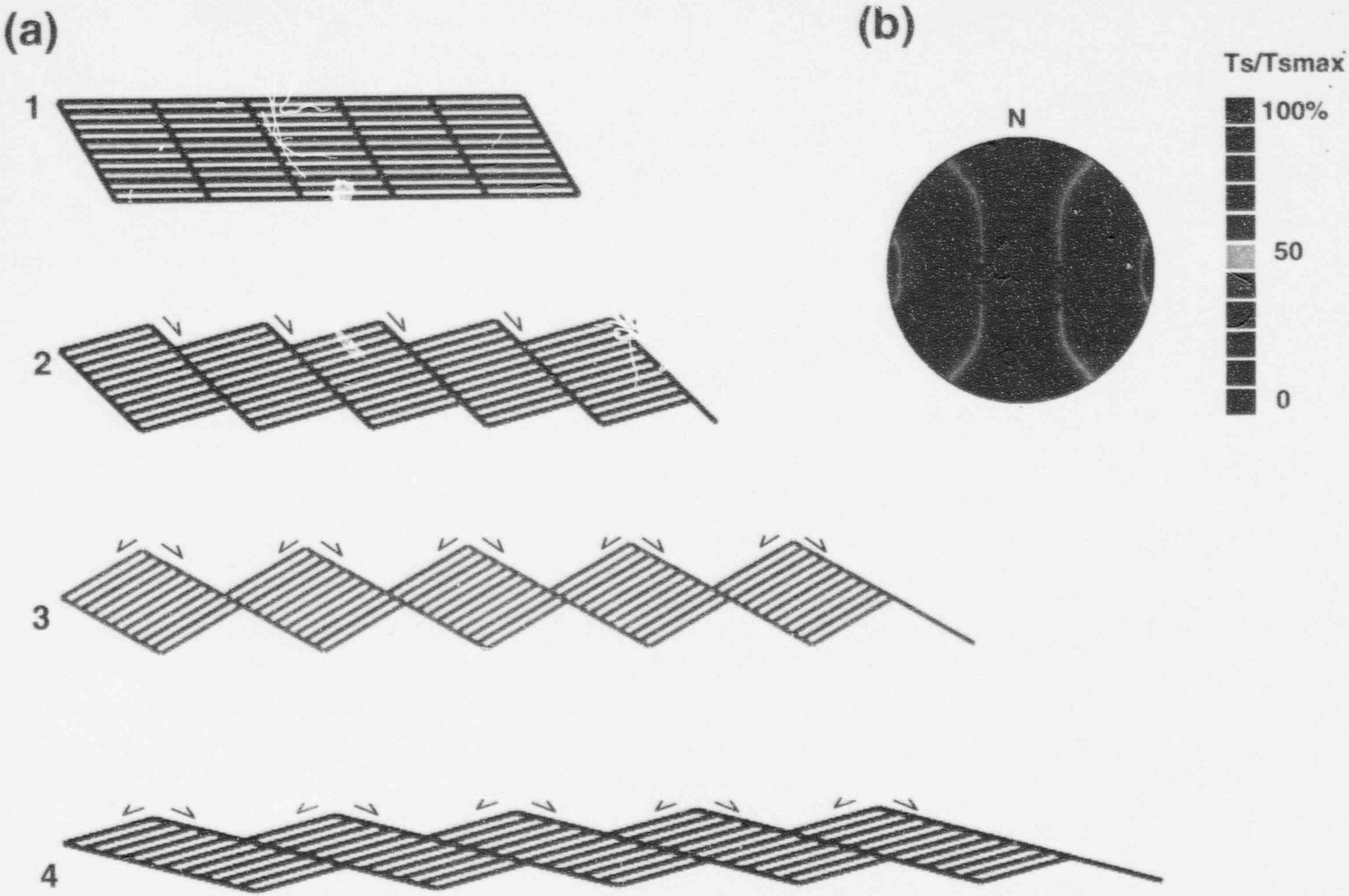


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Figure 2

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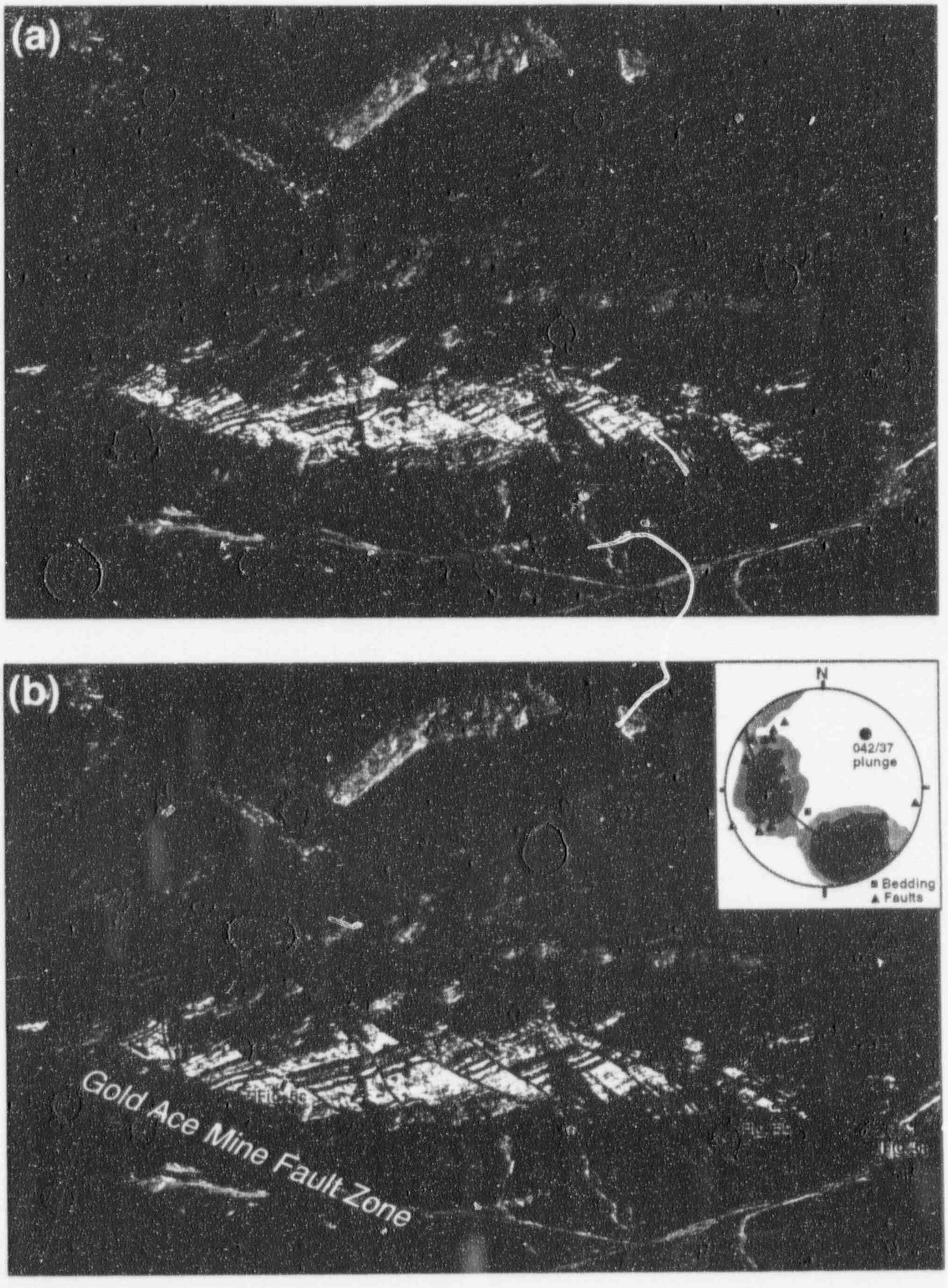

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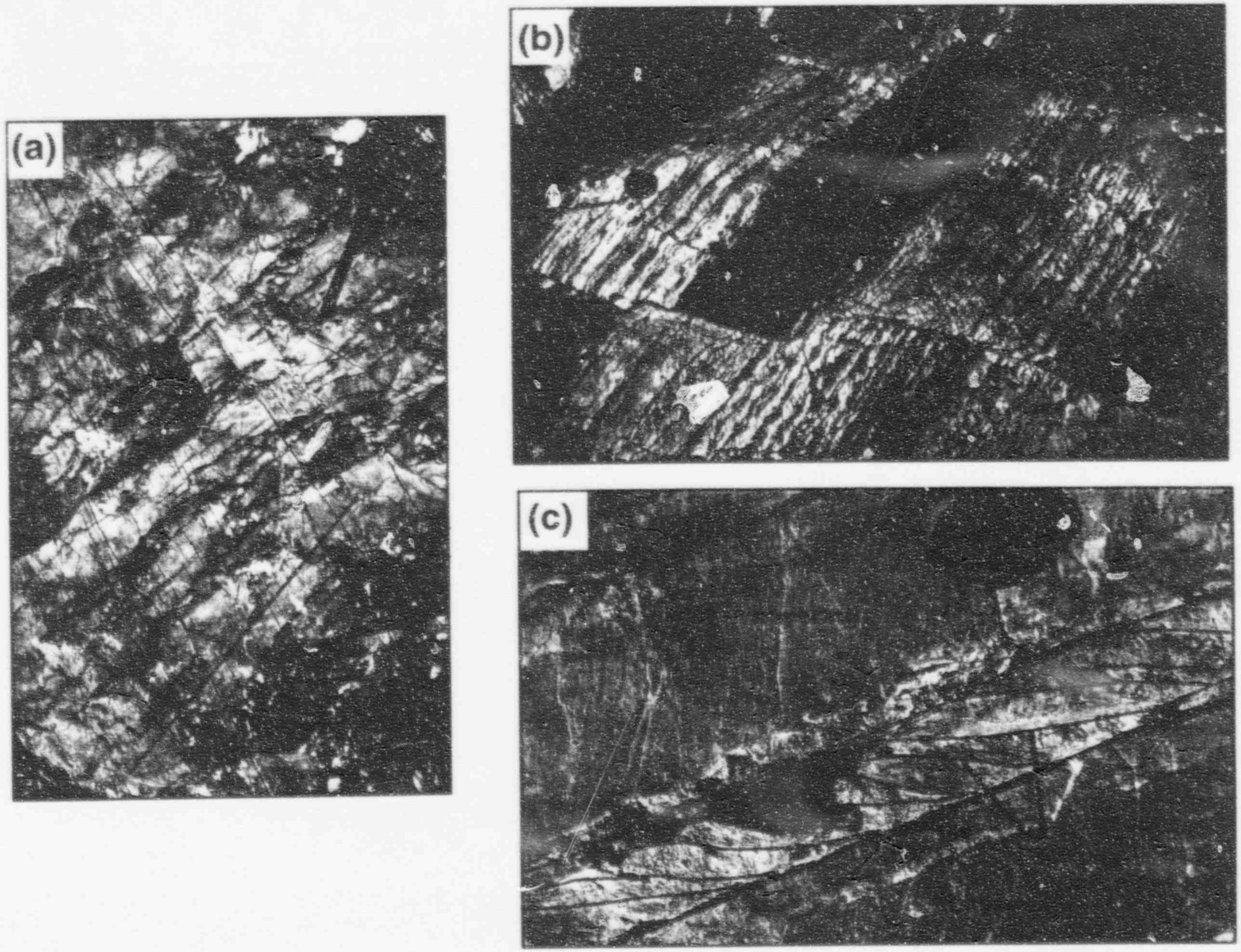

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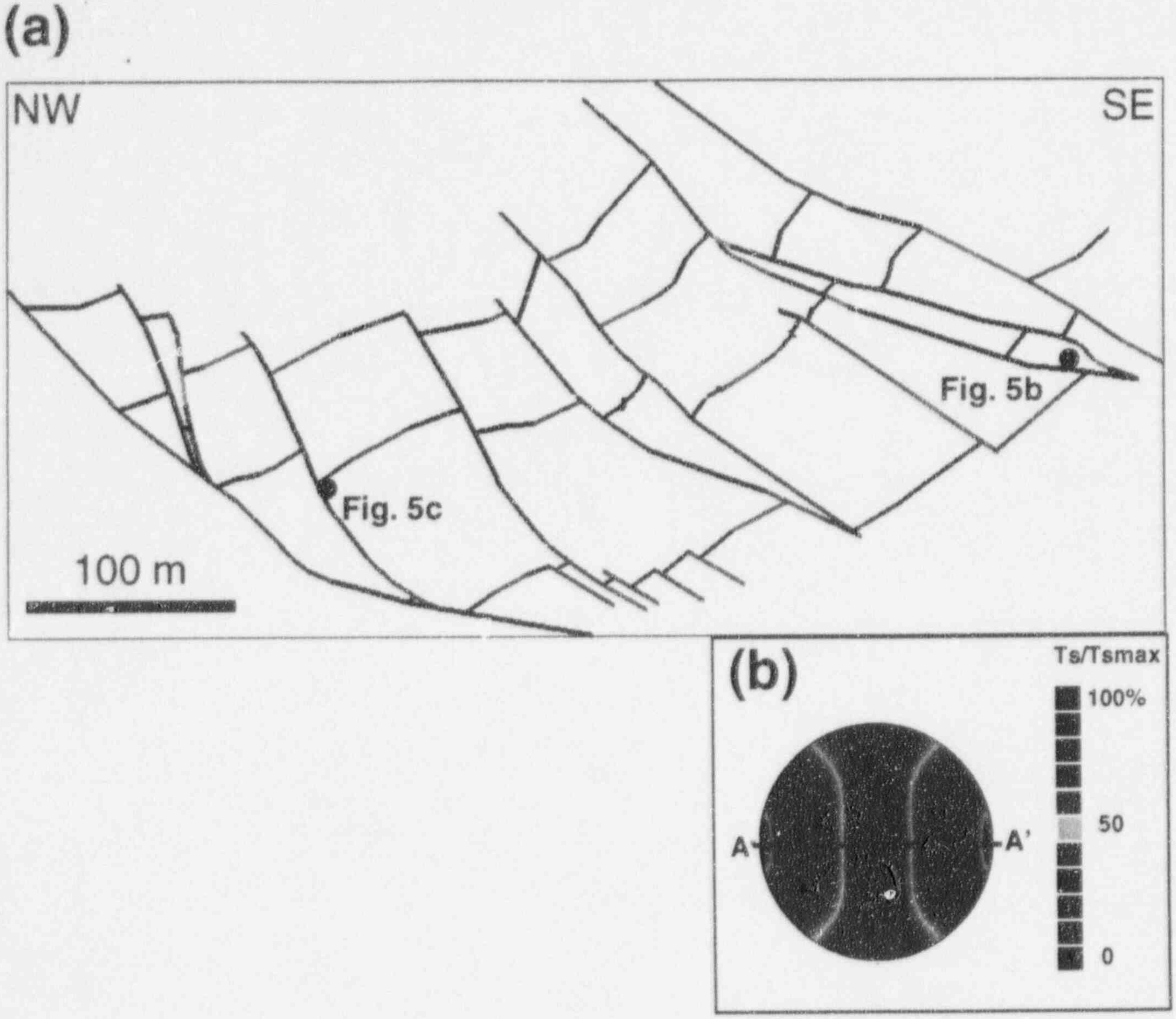

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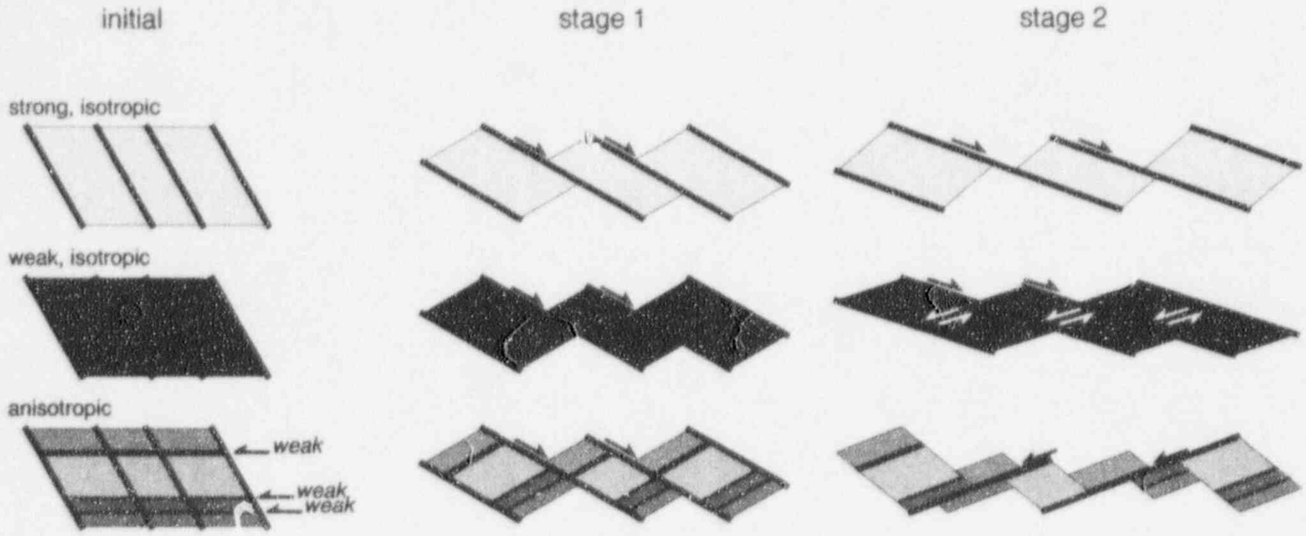
Figure 6.



Ferrill et al Figure 7