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KINEMATICS AND TIMING OF THE PINTO SHEAR ZONE, NEW YORK MOUNTAINS, NORTHEASTERN MOJAVE DESERT, CALIFORNIA

by

Mengesha Assefa Beyene

Bachelor of Science
Addis Ababa University, Ethiopia
1989

A thesis submitted in partial fulfillment of the requirement for the

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ABSTRACT

Kinematics and Timing of the Pinto shear zone, New York Mountains, Northeastern Mojave Desert, California

by

Mengeha Assefa Beyene

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University of Nevada, Las Vegas

New studies of the Pinto shear zone, New York Mountains, California, improve our understanding of the importance of Mesozoic extension in Mojave Desert and also contribute to the growing body of evidence for syncontractional extension in the Mesozoic Sevier orogen. The Pinto shear zone has a Z-shaped map pattern and foliation in the ~92-97 Ma Mid Hills adamellite of the Pinto shear zone generally dips 20-65° S and SW. Sense of shear indicators demonstrate top-to-the S-SW shearing, parallel to a S-SW plunging lineation, suggesting the Pinto shear zone is a normal fault. Hanging-wall deformation is accommodated by antithetic high-angle faulting localized along porphyry dike margins. Deformation fabric within the shear zone grades structurally upwards from undeformed footwall granitoids beneath the shear zone to protomylonite, mylonite, and ultramylonite near its top. Microstructural studies of mylonite and ultramylonite indicate that deformation occurred over a broad range of
decreasing temperatures, from lower amphibolite-uppermost greenschist through lower greenschist facies conditions. The decrease in temperature of deformation probably occurred during progressive deformation. Timing of deformation is constrained by \(^{40}\text{Ar}/^{39}\text{Ar}\) thermochronology of K-feldspar, biotite, and muscovite. The deformation of 80 Ma porphyry dikes within the shear zone together with evidence of rapid cooling during deformation indicate that the Pinto shear zone was active from <80 to 66 Ma. The similarity between footwall muscovite (69.1 ± 0.4 Ma and 70.4 ± 0.4 Ma) and biotite (70.9 ± 0.4 Ma) ages indicates rapid cooling. Hydrothermal muscovite filling microfractures in feldspar porphyroclasts and within quartz veins yield ages similar to igneous biotite, implying hydrothermal mineral growth in fractures occurred during the shearing event. Two K-feldspar multidomain analyses suggest moderately rapid cooling of the footwall at 44°C/m.y.. The hanging wall cooling curve also shows relatively rapid cooling (23 °C/m.y.). The relatively rapid cooling of the hanging wall and the lack of significant discordance in mica ages between the hanging wall and the footwall may result from heating of the hanging wall adjacent to a hotter footwall, perhaps aided by fluids during shearing. The Pinto shear zone is coeval and perhaps kinematically related to other late Cretaceous extensional structures in the eastern Mojave Desert including those in the Old Woman and Funeral Mountains.
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INTRODUCTION

The Pinto shear zone of the southern New York Mountains is situated in the region of intersection between the Mesozoic to early Cenozoic Sevier fold and thrust belt and the Mesozoic magmatic arc (Fig. 1). At this latitude, the fold and thrust belt departs from the Cordilleran miogeocline, cuts into the craton, and is characterized by deformed Paleozoic and Mesozoic metasedimentary rocks and Mesozoic volcanic rocks within roof pendants and wall rocks of the Mesozoic Teutonia batholith. In this region Mesozoic contraction was followed by Miocene extension. Elsewhere within the Sevier orogenic belt, important episodes of extension of Mesozoic age occurred both during and immediately following contractional mountain building during the Sevier orogeny (Fig. 2). In the eastern Mojave Desert region, the importance of Mesozoic extension to the tectonic history remains unclear.

The Pinto shear zone is an ideal area to study the dynamics of mountain building and extensional collapse in the Basin and Range province because it is adjacent to areas where the timing of pre-intrusion contraction is well documented, it exhibits potential late Cretaceous extensional structures that postdate Cretaceous magmatic intrusion, and it was apparently little overprinted during Miocene extension (Burchfiel and Davis, 1977).

The principal research question to be addressed by this study is whether the Pinto shear zone in the southern New York Mountains (Fig. 3) records Mesozoic contraction, Mesozoic extension, Miocene extension, or a combination of these histories. This question is addressed by (1) determining the kinematics (strain path and
Figure 1. Simplified tectonic map of the western Cordillera, showing location of the study area in eastern Mojave Desert. Modified from Hodges and Walker (1992) and Lowell (1983).
Figure 2. Simplified tectonic map of the western Cordillera, showing locations of areas containing evidence of Cretaceous extension. Dark solid circles = locations of areas showing Cretaceous extension, and Barbed lines = leading edge of the Sevier orogenic belt. Modified from Hodges and Walker (1992).
Figure 3. Location map of study area in the eastern Mojave Desert region with emphasis on Mesozoic structures and selected Cretaceous batholiths. The solid lines with teeth indicate Mesozoic thrust faults and the dashed lines with teeth indicate the locations of inferred late extensional Mesozoic mylonite zones (from John and Mukasa, 1990). Location of Cretaceous batholiths from Beckerman et al. (1982) and John (1981). BMM, Big Maria; CM, Chemehuevi; CTM, Castle; EM, Eldorado; DM, Dead; CXM, Coxcomb; KH, Kilbeck Hills; LMM, Little Maria; MM, Mule; MR, McCoullough; NM, Newberry; IM, Ivanpah; OWM, Old Women; PM, Piute; RM, Riverside; SM, Sacramento; TM, Turtle; WM, Whipple Mountains.
sense of shear) of deformation in the shear zone, (2) determining the temperature and metamorphic conditions of deformation by studying the operative deformation mechanisms of different minerals, and (3) determining the age of ductile shearing. The latter question is addressed by comparing the cooling history of the footwall to the hanging wall and comparing the temperature of deformation to the footwall cooling history.

It is determined by this study that the Pinto shear zone records extension of latest Cretaceous age. This result improves our understanding of the timing and processes of deformation in the Mojave Desert and the Sevier orogen; and improves our understanding of the importance of Mesozoic extension in the Mojave Desert. Furthermore, determination of a latest Cretaceous age and extensional shearing for the Pinto shear zone contributes to a growing body of evidence for syn-contractional extension in the Mesozoic Sevier orogenic belt, and fills the gap between the well known areas of late Cretaceous extension in the south (Old Woman Mountains) and in the north (Funeral Mountains).

Previous work

D. F. Hewett (1956) studied the mineral resources of the Ivanpah Quadrangle and proposed the name Teutonia quartz monzonite (adamellite) for rocks forming Teutonia Peak along the eastern side of Cima Dome and all similar granitic rocks within the quadrangle. Sutter (1968) dated samples from what is now known to be the Kesseler Springs adamellite (K-Ar hornblende age of 92.1 Ma) and the Ivanpah granite (minimum K-Ar biotite age of 137 Ma).

Robinson (1979) and Robinson and Anderson (1979) named and described the Ivanpah granite of the Ivanpah Mountains and restricted usage of the Teutonia adamellite to granitoid rocks that underlie much of the Cima Dome. Beckerman and Anderson (1981) and Beckerman et al. (1982) mapped and characterized plutonic rocks of the New
York Mountains and Mid Hills and named the intrusive complex the Teutonia batholith, which includes much of the New York Mountains, Ivanpah Mountains, Mid Hills, and Cima Dome region of southern California.

De Witt et al. (1984) dated the Teutonia adamellite northwest of Cima Dome at 97 Ma by U-Pb on zircon. The Mid Hills adamellite has been dated at about 93 Ma by U-Pb on zircon (Miller et al., 1996). The Rock Spring monzodiorite, which intrudes the Mid Hills adamellite, appears to be among the oldest of the Cretaceous plutons in the batholith. Nearly concordant fractions of the Rock Spring monzodiorite have ages of 97 ± 1 Ma (Miller et al., 1996).

A mylonite zone first identified by Beckerman et al. (1982), and subsequently named the Pinto shear zone (Miller et al., 1996), crops out along the north side of Pinto Valley and continues northwest into the New York Mountains (Figs. 3 and 4). K-Ar dating of hornblende from dikes deformed by the shear zone yielded an age of 78.4 ± 2.0 Ma (Miller et al., 1996). Beckerman (1982) reported a 73.4 ± 4.4 Ma K-Ar date on biotite plus chlorite from the shear zone.

Miller et al. (1996) described and correlated several faults (the East Providence, Pinto, and Cima fault zones) that may represent strands of a larger Late Cretaceous normal fault system termed the East Mojave fault. The primary reason to correlate these faults is that they all represent major down-to-the-southwest faults in the region that cut the Late Cretaceous Teutonia batholith and its dikes. In addition, each fault predates Miocene faults and eruption of early Miocene volcanic rocks (Miller et al., 1996). However, the East Providence fault differs from the other two in that it strikes nearly north and mainly dips east, and has no associated mylonite. The East Providence and Pinto segments are cut by the Cedar Canyon fault (early Miocene?). The Cima fault is cut by the ~13 Ma Nipton fault (Miller, 1996).
Figure 4. Regional geology of the Teutonia batholith and surrounding region. Modified from Burchfiel and Davis (1977).
Numerous NE-striking dikes cut plutonic phases of the Teutonia batholith and its country rocks and are deformed by the Pinto shear zone. The dikes are abundant in the Teutonia batholith near its walls and roof and have yielded ages of 76 to 80 Ma by the combined U-Pb and K-Ar methods (Miller et al., 1996). Burchfiel and Davis (1977) dated a feldspar and quartz mixture from pegmatite in the southeastern New York Mountains by K-Ar at 71.7 ± 0.8 Ma. U-Pb zircon analyses for pegmatite in the same area of the New York Mountains have yielded data that can be interpreted as a crystallization age between 76 and 77 Ma (Miller et al., 1996). U-Pb zircon analyses from a porphyry dike (Fig. 5) yield an age of 80 ± 2 Ma (Wells, unpublished data).

Regional geological setting

The eastern Mojave Desert region is located at the site of intersection between the Mesozoic to early Cenozoic Sevier fold and thrust belt and the partly coeval, long-lived, composite magmatic arc (Fig. 1). The Teutonia batholith is one of the larger intrusive complexes in the eastern Mojave Desert (Figs. 3 and 4). It is comprised of Jurassic to Cretaceous metaluminous to weakly peraluminous, granitic plutons (Beckerman et al., 1982). The Teutonia batholith consists of seven Mesozoic plutons: the Rock Spring monzodiorite and the Ivanpah granite (Jurassic age by K-Ar dates), the Mid Hills adamellite, the Teutonia adamellite, the Kessler Springs adamellite, the Live Oak Canyon granodiorite, and the Black Canyon hornblende gabbro (Cretaceous in age by K-Ar dates) (Beckerman, et al., 1982) (Fig. 4).

The Sevier orogenic belt shows a significant variation in structural style and orientation within the eastern Mojave Desert region. To the north, thrust faults comprising the orogenic belt are generally north-striking, thin-skinned thrusts lacking significant penetrative deformation with thrust transport towards the east. In contrast, in the south the Mesozoic contractile belt in southwestern Arizona and southeastern
California (Maria fold and thrust belt) is oriented E-W (Fig. 1) and the Proterozoic basement rocks are commonly thrust to the southwest and south over thin Paleozoic and Mesozoic cratonic rocks (thick-skinned thrusts), and plastic deformation is common (Reynolds et al., 1988).

Structures present in the New York Mountains are the southernmost of the Sevier foreland fold and thrust belt that is continuous to the north into Canada. The study area in the New York Mountains lies within the region where the structural trends and styles undergo significant changes (Fig. 1 and 2). Cenozoic extension has overprinted and obscured much of the Mesozoic fabrics within the Mojave Desert, but these fabrics are well preserved in the New York Mountains because they are relatively unaffected by Cenozoic extension (Burchfiel and Davis, 1977).
CHAPTER 2

RESEARCH METHODS

A combined structural, geochronological and thermochronological approach, utilizing both field and laboratory studies, was used to determine the timing and kinematics of ductile shearing and whether the Pinto shear zone records contraction or extension. The field methods included mapping of the Pinto shear zone and surrounding areas in the southern part of the New York Mountains at 1:12,000 scale. The objectives of field mapping were (a) to determine the thickness of the overall shear zone and different types of fault rock (e.g., mylonite and ultramylonite), (b) to determine the relationship between ductile shearing and the dated 80 Ma dikes, (c) to carryout kinematic analysis and document mesoscopic structural features, (d) to collect forty oriented samples for microstructural and lattice preferred orientation studies, and five samples for \(^{40}\text{Ar}/^{39}\text{Ar}\) thermochronology and U-Pb geochronology (two from the footwall, two from the center of the shear zone, and one sample from the hanging wall).

The laboratory work included the dating of deformation by the \(^{40}\text{Ar}/^{39}\text{Ar}\) method, kinematic and deformation mechanism analysis using microstructural and quartz C-axis preferred orientation studies, staining of selected thin sections for both K-feldspar and plagioclase, and analysis of foliation and lineation measurements using lower hemisphere, equal-area stereographic projections. All oriented samples were prepared from slabs cut parallel to lineation and perpendicular to foliation approximating the XZ principal plane of the finite strain ellipsoid. Quartz C-axis preferred orientations of oriented samples from quartz veins were measured using a 4-axis universal stage on a polarizing petrographic microscope and plotted on stereograms. The staining aided in
identifying K-feldspar, plagioclase, and quartz in fine-grained quartz-feldspar aggregates. Samples collected during geological mapping were prepared for \(^{40}\text{Ar}^{39}\text{Ar}\) thermochronology and U-Pb geochronology using bromoform and methylene iodide, magnetic separation, and handpicking techniques. The mineral separates of the five samples collected from the footwall, hanging wall, and the shear zone were analyzed in the Nevada Isotope Geochronology Laboratory, at the University of Nevada Las Vegas. With the exception of the two samples collected from the center of the shear zone (only muscovite), mineral separates of muscovite, biotite, and K-feldspar were prepared and analyzed for each sample. The K-feldspar samples collected from the hanging wall and the footwall were modeled using the multiple diffusion domain approach of Lovera et al. (1989, 1991), and using the software of Lovera (1993) to determine the cooling histories of the footwall and the hanging wall.
CHAPTER 3

DESCRIPTION OF THE PINTO SHEAR ZONE

Introduction

The Pinto shear zone has a “Z” shaped map pattern and strikes E-W in the eastern part, NW in central and northwest part, and again E-W in the western part (Fig. 4, plate 1). The shear zone generally dips 20-65° S and SW, and lineation plunges SSW. The shear zone has a thickness of about 550-600 meters in the central part and is thinner towards the north and ultimately grades northward into a localized britley deformed zone. The shear zone is bounded by the hanging wall in the southwest and the footwall in the northeast (Fig. 5). Deformation fabric is gradational at the base of the shear zone and sharp at the top, and strain increases upwards. The top of the shear zone refers to a transition from strongly deformed rock within the shear zone to undeformed rock in the hanging wall. Kinematic studies of the Pinto shear zone consistently yield a significant component of non-coaxial top-to-the-SSW shearing. Hanging wall deformation is accommodated by antithetic high-angle normal sense shear zones localized along the porphyry dike margins. Based on foliation and lineation patterns, the Pinto shear zone is divided into six structural domains. Domain 1 occupies the eastern part, domain 2 the southeastern part, domain 3 the central part, domains 4 and 5 the northwestern parts, and domain 6 the western part of the shear zone (Fig. 5).
Figure 5. Map showing the six structural domains of the Pinto shear zone. Dark squares = poles to foliation (poles to fol), and dark circles = lineation (lin).
Geology of the southern New York Mountains

Phanerozoic rocks are preserved along the eastern margin and within the roof of the Early-Late Cretaceous Teutonia batholith in the southern New York Mountains, about 25 kilometers southeast of the southern extent of the Clark Mountain thrust complex exposed in the Mescal Range (Burchfiel and Davis, 1977; Beckerman et al., 1982) (Fig. 4). These rocks record a comprehensive Mesozoic deformational history involving superposed plastic deformation and low-angle faulting (Burchfiel and Davis, 1977). Two phases of the Teutonia batholith crop out in the New York Mountains, the Mid Hills adamellite and the Live Oak Canyon granodiorite (Beckerman et al., 1982; Miller and Wooden, 1993). The Mid Hills adamellite hosts the Pinto shear zone and has been dated at about 93 Ma by U-Pb on zircon (Miller et al., 1996). The Mid Hills adamellite crops out over a large area (300 km²) that extends from the eastern New York Mountains to the southern Mid Hills. The Mid Hills adamellite intrudes Precambrian gneiss along its southern margin and both Paleozoic and Mesozoic metasedimentary rocks along its eastern margin. Present mapping shows that the Mid Hills adamellite also intrudes gneiss along its northwestern margin.

Geology of Pinto shear zone

Deformation fabric grades structurally upward from undeformed footwall granitoids beneath the shear zone to protomylonite, mylonite, and ultramylonite near its top. Foliation in the Pinto shear zone generally dips 20-65° S and SW, and lineation plunges to SSW.

The Mid Hills adamellite of the Pinto Valley and Fourth of July Canyon areas contains medium to coarse grained equigranular biotite adamellite and a porphyritic biotite adamellite that is present in the central eastern and northwestern part of the shear zone and its footwall. The equigranular type contains 50-60% alkali feldspar, 25-30%
quartz, and 10-15% plagioclase, whereas the porphyritic type contains 10-20% alkali feldspar phenocrysts (1.0 - 7.5 cm) and tends to have more plagioclase and less quartz than the equigranular phase.

Porphyry dikes and leucocratic dikes occur in the field area. Most of the porphyry dikes were mapped in the hanging wall of the Pinto shear zone (Miller, unpublished map), some in the northwestern part of the shear zone and few in the footwall (Fig. 4). These dikes are grayish on fresh surfaces and are generally composed of about 60-80% matrix and 20-40% phenocrysts of quartz, plagioclase and K-feldspars. Quartz phenocrysts are commonly subhedral and embayed whereas the plagioclase and K-feldspars, and biotite phenocrysts are euhedral in shape in undeformed dikes. In contrast, the phenocrysts in the deformed equivalents decrease in size and lose their magmatic shape due to deformation. At one locality, in the northwestern hanging wall of the shear zone, an aplitic dike is found cut by the porphyry dike, implying that the porphyry dikes are younger than the aplitic dikes.

Leucocratic dikes are very common in the southern and eastern part of the shear zone and are light colored, fine-grained equigranular leucocratic (aplitic) dikes. Locally the dikes are folded. The leucocratic dikes are rare and unfolded towards the northern part of the shear zone.

Structure

Introduction

A shear zone is a zone of highly strained rocks bounded by undeformed adjacent rocks. A shear zone can be formed by different deformation conditions. A brittle shear zone is formed by brittle deformation mechanisms and contains fractures and other features that reflect the regime of deformation. A ductile shear zone is formed by ductile flow and contains structures such as foliation and lineation. Brittle-ductile shear zones
are formed by both ductile and brittle mechanisms and shows evidence for both brittle and ductile deformation which indicate conditions during shearing were either intermediate between brittle and ductile or changed from ductile to brittle or vise versa (Davis and Reynolds, 1996). The onset of dynamic recrystallization can have a strong effect on the mechanical properties of deforming rocks. When shear zones are formed under ductile conditions, deformation is accompanied by metamorphism and produces rocks with foliation, lineation, folds, and related features (Davis and Reynolds, 1996).

Ductile shear zone fabric overprinted by a brittle zone at its top characterize the Pinto shear zone. The details of these fault rocks are discussed below.

**Ductile shear zone and associated rocks**

Ductile shear zones are formed by deformation of rock under ductile conditions. The localization of deformation into shear zones indicates that it is easier to continue deforming rocks within the zone than to broaden the zone by deforming the wall rocks. Different fault rocks can be formed during a progressive deformation of rocks within the shear zone. Mylonite is the type of foliated fault rock which contains 50-90% matrix or recrystallized grains (Sibson, 1977), in which the grain size has been reduced because of intense shearing. The grain size reduction is a result of ductile or mixed brittle-ductile deformation mechanisms, especially dislocation creep, dynamic recrystallization, and fracturing of brittle grains. Mylonite commonly occurs within the high strain environment of ductile shear zones. Further concentration of strain and grain size reduction in a certain zone of a mylonite produces ultramylonite (> 90% matrix) (Sibson, 1977).

The Pinto shear zone is characterized by moderately to strongly foliated and lineated mylonitic and ultramylonitic Mid Hills adamellite. Deformation in the hanging wall of the shear zone is characterized by high angle down-to-the-north faulting parallel to the margins of porphyry dikes, and minor ultramylonites within the Mid Hills.
adamellite. Several mappable and numerous smaller and unmapped ultramylonites were studied within the Pinto shear zone and its hanging wall. Ultramylonites observed in the field area are described below.

Ultramylonites mapped within the shear zone include (1) ultramylonite of Mid Hills adamellite protolith, (2) leucocratic ultramylonites, and (3) carapace-forming ultramylonites. The ultramylonite of Mid Hills adamellite protolith is fine grained, grayish, and a millimeter to 1.5 meters wide, and commonly occurs in the northwestern part of the shear zone. For example, in the central part of the shear zone, about 7-centimeter wide ultramylonite is present. The ultramylonite strikes 350° and dips 55° to the west and its lineation trends 230° and down dip. The foliation of the mylonite in contact with the ultramylonite strikes 315° and dips 29° to SW and its lineation plunges 29° towards 230° (Fig. 6A). The foliation within the ultramylonite dips at a higher angle than the main foliation.

The leucocratic ultramylonite is generally a light colored, fine grained, muscovite and biotite rich ultramylonite derived from aplite dikes. This ultramylonite is mapped only within the eastern part of the shear zone. The thickest ultramylonite has a width of about 8 meters and its foliation strikes 250° and dips 20° to the southeast. The lineation has trend and plunge ranging from 145° to 155° and 15° to 19°, respectively. The northern margin of this ultramylonite is slightly mylonitic aplite (1.5-2 meters wide), indicating an aplitic protolith. Ultramylonite of a millimeter to centimeter thickness are noted (three or four places) just to the north of this transect (eastern part). In the central northwest part of the shear zone, another 1-meter wide, light, leucocratic ultramylonite was noted. This ultramylonite has foliation trending 338°/46° SW and lineation of 205°/40° and is continuous to the north for about a kilometer. In its northern part, the ultramylonite is trenched along its strike for about 300 meters (most probably for
Figure 6. Foliation and stretching lineation from ultramylonite within the Pinto shear zone and its hanging wall. (A) Both Mid Hills and leucocratic type ultramylonite within the shear zone. (B) Carapace-forming ultramylonite which overlie the mylonite. The mean foliation attitude is 183°, 23° W. (C) Ultramylonites of the hanging wall. Data are plotted on lower hemisphere, equal-area stereographic projections.
mineral exploration purposes). In the trenched part, the foliation of the ultramylonite is
345°/24° W and lineation of 162°/6° (Fig. 6A).

A zone of ultramylonitic rock forms a carapace that caps the top of the shear zone in
the northwestern and western part of the shear zone. Float and patchy outcrops of
ultramylonite at similar structural positions in areas to the south suggest that
ultramylonite is continuous at the top of the shear zone. In the northwestern part of the
shear zone, the ultramylonite has a measurable thickness from 7 to 15 meters,
demonstrably thicker than to the south and east. The ultramylonite outcrop is cliff
forming, altered (silicified and sericitized), and at places overprinted by brittle
deformation. The thinning of the shear zone towards the northwest and west and the
widening of the ultramylonite in the same direction is a compatible phenomenon.
Localization of deformation in a relatively narrow zone results in further grain size
reduction and formation of ultramylonites.

The carapace-forming ultramylonite strikes NNW and dips west at angles
ranging from 17-38° (Fig. 6B). The mean vector trend and plunge of the poles to the
foliation is 92.7°, 66.8°, corresponding to a foliation attitude of 182.7° 23.2° W (Fig.
6A). The lineation plunges at shallow angles (5-28°) towards both the north and south
(Fig. 6A). The foliation of other ultramylonites from the center of the shear zone strikes
NW and dips west and southwest at angles ranging from 24-40°. The lineation plunges
19-40° towards the south and southwest (180-230°) (Fig. 6B).

Three larger ultramylonite zones occur in the hanging wall of the Pinto shear
zone within the Mid Hills adamellite. The first occurs in the northwestern part of the
study area, and is about 30 centimeters wide. The ultramylonite strikes 43° and dips 45°
southeast and the lineation plunges 20° towards 210°. The foliation trajectory
(sigmoidal foliation pattern) shows top-to-south shear sense. In this outcrop, a
crenulation lineation (112° /38°) is perpendicular with the stretching mineral lineation.
The second and third ultramylonite outcrops were mapped about 1-kilometer southwest and 5 kilometers northwest of the ultramylonite mentioned above. The ultramylonitic foliation of the second strikes 60° and dips at 55° to the west, and lineation is horizontal (plate 1). The foliation trajectory shows a west side to SW sense of shear. The ultramylonite foliation of the third strikes 345° and dips 38° to the west, and the lineation plunges 31° towards 208° (Fig. 6C).

Besides these larger ultramylonite zones, there are numerous minor lenses of ultramylonite within the mylonite, indicating strain partitioning and further localization of deformation within the shear zone. Since many deformation mechanisms are most efficient in fine-grained rocks, a reduction of grain size can lead to strain softening and continued localization of shear in the most deformed, finest grained parts of the shear zone (Fig. 7).

Collectively, foliation of ultramylonites strike both to the NE and NW, with dips both to the west and south, but the lineation consistently plunges towards the south and southwest. All the above measurements and observations show that all ultramylonites in the hanging wall are kinematically compatible with the ultramylonites and mylonites of the central part of the shear zone. Ultramylonites of variable thickness are not uncommon at the dike margins in the hanging wall and the shear zone.

Heterogeneity of deformation and strain partitioning in the Pinto shear zone is indicated by the presence of vertical strain gradients, grading structurally upwards from undeformed footwall granitoids (both equigranular-type and porphyritic type) beneath the shear zone to slightly mylonitic granite (protomylonite?), mylonite, and ultramylonite near its top. The heterogeneity of deformation and strain partitioning is also evidenced by the presence of numerous minor shear zones (defined by ultramylonites) observed dominantly in the mylonitic portion of the shear zone and at
Figure 7. Ultramylonite within the mylonite in the northwestern central (domain 4) part of the shear zone (plate 1), showing partitioning and localization of strain.
few places in the hanging wall, and composite planar S-C fabrics documented in the central and northwestern part of the shear zone.

The presence of strongly foliated and lineated rocks in the Pinto shear zone indicates that the shear zone was formed under ductile conditions. During the localization of deformation in the Pinto shear zone, mylonites and ultramylonites were formed.

**Brittle zone**

A NW-striking zone of brittle deformation overprints the top of the ductile fabric of the Pinto shear zone. However, due to Quaternary alluvial cover in the eastern part of the study area, the continuation of the zone towards the eastern part of the shear zone remains unclear (plate 1). The brittle zone overprints two levels of the shear zone, the ultramylonite and locally the underlying mylonite. The width and intensity of overprinting increases dramatically towards the northwest to the extent that it becomes difficult to delineate the ductile fault zone. This zone shows extreme cataclasis of both the top part of the shear zone (ultramylonite) and the hanging wall (Mid Hills adamellite). This hinders identification of the boundary between the shear zone and the hanging wall. In the extreme western part of the shear zone, the ductile fabric apparently becomes thinner and is completely overprinted by the brittle zone. However, there are mylonitic rocks close to the footwall that survived the overprinting, indicating the brittle deformation obliterated much, but not all of the fabric towards the top of the shear zone, and that the Pinto shear zone was ductile at one time in its north reaches. Further to the west, ductile fabric is completely overprinted by the brittle zone. In the extreme west, the shear zone dies out (plate 1).

In general, the brittle zone overprints Precambrian gneiss in the west, hanging wall Mid Hills adamellite, ultramylonite, and mylonite in the NNW, ultramylonite in the NW, and mylonite in the central part of the shear zone. The overprint of the brittle fault
on the earlier fabric (mylonite and ultramylonite) is indicated by fault breccia observed in
the northern part of the shear zone (near the hanging wall). The fault breccia consists of
clasts of mylonite and ultramylonite cemented by clay-rich gouge materials. The brittle
zone is characterized by chloritic alteration, greenish-gray, fine grained, intensively
brecciated and crushed, deformed (mylonitic and ultramylonitic) and undeformed
hanging wall rocks (Mid Hills adamellite). The brittle zone overprints a wider
ultramylonite zone and hanging wall Mid Hills adamellite in the northern part of the
shear zone, and gets narrower towards the south and overprints the mylonite in the
central part of the shear zone, then disappears within the alluvium at Fourth of July
Canyon.

In the easternmost part of the shear zone, a brittle fault with a NE-SW orientation
overprints the top of the shear zone, particularly the hanging wall carbonate rock. This
fault apparently cut the shear zone but the relationship is not clear due to the alluvial
cover. However, the fault is continuous towards the NE tracking the carbonate rock.
This fault is characterized by green, brecciated chloritic carbonate rock. The fault may be
a branch of the anastomosing brittle fault mapped by Miller (1996) as the Miocene
Cedar Canyon fault (Fig. 5 and plate 1), or be correlative to the brittle fault described
above.

Ductile-brittle fault zone (?)

A 70-150 meters wide, E-W striking ductile-brittle fault zone was mapped in the
central shear zone hanging wall (plate 1). This fault is characterized by greenish-gray,
fine-grained ultramylonite and greenish gray, medium grained sheared dike rocks, both
of which are associated with chloritic alteration. The attitude of the ultramylonitic
foliation varies from 280°/65° N to 275°/45° N. The lineations plunge from 31° to 38°
towards 300°-310°. The fault zone gets wider towards the west and is accompanied by
wider zones (up to 3 meters) of ultramylonite outcrop.
The presence of ultramylonite reflects the ductile nature of the fault whereas the presence of ubiquitous float of broken ultramylonite, unusual high-angle joints in the Mid Hills adamellite at the margin of the fault zone, fault grooves (plunges 7° towards 305°), and alteration (chloritization, epidotization, and feldspathization) in the western part of the fault zone indicate a late movement as a brittle fault.

The ultramylonite in this fault zone localized along a zone with aplite (Fig. 8A) and porphyry dikes (Fig. 8B). Ultramylonite of Mid Hills adamellite protolith is also clearly noted from the outcrop relationship (gradational contact) in the western part of the fault. Moreover, in the extreme west part of the map area, a very wide hill-forming, coarse grained, dull white, feldspathic rock is noted. This rock is associated with greenish yellow, heavily epidotized rocks. This fault seems fairly continuous towards the west outside the map area. Foliation measured from the fault zone dominantly dips to the north, and lineation has a mean vector trend and plunge of 303.9°, 25.5° (Fig. 9A).

**Deformation variation in porphyry dikes within the shear zone and its hanging wall**

When a continuous shear zone cuts a preexisting feature (such as compositional layering or a dike), the marker will generally show a gradual deflection in its orientation and a corresponding gradual change in thickness across the shear zone (Ramsay and Graham, 1970). The change in marker orientation and progressive change in thickness can be used to determine the sense of shear and magnitude of strain.

The antithetic porphyry dikes mapped in the hanging wall can be traced downwards towards the shear zone boundary. Mapping of several of the porphyry dikes show that the dikes are progressively thinned and deflected into parallelism with the shear zone boundary as they cross the shear zone downwards. The thinning and
Figure 8. Fault rocks from E-W striking fault zone in the hanging wall of the Pinto shear zone: (A) Intercalation of porphyritic dikes, ultramylonite, and the Mid Hills Adamellite. (view to NNW). Note the sharp contact between the Mid Hills adamellite and the dike. (B) Gradational nature of the contact between the dike and the ultramylonite (dashed line) (view to north).
Figure 9. Foliation and stretching lineation (solid dots). Arrow heads indicate the relative motion of the hanging wall with respect to the footwall. (A) Porphyry dike margin and ultramylonite from the E-W oriented fault zone in the hanging wall. Lineation has a mean vector trend and plunge of 310°, 26°. (B) Porphyry dikes in the hanging wall with sheared margins. The mean vector and trend and plunge of the lineation of these dikes is 348°, 55°. (C) Deformed porphyry dikes within the shear zone. In the NW part of the shear zone, the dike’s lineation plunges at angles ranging from 3°-40° towards NNW and NNE. However, lineation of a deformed dike from the central part of the shear zone plunges at angles ranging from 25°-28° towards SSW. Data are plotted as lower hemisphere, equal-area stereographic projection.
deflection of the porphyry dikes into parallelism with the shear zone boundary implies that the porphyry dikes are deformed by the continuous shear zone.

The deformation of porphyry dikes varies across the shear zone. Porphyry dikes are deformed throughout their width within the shear zone, deformed only at their margins in the hanging wall, and are completely undeformed in the footwall. However, at places in the northwestern part of the shear zone, a few undeformed porphyry dikes are also encountered within the shear zone structurally beneath the ultramylonite. The sheared margins of the porphyry dikes within the hanging wall, and some porphyry dikes within the lesser deformed lenses within the shear zone record antithetic (top-to-north) deformation, whereas the deformed porphyry dikes in the central part of the shear zone record a synthetic (top-to-southwest) deformation.

The foliation of the dikes in the hanging wall strikes ~ E-W (235°-279°) and dips to the north and northwest at angles ranging from 44°-75°. Lineations vary from northwest (312°/63°) to NNW (350/39). The mean vector trend and plunge of the lineation of these dikes is 347.7°, 54.9° (Fig. 9B).

In the shear zone, the porphyry dike margins have foliation that strikes NNW to NNE and dips dominantly to the west. In the northwestern part of the shear zone, the dike's lineation plunges at shallow angles (3°-16°) towards the NNW to NNE, as do some of the lineations within this part of the shear zone. However, at one locality in the central part of the shear zone, lineation in a deformed dike plunges at an angle of 28° towards SSW (225°), colinear with the surrounding mylonitic lineations. In general, the lineation in the dike within the shear zone trends NNW to N in the northwestern part of the shear zone and SSW in the central part of the shear zone (Fig. 9C). The dikes in the shear zone have a kinematic concordance at least with the local shear zone mylonites (compare Fig. 9C with Fig. 11).
Foliation and lineation pattern in Pinto shear zone

Mapping of the shear zone, study of foliation and lineation orientation measurements, and microstructural and lattice-preferred studies have been carried out to determine the nature of deformation in the Pinto shear zone. Alteration processes that affected the northwestern and northern part of the shear zone do not affect the central and southeastern part of the shear zone. This allows foliation and lineation to be studied during geological mapping and collection of samples for microstructural studies.

Detailed foliation and lineation measurements were conducted throughout the shear zone, and the orientation of foliation and lineation were systematically studied. Differences in foliation and lineation orientation were noted, which allowed subdivision into six structural domains (Fig. 5 and plate 1).

Domain 1

This domain occupies the easternmost part of the shear zone. The foliation in domain 1 strikes almost E-W (270°-315°), and dips to the south at angles ranging from 26°-48°. The foliation gets shallower as one goes from the top towards the center of the shear zone, indicating a higher strain towards the top of the shear zone. The poles to the foliation have a mean vector trend and plunge of 19.2°, 51.1°, corresponding to a foliation attitude of 289°, 40° S (Fig. 10).

The stretching lineation for this domain plunges at angles ranging from 14°-47° towards the south (185°-210°). The mean vector trend and plunge are 200.0°, 36.3° (Fig. 11).

Domain 2

This domain lies immediate northwest of Fourth of July Canyon. The foliation strikes W to NW (285°-325°) and dips S and SW at angles ranging from 33°-46°. The foliation has a mean vector plunge and trend of 35°, 51°, corresponding to a mean foliation attitude of 305°, 40° S (Fig. 10). The stretching lineation plunges at angles...
Figure 10. Poles to foliation, mean vector pole and the corresponding plane to the mean vector pole for each domain. Data are plotted as lower hemisphere, equal-area, stereographic projections, contouring is by the Kamb method. Contour interval = 2 sigma.
Figure 11. Stretching mineral lineation for each domain. Data are plotted as lower hemisphere, equal-area, stereographic projections, contouring is by the Kamb method. Contour interval = 2 sigma.
ranging from 29°- 48° towards the SSW (180°-230°). The mean vector of the lineation for this domain plunges 40° towards 200° (Fig. 11).

Domain 3

This domain occupies the central, widest, and best-exposed part of the shear zone. The foliation in this domain strikes from 284° to 345° and dips to the SW and W at angles ranging from 26°-65°. Overall, as one traverse from the hanging wall to center of the shear zone, the foliation becomes more shallowly dipping (Fig. 10 and plate 1). The poles to the great circles of the foliation have a mean vector trend and plunge of 49° and 54°, corresponding to a mean foliation attitude of 319°, 36° W. The mean strike of the foliation of this domain is more northwesterly than the mean strike of domain 2 and its dip is shallower by 3.3° (Fig. 10). A cylindrical best fit to the poles for domain 3 yields a fold axis of 216°, 35°, very similar to the mean vector trend and plunge (216°, 34°) for the stretching lineation.

The mean vector lineation for this domain plunges 34° towards 216°, indicating a SSW-NNE transport direction for the shear zone, plunging to SSW (Fig. 11). When compared to domain 2, the trend of the lineation has a difference of 10.7° and the plunge is shallower by 4.7°

Domain 4

This domain occupies the immediate north of domain 3 (central northern part of the shear zone) (plate 3). This domain has a wide variation in strike and dip. The strike varies from NNW to NE, and the dip varies from 5°-49°. The dip angles get shallower towards the north where the foliation picks up the southern and southwestern dip direction. The mean vector trend and plunge of the poles to the foliation for this domain is 102.3°, 63.8°, corresponding to a foliation attitude of 192.3° 26° W (Fig. 10). The difference in the mean strike of the foliation planes between this domain and domain 3 is
53°, a very significant change in foliation orientation. The dip of the foliation of this domain is shallower by 9.5°.

The dominant lineation in domain 4 has a N-S orientation and plunges shallowly both to north and south (Fig. 11). Millimeter-scale kink bands that deform the preexisting ultramylonitic foliation are common in carapace-forming ultramylonite within this domain. The hinge lines of the kink bands form a crenulation lineation with an E-W trend and west plunge (Fig. 12). Kink bands at high angles to stretching lineation are very common in extensional mylonites, and can be formed by either layer-parallel buckling, subvertical simple shear, or both. Layer-parallel buckling and subvertical simple shear can occur during uplift and passage of rocks through a rolling hinge (Manning and Bartley, 1994; Fletcher et al., 1995).

Domain 5

This domain occupies the northern part of the shear zone, where the foliation switches from NW to W strikes (345°-250°) and dips to the SW and W at angles ranging from 5°-43°. The rocks in this domain are very altered and full of empty cavities; as a result, in some places it is difficult to see the earlier ductile fabric. The mean vector of the poles to the foliation for this domain is 30.7°, 69.6°, corresponding to a foliation attitude of 300°, 20° S (Fig. 10). The lineation has a mean vector trend and plunge of 176.9°, 16°, indicating a N-S transport direction and a southerly plunge (Fig. 11).

Domain 6

This domain occupies a highly to completely brittly overprinted part of the shear zone. Measurable foliation and lineation are only found at localities near to the footwall. The strike of foliation varies from 240°-255° and dips to NNW and N at angles ranging from 26°-55°. Due to the thinning and brittle overprinting of the shear zone towards northwest and west, only a limited number of foliation measurements
Figure 12. Lower hemisphere equal-area plot of lineations from carapace-forming ultramylonite in domain 4. The W-trending lineations are crenulation lineations and the N-S-trending ones are stretching lineations. Contouring is by Kamb method.
were taken. As a result, only foliation great circles are plotted on the stereonet. The foliation has a mean strike and dip of 243.7° 37.8° N (Fig. 10).

The lineation in this domain has a trend that varies from NNW (355°) to NNE (12°) and the plunge angle varies from 26°-46° trending to the north. The stretching lineation for this domain plunges to the north (Fig. 12). Due to a limited number of lineation measurements, only the scatter plot of the lineation (solid circles) in the plane of foliation is plotted (Fig. 11).

**Interpretation and discussion of foliation and lineation pattern in the Pinto shear zone**

Mapping of the Pinto shear zone shows that the shear zone has a curviplanar or apparently folded geometry, particularly in the northern part of the shear zone (plate 1). Generally, the shear zone strikes E-W in the southeastern and eastern parts (domain 1), NW in the central part (domain 2 and 3), N in the northwestern part (domain 4), and W in the northern and western parts (domains 5 and 6) of the shear zone.

Measurements of foliations from all the six structural domains of the shear zone show that the foliation varies more or less in a systematic manner (Fig. 13). Two models are proposed to be tested if there is consistent variation in the lineation and foliation in Pinto shear zone, (a) folding and (b) younger shearing. Different groupings of foliation and lineation from different domains have been used to determine whether or not there is a consistent variation in foliation and lineation that could be explained by folding of the shear zone. Systematic foliation groupings considered are grouped by three adjacent domains (1, 2, 3; 2, 3, 4; 3, 4, 5; & 4, 5, 6) (Fig. 14). Only the group with domains 1, 2, and 3 shows a fold axis that is colinear with the lineation. In general, a significant foliation variation is seen between the northern (domains 4, 5, and 6) and the southern (domains 1, 2, and 3) parts of the shear zone, but is not precisely explained by a fold axis. A similar variation in lineation is also seen and can not be
Figure 13. Foliation from all domains showing the apparent fold axis (260°, 25°).
Figure 14. Systematic foliation and lineation groupings of three consecutive domains. (A) foliation groupings, (B) corresponding lineation groupings, and notice that the fold axis is colinear with the corresponding lineation only in the first combination but not in the other combinations. Confidence interval = 2 sigma.
explained by deformation about a fold axis. Foliation from all structural domains
produced an apparent fold axis plunging at 25° towards 260°. Stretching mineral
lineations from all domains are also plotted together and shows S-SSW to N-NNE
movement direction (Fig. 15B).

Two different types of folds are common in core complexes. One fold set has
axes that are subparallel to the stretching mylonitic lineation of the shear zone whereas
the second fold set has axes perpendicular to the extension direction. Fletcher et al.
(1995) described two orthogonal fold sets in extensional mylonites of the Cenozoic
central Mojave metamorphic core complex. Mesoscopic fabrics related to the transport-
parallel fold set indicates that the folds record true crustal shortening perpendicular to the
extension direction. They interpreted these folds to form in response to elevated
horizontal compressive stress perpendicular to the extension direction. Mesoscopic
fabrics related to the later fold set, whose axial surfaces are at high angle to the mylonitic
foliation, include joints, kink bands, and echelon tension-gash arrays. The authors
interpreted these fabrics to have formed after mylonitization and record both layer-
parallel extension and subvertical shear, and to be kinematically compatible with rolling
hinge-style rebound of the footwall during tectonic denudation. Isostatic folds are broad
folds that form in response to differential unloading of the footwall of normal faults and
are the only mechanism that will fold normal faults about strike-parallel axes during slip
on a single normal fault (Janecke et al., 1998).

Corrugations may be considered as folds of a planar surface (Spencer, 1999).
Spencer (1999) suggested that synextensional molding is a possible cause of
corrugations of mylonitic rocks in footwalls of metamorphic core complexes, and
proposed a mechanism for corrugation formation called “continuous casting”.
According to this model, corrugations form when a mid-crustal, plastically deforming
shear zone and its footwall are displaced beneath a more rigid hanging wall that contains
Figure 15. (A) Stretching lineation from all domains of the shear zone. (B) Equal-area stereoplot of poles to mylonitic foliation and stretching lineation from well-exposed part of the shear zone (domain 3). Notice the matching of the mean vector lineation and the fold axis (215°, 35°). Contouring is by Kamb method. Contour interval = 2 sigma.
primary corrugations in its segmented brittle fault. Structural studies of plastically
deformed rocks below corrugated detachment faults show constrictional strains with
elongation parallel to corrugations (Mancktelow and Pavlis, 1994; Fletcher et al., 1995),
compatible with this mechanism of formation.

In general, transport-parallel folds are synmylonitic, exhibit wide ranges of styles,
and generally have axis parallel to the extension direction of the shear zone (Fletcher et
al., 1995). In the Pinto shear zone, a transport-parallel fold axes may explain the
foliation variation between domain 3, domain 2, and domain 1 (Fig. 15A). However,
apparent fold axes for other combinations of domains are not subparallel to lineation,
suggesting that the variation in the lineations and foliation in the Pinto shear zone may
not be simply explained solely by the unroofing processes. Overall, the change in
foliation and lineation can't be explained by folding and the reason for their variation
remains unclear.

Younger deformations may have rotated the Pinto shear zone. The Pinto shear
zone is cut by the 13 Ma Nipton fault in the northwest and the Cedar Canyon fault in the
southeast (Miller et al. 1996). During the movement of these faults, which have very
different sense of movements, the Pinto shear zone block might have been rotated and
internally deformed. This may be especially true for the northwestern part of the shear
zone that is cut by the NE-striking Nipton fault.

Alteration in the Pinto shear zone

The northern and northwestern part of the shear zone and its footwall are
moderately to highly altered. The major alteration type is sericitization and silicification.
Sericitization is mainly seen at vein margins and along joint planes. The mylonitic
porphyritic phase of the Mid Hills adamellite seems more susceptible to alteration than
the equigranular type. Due to alteration, the mylonitic porphyritic granite in the shear
zone is weathered and irregular in outcrop distribution. The mylonitic porphyritic
granite in the eastern part of the shear zone and the undeformed granite in the footwall is altered and cut by quartz veins ranging in thickness from 1 to 7 meters. In most cases, quartz veins fill E-W oriented joints; however, in places undeformed muscovite-rich quartz veins ranging in thickness from 1-16 centimeters (central part of the shear zone) also fill N-S joints. In most places joints running parallel to the lineation (~ N-S) are not filled by quartz veins. The intensity of alteration increases dramatically towards the northern part of the shear zone to the extent that, in places, it is difficult to identify the protolith. The northern part of the shear zone and its footwall are characterized by intense alteration and quartz veins.

Miller et al. (1996) also mapped a hydrothermally altered zone to the north in the footwall of the Pinto shear zone. The reason why the alteration is apparently confined to the northern part of the shear zone and its footwall is not clear.

Microscopic studies indicate that samples collected from different parts of the shear zone have extension fractures filled by muscovite and quartz. This is particularly true for samples (MB99NY-30 and 31) collected from the southeastern part of the shear zone. In this locality, fractures filled by muscovite and subordinate quartz in feldspar porphyroclasts (MB99NY-30 and 31) indicate a syn-shearing alteration process. Muscovite is not observed in undeformed Mid Hills adamellite, but is common in the mylonite. Additionally, breakdown of plagioclase feldspars into muscovite and white mica is not uncommon throughout the length of the shear zone. In the northwestern and northern part of the shear zone and its hanging wall, pulled-apart plagioclase feldspars and fractures are filled by fibrous K-feldspar grains and subordinate quartz. Additionally, fibrous quartz grown in strain shadow of pyrite was noted within the shear zone and in the hanging wall.

Strain softening could be assisted either by reaction softening or fluid related softening, or a combination of the two processes (White and Knipe, 1978; Beach, 1980).
Reaction softening occurs when deformation is accompanied by the formation of new minerals that deform more easily than the minerals from which they were derived (White and Knipe, 1978; Beach, 1980). Fluid-related softening occurs when fluids dissolve and remove grains that otherwise resist ductile deformation. The dissolved materials may not necessarily form new minerals of different composition, as in reaction softening, but may instead be reprecipitated as the same mineral in pressure shadows or veins, or else be entirely lost from the rock as the fluid flows out of the shear zone.

The presence of face-controlled pressure shadows around pyrite and the development of white mica (muscovite) along fractures in feldspar may indicate that sufficient fluids were present to induce strain softening by reaction softening and fluid related softening. The northern part of the shear zone has a lot of leached cavities of different sizes (millimeter to a centimeter in diameter), probably indicating dissolution and loss of the dissolved materials out of the shear zone during the fluid flow.

The genesis of fracture fill K-feldspar is not clear. However, the presence of syntectonic, ubiquitous myrmekites in almost all of the thin sections may suggest a source of free potassium ion to form the new K-feldspars. The replacement of K-feldspar by myrmekite (quartz + plagioclase) during deformation may have produced a free potassium cation and which may have in turn combined with silicate cation to form K-feldspar which precipitated in network fractures and pull aparts plagioclase feldspar.

The E- and NW-striking ridge-forming muscovite-quartz veins in the shear zone are deformed, indicating two possibilities, both the alteration and quartz veining were pre-shearing, or the alteration and the quartz veining were syn-shearing. If the interpretation that alteration occurred during shearing is correct, then deformation in the Pinto shear zone was assisted by the introduction of fluids, which helps to soften and localize strain in a narrow zone.
CHAPTER 4

KINEMATIC STUDIES OF PINTO SHEAR ZONE

Introduction

Kinematic analysis is the study of indicators of the flow regime operating during deformation. Kinematic indicators are structures that allow reliable inferences about the displacement field of material particles (flow) in the rock during progressive deformation to be made. The direction of movement of a ductile shear zone is usually assumed to lie subparallel to stretching mineral lineations with the exception of transpressional shear zones (Passchier and Simpson, 1986). According to the strain model of simple shear, the extension lineation measured in the field closely tracks the shear direction in strongly strained rocks (Hanmer and Passchier, 1991). Shear-sense observations are best viewed in the XZ plane of the finite strain ellipsoid. Foliation is taken to lie approximately parallel to the XY plane of the finite strain ellipsoid, and the lineation is taken to mark the X direction. Shear-sense indicators are a subset of kinematic indicators that indicate the sense of shear in progressively noncoaxially deformed materials.

Kinematic studies in the Pinto shear zone were mainly done using microstructural and lattice-preferred orientation studies, and mesoscopic features. These studies were performed to test the hypotheses that the Pinto shear zone is a low-angle normal fault. Each of these studies is presented below.
Mesoscopic structures

Lineation and foliation are the major mesoscopic structures documented in the Pinto shear zone, however, S-C fabrics in the central and near the top of the northwestern parts of the shear zone and small folds of aplitic dikes in the central-southeastern part of the shear zone were also noted.

S-C fabrics are the most useful sense-of-shear indicator in ductile shear zones (Berthé, et al., 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984; Hanmer and Passchier, 1991). S-C fabrics are composite planar fabrics formed during non-coaxial deformation (Berthé et al., 1979; Lister and Snoke, 1984). They consist of two sets of foliations: S-surfaces and C-surfaces. As the rock progressively deforms in non-coaxial deformation, the S-surfaces generally form first and with increasing shear strain C-surfaces start to form, and then S and C continue to develop together. The S-surfaces are defined by elongate quartz ribbons and are approximately parallel to the XY plane of the finite strain ellipsoid whereas the C-surfaces are zones of high shear strain approximately parallel to the shear zone boundary and are marked by mica-rich zones. With increasing deformation, S-surfaces progressively rotate toward parallelism with C, and the C-surfaces may become more closely spaced and better developed. At very high strain, S becomes subparallel to and indistinguishable from C.

S-C fabric is most clear in weakly to moderately foliated mylonites with small percentages of micas, and probably reflects inhomogeneous simple shear (Passchier and Trouw, 1996). There are two types of S-C fabrics: Type-I and Type-II. Type-I is common in granitoid rocks and consists of S planes (defined by feldspar porphyroclasts) transected by C planes (defined by concentrated flow of phyllosilicates and quartz ribbons) that are continuous, and parallel to shear zone boundaries. Type-II S-C fabrics are most common in micaceous quartzite and are dominated by C planes.
Type-I S-C fabrics are found in the Pinto shear zone. The S planes are defined by the long dimension of feldspar porphyroclasts whereas the C planes are defined by concentrations of mica (Fig. 16). The angle between S and C planes was measured and generally varies from 15° to 35°. The variation of angles between S and C surfaces reflects the heterogeneity of strain in the shear zone with lower angles corresponding to higher shear strains. The S-C fabric in the shear zone shows top-to-the-SW sense of shear (Fig. 16).

Minor folding of the aplitic dikes are not uncommon in the eastern and central part of Pinto shear zone. At one locality in the central part of the shear zone, a fold hinge plunges at 24° towards SSW (200°) and is parallel to the mylonitic lineation (shear direction).

Microstructures within the shear zone

Microstructural features encountered from different parts of the Pinto shear zone, including oblique grain-shape fabrics, winged feldspar porphyroclasts, S-C fabrics, mica fish, and shear bands are considered to provide important information on the kinematics of deformation.

Oblique grain-shape fabrics

An oblique grain-shape fabric is defined by aligned subgrains and dynamically recrystallized new grains oblique to the long axis of C-foliation defined by larger individual grains, ribbons, and mica. Aggregates of dynamically recrystallized small grains in monomineralic aggregates (quartz and calcite), showing a preferred alignment oblique to the mylonitic foliation (with constant sense of obliquity) have been observed by many previous workers (Law et al., 1986; Means 1981; Lister and Snoke, 1984) and used as a sense of shear indicator.
Figure 16. Photograph of S-C fabric, from the central (domain 3) part of the Pinto shear zone (Plate 1), indicating top-to-the-SW shear sense.
In the Pinto shear zone, dynamically recrystallized quartz grain aggregates are commonly aligned oblique to the C-foliation. These microstructures are observed in samples from most localities of the shear zone (Fig. 17A). The oblique grain-shape fabrics indicate top-to-the-southwest sense of shear.

**Winged feldspar porphyroclasts**

Winged feldspar porphyroclasts with recrystallized tails are extremely important for sense of shear determination in high strain zones (Simpson and Schmid, 1983; Lister and Snoke, 1984; Passchier and Simpson, 1986). Winged porphyroclasts can be of two types, σ and δ, depending on the rate of recrystallization relative to the rate of shear strain. If the rate of recrystallization to shear strain is high, the flow of recrystallized material in the tails away from the porphyroclast is continuously supplemented by the production of new recrystallized grains, resulting in the wedge-shaped tails of σ grains. In the reverse condition, there is insufficient new recrystallized material added to the tail to form a wedge, as a result, the narrow tails are dragged around with the rotating δ-type grain. The sense of shear is given by the sense of stair-stepping of the tails (wings) on either side of the porphyroclast.

In the Pinto shear zone, σ-type K-feldspar porphyroclasts are commonly observed. The σ-type K-feldspar porphyroclasts demonstrate top-to-the-southwest sense of shear (Fig. 17B).

Winged K-feldspar porphyroclasts cut by syntectonic, muscovite and quartz filled tensile fractures are noted from the thin sections collected from the central and southeastern part of the shear zone (Figs. 18C, 18D).

**S-C fabrics**

Samples collected from the southeastern, central, and northwestern part of the shear zone show elongate quartz ribbons and mica-rich zones of concentrated shear, defining S-C fabrics, that consistently indicate top-to-the southwest sense of shear,
Figure 17  Microstructures from the eastern part of the shear zone that indicate top-to-SW shear. (A) Oblique grain shape of quartz. $S_A$ is defined by mica-rich zones and $S_B$ is defined by the long axis of dynamically recrystallized quartz grains, indicating top-to-the-SW (sinistral) shear. (B) $\sigma$-type K-feldspar porphyroclasts showing top-to-the-SW (sinistral) sense of shear.

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Figure 18. Microstructures from the southeastern part of the Pinto shear zone, indicating top-to-southwest sense of shear. (A) Elongate quartz ribbons and mica-rich zones of concentrated shear, respectively, define S and C foliations indicating top-to-southwest (sinistral) shear. (B) Preferred alignment (S_B) of elongate quartz ribbons is oblique to foliation (S_A) defined by mica and relict of elongate quartz ribbons. (C) K-feldspar porphyroclast from the same thin section as of (A) showing recrystallized new grains in the tails of a σ porphyroclast parallel to the S surfaces. Note the tensile fractures filled by quartz developed almost perpendicular to the long-axis of the feldspar porphyroclast. (D) K-feldspar porphyroclast from the same thin section as (B), showing muscovite-filled tensile fractures. Note also the recrystallization of the K-feldspar on the two ends of the grain parallel to the S surfaces (incremental extension direction) and the development of myrmekite on the sides of the porphyroclast facing the incremental shortening direction.
Parallel to the stretching mineral lineation (Figs. 18A, 18B). The S planes are commonly defined by oblique quartz ribbons whereas C planes are defined by micas and very fine-grained dynamically recrystallized quartz.

**Mica fish**

Mica that exhibit stair-stepping of their wings are referred to as mica fish and are a reliable sense of shear indicator (Lister and Snoke, 1984). In most cases trails of small micas extend into the matrix from the tips of isolated mica fish defining C-surfaces (Lister and Snoke, 1984). The stair-stepping across the fish can be used as a sense of shear indicator. Mica fish were especially useful as a shear sense indicator from the deformed porphyry dikes.

A sample collected from a deformed dike in the central part of the shear zone has biotite fish which indicate top-to-the-southwest sense of movement, parallel to the gently southwest (228°) plunging lineation (Fig. 19).

Biotite fish from two different outcrops of deformed porphyry dikes in the northwestern part of the shear zone show top-to-the-north sense of shear (Fig. 20A). The first thin section collected from an outcrop beneath the top of the shear zone whereas the second thin section is collected from a porphyry dike within the center of the shear zone. Field observation and microscopic studies of the mica fish from the dikes indicate top-to-the-north sense of shear, parallel to the northerly plunging lineation.

**Shear bands**

Shear bands are thin zones of very high shear strain within the main shear zone and many of them are microscopic and can be either parallel or oblique to the main shear zone (Davis and Reynolds, 1996). A shear band is synthetic if it is inclined in the same direction as the overall sense of shear, and antithetic if inclined in the opposite direction.
Figure 19. Mica fish from a deformed porphyry dike in the central, well exposed part of Pinto shear zone, indicating top-to-the-southwest (sinistral) shear.
Figure 20. Microstructures in the northwestern part of the shear zone indicating dominantly top-to-north shear. (A) Biotite fish and weakly developed shear bands from a deformed porphyry dike within the shear zone indicating top-to-north sense of shear. (B) Weakly developed shear bands indicating top-to-the-south shear. (C) Preferred alignment of elongate, dynamically recrystallized quartz grains ($S_B$) developed from the mylonitic foliation ($S_A$) defined by elongate quartz relict grains, indicating top-to-the-north shear. (D) Antithetic shear fractures in feldspar porphyroclast. Note that the fractures are developed along the cleavage planes.
Samples of mylonite and deformed porphyry dike in the northwestern part of the shear zone close to the zone overprinted by the brittle deformation show weakly developed oblique shear bands. The shear bands from the mylonite indicate top-to-the-south (synthetic) sense of shear (Fig. 20B) whereas the shear bands from the dike show top-to-the-north (antithetic) sense of shear (Fig. 20A).

Microstructures from the sheared margins of the porphyry dikes

Mica-fish

The mica (biotite) fish from the sheared margins of the porphyry dikes in the northwestern part of the Pinto shear zone hanging wall consistently show top-to-the-northwest sense of shear (Fig. 21A). Porphyry dikes in the E-W striking ductile-brittle hanging wall fault zone exhibit biotite fish that show top-to-the-NW sense of movement parallel to the shallowly plunging lineation.

Bookshelf synthetic microfracturing

Synthetic microfractures along the cleavage of plagioclase feldspar is observed from a sample collected from the sheared margin of the porphyry dike in the hanging wall of the northwestern part of the shear zone (Fig. 21B). The sense of slip of the book shaped feldspars is in agreement with the sense of shear of the biotite fish described above.

Quartz C-axis preferred orientation studies

In any deformed rock, the lattice orientations of crystals are not randomly distributed but arranged in a systematic way that reflects the mechanism and temperature of deformation. Lattice-preferred orientation studies are used to study the kinematics (strain path and sense of shear) and temperature conditions in combination with microstructural and deformation mechanism studies. Law et al. (1982) have pointed out

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Figure 21. Microstructural kinematic indicators from the sheared margins of the porphyry dikes in the hanging wall of the Pinto shear zone. (A) Biotite fish, indicating sinistral (top-to-the-northwest, toward 312°) sense of shear. (B) "Book shelf" synthetic microfracturing along the cleavage of feldspar, indicating top-to-northwest (sinistral) sense of shear. Notice the splitting of the grains into elongate book shaped fragments.

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that on theoretical grounds there exists a complete spectrum of deformation paths of differing non-coaxiality (vorticity). A commonly used measure of the degree of non-coaxiality deformation is the kinematic vorticity number ($W_k$) which is a measure of the rate of rotation relative to the rate of shortening. It is expressed by $W_k = \cos \beta$, where $\beta$ (beta) is the angle between the eigenvectors of zero angular velocity or the angle between the simple shear plane and the inclined eigenvector of the strain. For pure shear, $W_k = 0$ (zero averaged angular velocity) whereas for simple shear, $W_k = 1$ (non-zero averaged angular velocity). The variation in the degree of non-coaxiality will clearly be reflected in the crystallographic fabric produced by deformation. The asymmetry of fabric relative to foliation and lineation were used to deduce the sense of shear in the shear zone because with increasing shear strain, foliation and lineation are progressively rotated towards alignment with the shear zone boundaries.

In the theoretical modeling of quartz crystallographic fabric development by Lister and coworkers (e.g., Lister et al., 1978), they demonstrated a clear set of relationships between strain symmetry fabric pattern and finite strain axis for coaxial deformation. These relationships are supported by both experimental studies (e.g., Tullis et al., 1973) and analysis of naturally deformed quartzites (see review by Price, 1985). For approximate plane strain deformation, fabric simulations indicate that the quartz C-axis fabric will either display a cross-girdle (Lister et al., 1978) or a single girdle (Etchecopar and Vasseur, 1987) pattern intersecting the foliation perpendicular to the lineation. In the case of non-coaxial progressive plane strain deformation, other C-axis patterns develop, asymmetric to foliation and lineation (Fig. 22A and B, C and D). In the southeastern and central part of the shear zone, the asymmetry of the fabrics to foliation and lineation is marked (Fig. 22E and F, G and H), probably indicating the non-coaxial strain path increases towards the southeastern and central part of the shear zone. All the quartz C-axis preferred orientation plots produced a pattern that could
Figure 22. Quartz C-axis preferred orientation plots from different parts of the Pinto shear zone. (A) Scatter plot and (B) Kamb contour of a quartz vein from domain 1 of the shear zone. (C) Scatter plot and (D) Kamb contour of a quartz vein from the domain 1 of the shear zone. (E) Scatter plot and (F) Kamb contour of a quartz vein from the domain 2 of the shear zone, showing top-to-the-southwest (sinistral) sense of shear. (G) Scatter plot and (H) Kamb contour of a quartz vein from the domain 3 of the shear zone. All the Quartz C-axis plots indicate a pattern which could be formed at low temperature conditions of deformation. Note the degree of asymmetry of the pattern to the macroscopic foliation (east-west great circle) and lineation (open circle).
be formed in non-coaxial, relatively low temperature conditions of deformation (Fig. 22).

**Kinematic Models for porphyry dike deformation**

Based on the field relation of progressive attenuation and rotation of the porphyry dikes within the shear zone margin, deformation differences between the dikes in the hanging wall and within the shear zone, mesoscopic and microscopic kinematic studies, and the age of the dikes, two possible dike deformation models are proposed. (1) Top-to-the-N deformation of the dike margins occurred synchronously with shearing within the Pinto shear zone or, (2) Top-to-the-N shearing of the dike margins was followed by top-to-the-SW shearing within the Pinto shear zone.

In model 1, sheared dike margins in the hanging wall of the Pinto shear zone and deformation of the Mid Hills adamellite and associated dikes within the shear zone occurred at the same time. At this stage, the dikes are deflected where they cross the lower and upper shear zone boundaries (Fig. 23A). Subsequent movement and localization of strain at higher levels of the shear zone results in the formation of ultramylonite and further attenuation and deflection of the dikes towards parallelism with the shear zone boundary (Fig. 23B). The attenuation and progressive rotation of the porphyry dikes downward as they pass from the hanging wall into the shear zone is clearly observed in the field.

In model 2, top-to-the-north shearing along the dike margins occurred first (Fig. 23C), followed by top-to-the-southwest shearing within the Pinto shear zone (Fig. 23D). The Mid Hills adamellite and porphyry dikes (that were already deformed at their margins) were deformed within the shear zone. The model predicts that in some places in the shear zone, porphyry dikes record top-to-the-southwest shear, similar to the shear sense recorded in the Mid Hills adamellite within the shear zone. At this stage, the dikes are deflected where they cross the lower and upper shear zone boundaries.
Figure 23. Schematic cross sections showing two possible models for dike deformation. Model 1, deformation of dike margins synchronously with shearing within the Pinto shear zone. Model 2, shearing of dike margins and subsequent deformation during the main Pinto shearing (see text for details).
Subsequent movement and localization of strain results in the formation of ultramylonite and further attenuation and deflection of the dikes towards parallelism with the shear zone boundary (Fig. 23E).

The high-angle dike-margin faults that record top-to-the-north shearing and the main shear zone that records top-to-the-south shearing, might develop as conjugate shear zones. If they are conjugate, the faults occur in two intersecting sets that are coordinated kinematically. The direction of principle stress can be inferred as the bisector of the angle between the two fault sets. In one locality in the shear zone, close to a deformed dike margin, weakly deformed Mid Hills adamellite show an abrupt increase in foliation development and gradually rotates (wraps) into parallelism with the dike margin, suggesting the weak "background" foliation in Mid Hills adamellite is part of the main top-to-the-SW fabric, whereas the strong dike margin foliation is part of the top-to-the-N fabric (Fig. 24). This observation implies that either the deformation of the porphyry dikes with top-to-the-north sense of shear postdates top-to-the-SW shearing or occurred synchronously. Similar azimuths of movement direction were inferred from the lineation plots of the sheared margin of the porphyry dike in the hanging wall, deformed porphyry dike within the shear zone, and mylonites and ultramylonites within the shear zone. (Fig. 25). Mapping of several of the porphyry dikes shows that the dikes are progressively thinned and deflected in orientation where they cross the upper shear zone boundary (Fig. 24 and Plate 1). The porphyry dikes are entirely deformed within the shear zone and the lineation plunge in the same direction as the local mylonitic lineation (Fig. 25). For example, in the northwestern part of the shear zone (domain 4), the lineation within the dikes plunge at shallow angles (3-16°) to the north, as do some of the lineation in this part of the shear zone (Figs. 25B, 25C). Additionally, lineation within a porphyry dike and the mylonitic adamellite in the central part of the shear zone both plunge to the SSW (Figs: 25D, 25E).
Figure 24. (A) Kinematic model showing deformation style of the Mid Hills adamellite and associated dikes within the shear zone and in the hanging wall. Note that the dikes are entirely deformed by top-to-the-north shearing within the shear zone but only deformed at the margins in the hanging wall. (B) Photograph showing deflection of weakly developed foliation in the Mid Hills adamellite towards parallelism with the dike margin.

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Figure 25. Comparison of lineations between deformed dikes and Mid Hills adamellite. (A) Lineation of the sheared margin of the porphyry dikes in the hanging wall. Mylonitic lineation in the Mid Hills adamellite (B) is colinear with that in the dikes (C) in the northwestern part of the shear zone. (D) Mylonitic lineation in Mid Hills adamellite is colinear with the deformed dike lineation (E) in the central part of the shear zone.
Regardless of the fact that R and R’ shears occur in the same rock mass and same structural level, in the Pinto shear zone, the high-angle faults that record-top-to-the-north shearing is similar to conjugate Riedel shears (R’-shears)-type. The Pinto shear zone was formed by top-to-the-south shearing whereas the sheared margins of the porphyry dikes in the hanging wall were formed by top-to-the-north shearing. It is known that conjugate faulting brings about simultaneous stretching and shortening (Wilcox et al, 1973). The above discussion supports model (A) as a preferred model to link dike shearing in the hanging wall with deformation in the main shear zone.

**Interpretation of kinematic studies**

All sense of shear indicators within the Pinto shear zone consistently show generally down-dip, top-to-the-SSW sense of shear, indicating the Pinto shear zone is a low-angle normal fault. Sense of shear indicators from the sheared margin of the porphyry dike in the hanging wall record antithetic, down-to-the-NNW shear sense. East-striking deformed porphyry dikes within the less strained part of Mid Hills adamellite in the northwestern part of the shear zone are also deformed by top-to-the-N shear. However, deformed porphyry dikes from the central part of the Pinto shear zone records top-to-the-SW sense of shear, similar to the country rock mylonites.

Top-to-the-NNW and N shearing of the porphyry dike in the hanging wall and in the northwestern part of the Pinto shear zone occurred synchronously with top-to-SW shearing within the shear zone. The similar azimuths of the movement directions inferred from the lineation plots of the deformed dikes in the shear zone, sheared margins of the porphyry dikes in the hanging wall, and mylonites within the shear zone, supports the interpretation that porphyry dikes were deformed synchronously with Mid Hills adamellite. Further support for the synchronous deformation interpretation is provided by field relationships across the upper shear zone boundary. The difference in deformation probably resulted from the difference in composition between the Mid Hills adamellite.
adamellite and the porphyry dikes and initial orientations of the porphyry dikes. Therefore, both top-to-the-north and -southwest shearing of the porphyry dikes probably occurred synchronously with top-to-the-southwest shearing of the Mid Hills adamellite.

In the E-W striking hanging wall ductile-brittle fault zone, at least the dike margin shearing and ultramylonite formation might have been initiated at the same time as shearing of the porphyry dikes in the other parts of the hanging wall. This is supported by similarity between lineation orientation between the sheared dikes and ultramylonites from this fault zone (northwest plunge and NW-SE movement direction) and the lineation orientation of the sheared margin of the porphyry dikes in the hanging wall. The ubiquitous occurrence of ultramylonite float throughout the length of this fault zone indicates that the ductile fault rocks (ultramylonites) have been overprinted by a brittle fault. This brittle fault might be temporally related to the Miocene Cedar Canyon fault that cuts the Pinto shear zone in the eastern part of the shear zone (plate I).

Based on the difference in deformation style of the porphyry dikes in the hanging wall and in the shear zone, field relation of the dikes and the shear zone boundary, and age of the 80 Ma porphyry dikes, the following sequence of events is proposed: (1) intrusion of the Mid Hills adamellite (97-92 Ma) followed by intrusion of leucocratic (aplitic) dikes; (2) intrusion of the porphyry dikes (80 Ma) along shear fractures (?); (3) top-to-the-south ductile shearing in the Pinto shear zone, top-to-the-north shearing of the porphyry dikes in the hanging and locally within the shear zone; (5) brittle overprinting along the Pinto shear zone; and (6) brittle overprinting in the E-W striking ductile fault in the hanging wall.
Summary of kinematics studies in Pinto shear zone and in its hanging wall

All sense of shear indicators, including oblique grain-shape fabrics, S-C fabrics, biotite fish, winged feldspar porphyroclasts, quartz C-axis preferred-orientation studies, and shear bands from the mylonite, ultramylonite, and deformed dike (in the central part of the shear zone), consistently demonstrate top-to-the-S-SW, generally down-dip shear sense (Figs. 16, 17, 18, 19, 20, and 22). This down-dip, top-to-the-S-SW movement within the Pinto shear zone suggests a normal-sense movement.

All thin sections studies from the sheared margins of the porphyry dike in the hanging wall, and deformed dike within the lesser deformed lenses within the shear zone record top-to-the-N-NW down-dip sense of shear. However, deformed porphyry dike from the central part of the Pinto shear record top-to-the-SW sense of shear, similar to the country rock mylonites. Additionally, observations of deflection of foliation along the sheared margins of the porphyry dike help to determine sense of shear in the field (Fig. 24). The deflection of foliation indicates down-to-the-north sense of movement.
CHAPTER 5

DEFORMATION MECHANISM STUDIES

Introduction

Deformation in rocks is achieved by a large number of processes on the scale of individual grains. The actual processes involved depend on lithological controls such as mineralogy, composition and abundance of intergranular fluid, grain size, lattice-preferred orientation, porosity and permeability, and on external controls such as temperature, lithostatic pressure, differential stress, fluid pressure and externally imposed strain rate (Passchier and Trouw, 1996). Each deformation mechanism is important in a specific range of temperature and strain rate. Each deformation mechanism produces specific microstructures in a specific temperature range. As a result, microstructures can be used to infer temperatures during deformation (Simpson and De Paor, 1991). Ductile deformation of rocks is to a large extent achieved through the migration of dislocations and vacancies. Dislocations have a distinct orientation with respect to the crystal lattice and can move only in specific crystallographic planes and directions. The type of slip system active in the crystal depends on the magnitude and orientation of the stress field and the strongly temperature dependant, critical shear stress (the shear stress required to activate each slip). Microscopic studies of grain-scale microstructures were carried out in each domain to identify the deformation mechanisms operating during deformation.
Furthermore, by identifying deformation mechanisms, the approximate range of temperature at which the rocks were deformed in each domain is estimated.

Microstructural studies for deformation conditions

Since feldspar and quartz are the major rock forming minerals in the deformed Mid Hills adamellite (granitic rocks), microstructural studies of these minerals were carried out to identify the deformation conditions in the Pinto shear zone. There is no major difference in deformation condition of these minerals from domain to domain along the length of the shear zone, so the observations are not presented separately for each domain. Deformation conditions of feldspar and quartz are presented separately below.

Deformation condition of feldspar

Overall, K-feldspar throughout the shear zone displays a core-and-mantle texture (Figs. 26A and B), whereas plagioclase feldspar in most cases behaves brittley (Fig. 27B). A core-and-mantle texture is used here as a purely descriptive term for any grain with small new grains in an outer mantle surrounding a much less deformed inner zone (core). White (1976) interpreted mantled porphyroclasts as a consequence of plastic deformation and storage of dislocation tangles in the rim of porphyroclasts, in response to flow in the matrix. Rims of the porphyroclast then preferentially recrystallize to a core-and-mantle structure. The fine-grained soft mantle can be deformed into wings (tails) that extend on both sides of the porphyroclast parallel to the shape fabric in mylonite (Passchier and Simpson, 1986).

K-feldspar displays an early dynamic recrystallization followed by cataclasis. In most thin sections, about 90% of the K-feldspar porphyroclasts show mushroom-shaped myrmekite (quartz + plagioclase) on grain margins that are facing the inferred incremental shortening direction (Fig. 28), and dynamically recrystallized
Figure 26. Microstructure showing core-and-mantle structure. (A) K-feldspar porphyroclast with rims of recrystallized myrmekite and tails of recrystallized K-feldspar, forming a core-and-mantle structure. (B) K-feldspar porphyroclast with rims and tails of fine-grained mantle, forming a core and mantle structure, probably indicating subgrain rotation recrystallization.
Figure 27. Microstructure showing brittle deformation of feldspar. (A) Feldspar porphyroclasts show both ductile (recrystallized into fine-grained feldspars at rims and tails) and brittle (grain size reduction along fractures) deformation. (B) and (C) Feldspar porphyroclasts deformed by network fractures, grain size reduction along the fractures and grain boundaries.
Figure 28. Photomicrographs showing myrmekite. (A) Sigma-type K-feldspar porphyroclast showing mushroom-shaped myrmekite developed on the side of the grain facing the incremental shortening direction, and recrystallized new feldspar grains in the tails of the porphyroclasts facing the incremental extension direction. Note also the fine-grained mantle surrounding the myrmekite which has the same size and composition as the matrix. (B) Closeup of myrmekite from one side of the K-feldspar porphyroclast (A) facing the shortening direction. (C) Closeup of myrmekite developed from two neighboring K-feldspar porphyroclasts. Note the fine-grained zone formed by the myrmekite, indicating myrmekite probably promoted strain softening. (D) K-feldspar porphyroclast showing myrmekite altered into muscovite at the margin of the intergrowth.
new grains in their tails. Simpson and Winstch (1989) reported evidence for deformation-induced K-feldspar replacement by myrmekite, including the observation that myrmekite occurs only on the two ends of the grain that faced the incremental shortening direction. The two ends of the grains that faced the incremental stretching direction, on the other hand, have recrystallized into new grains of K-feldspar, coarser than the matrix. The replacement of K-feldspar by myrmekite ("a plagioclase-vermicular quartz symplectite") during deformation was suggested first by Futterer (1894) who observed a greater development of myrmekite in deformed plutonic rocks than in their undeformed equivalents. More recently, Hanmer (1982) and Tullis (1983) have suggested a correlation between myrmekite growth and crystal-plastic deformation. A sample collected from the northwestern part of the shear zone (domain 4) shows a relatively fine grained, deformed zone of myrmekites developed from two adjacent K-feldspar porphyroclasts (Fig. 28C). This implies myrmekite formation might have eased deformation by promoting strain softening due to a reduction in grain size inherent in myrmekite growth. The composition (plagioclase + quartz) and grain size of the mantle is similar to the matrix, implying that the formation and deformation of myrmekite may have been a significant matrix-forming process.

In the central and northwestern part of the shear zone (domain 3, 4, and 5), K-feldspar shows a flame-shaped perthite tapering towards the center of the grains (Fig. 29). Perthite is thought to develop by exsolution of albite in K-feldspar that formed at high temperature. Exsolution proceeds preferentially at sites of intracrystalline deformation such as grain-to-grain contacts between two feldspar grains (Passchier, 1982; Pryer, 1993).

In the southeastern and central part of the shear zone, it is common to find muscovite and quartz-filled, dilational fractures (tensile fractures) (Figs. 18C & D) which cut K-feldspar porphyroclast cores, myrmekites and dynamically recrystallized...
Figure 29. K-feldspar porphyroclast showing flame-perthite developed parallel to S surfaces and myrmekites developed in the opposite direction facing the incremental shortening direction.
K-feldspars. Overprinting of brittle deformation on the earlier ductile features is greatest towards the top of the shear zone. In the northwestern and western part of the shear zone, particularly towards the top part of the shear zone, the feldspar grains exhibit fracture networks with a reduction in grain size along the fractures (Figs. 27B and C). These fractures are most probably related to the overprinting of the NW-striking brittle zone on the top of the shear zone. Since the intensity and thickness of the zone of brittle deformation increases towards the northwest, it affected much of the earlier ductile features.

The growth of biotite as pressure shadows on the two ends of K-feldspar porphyroclasts in the western part of the shear zone (domain 6) indicates a syntectonic growth of biotite which requires a temperature ranging from 350-650 °C (Rutherford, 1969) (Fig. 30A and B). Dark quartz grains in XZ sections in crossed polars which indicate C-axis maxima around the Y-axis also support this interpretation. Single C-axis maxima around the Y-axis are common at medium to high temperature (450-600 °C) (Mainprice et al., 1986).

**Deformation condition of quartz**

Hirth and Tullis (1991) and Passchier and Trouw (1996) demonstrated the presence of different microstructural features in quartz formed at different deformation temperatures. In low temperature deformation, different slip systems intersect in a crystal and migrating dislocations can become entangled and create strain hardening. During this stage, microstructures like deformation lamellae and undulose extinction can be formed. Gentle bending of the lattice by distributed dislocations result in undulatory extinction that is marked by sweeping extinction of crystals in crossed polars (Passchier and Trouw, 1996). At elevated temperature, climbing of dislocations is easily achieved, and recovery processes concentrate dislocations into walls and deformation bands, subgrains, and eventually new grains are formed.
Figure 30 (A) and (B) Syntectonic growth of biotite in strain shadows of feldspar porphyroclast.
In the Pinto shear zone quartz shows variable degrees of dynamic recrystallization. Quartz shows evidence for both relatively high temperature and low temperature deformation (Fig. 17A). Quartz is entirely recrystallized showing well developed straight to irregular (lobate) grain boundaries (domain 1 and 4) (regime 3 of Tullis and Hirth, 1993), indicating recovery by grain boundary migration recrystallization (Figs. 17A and 31A). On the other hand, quartz also shows deformation lamellae and undulose extinction, indicating deformation at low temperature conditions (Fig. 32C).

Thin sections of quartz veins at the top of the shear zone show stretched and irregularly flattened quartz ribbons (domain 2 and 3). The ribbons show variable degree of recrystallization at grain boundaries (Fig. 31C). The preservation of small grains in mylonites indicates that little growth has occurred after recrystallization. In some instances this may be due to grain growth inhibition by grain boundary inclusions and bubbles (White, 1979). In other cases there is no clear cause for the fine grain size, but may be due to the rapid equilibration of dislocation densities from grain to grain after recrystallization (White, 1976) because temperature is too low to permit grain growth by grain boundary migration recrystallization. In the same transect, a quartz vein collected from the center of the shear zone shows well-defined, irregular grain boundaries and bulging structure. The direction of the bulging indicates the direction of grain boundary migration during deformation.

Discussion and interpretation of deformation mechanism studies

Quartz microstructures indicate that dynamic recrystallization was operating in quartz in all domains of the shear zone whereas feldspars in general show a core-and-mantlestructure, myrmekite, reaction to muscovite, perthite (exsolution), and tensile...
Figure 31. Photomicrograph showing quartz deformation. (A) Quartz showing irregular grain boundaries and almost equigranular size indicating grain boundary migration recrystallization. (B) Deformed quartz band showing recrystallization of new quartz grains oriented at an angle with the old quartz ribbon. (C) Stretched and flattened quartz ribbons. The ribbons by show undulose extinction and recrystallization at their grain boundaries into relatively fine-grained quartz grains, indicating dislocation creep and recovery by grain boundary migration recrystallization.
Figure 32. Photomicrograph showing quartz deformation. (A) and (B) Irregularly flattened and elongated quartz ribbons from quartz veins, showing incipient recrystallization at grain boundaries. Note the irregular flattening of the original quartz ribbon in (A). (C) Deformed quartz vein showing deformation lamellae.
fractures. This indicates quartz has undergone entirely plastic (>250-300 °C) deformation whereas K-feldspars have undergone dominantly plastic (450-550 °C) and lesser brittle deformation (< 450 °C) (Simpson and De Paor, 1991). The presence of core-and-mantle structure and new grains at boudin necks in feldspars, and completely recrystallized quartz ribbons with straight and irregular boundaries indicate that the rocks had been deformed by dislocation creep and recovered by subgrain rotation recrystallization (dominantly for feldspar) and grain boundary migration recrystallization (dominantly for quartz). Subgrain rotation recrystallization occurs when dislocations are continuously added to subgrain boundaries. This happens only if dislocations are relatively free to climb from one lattice plane to another (climb-accommodated dislocation creep). These microstructures are likely to have developed in the temperature range of 450-500 °C (Passchier and Trouw, 1996).

The presence of myrmekite on the sides of feldspar grains that faced the incremental shortening axis and not on the long ends of feldspars that faced the incremental stretching axis provides evidence for the development of myrmekite during deformation of the Mid Hills adamellite. The occurrence of both well-formed myrmekite and recrystallized grains in distinct kinematic quadrants of the same feldspar grain implies that the processes responsible for producing these microstructures must have operated synchronously.

Quartz microstructures indicate that dynamic recrystallization was active throughout the shear zone. Intracrystalline creep is thermally activated and the lower limit of dynamic recrystallization in wet quartz occurs between 250 °C and 300 °C (Tullis, 1989). Assuming a linear geothermal gradient of 30° C/ km, this would occur at minimum depths of 8 to 10 kilometers. Dislocation climb becomes possible in feldspars and recrystallization starts at grain boundaries to form a core-and-mantle structure at a temperature range of 450-500 °C (Simpson and De Paor, 1991), corresponding a depth of 15 to 17 kilometers.
There is no significant difference in deformation mechanism between the porphyry dikes within the shear zone and those in the hanging wall. However, thin sections from the central part of the shear zone show flattened quartz ribbons partially recrystallized into new fine-grained quartz at grain boundaries and necks. Another porphyry dike from the northwestern part of the shear zone shows typical grain boundary migration recrystallization (bulging and nucleation) (Fig. 33). On the other hand, quartz microstructure of the porphyry dikes taken beneath the ultramylonite (close to the hanging wall) shows irregular quartz ribbon flattening, undulose extinction, and subgrains (Fig. 33D). This suggests that the degree of recovery decreases as one goes from the center of the shear zone towards the hanging wall, implying that deformation continued in structurally higher parts of the shear zone during decreasing temperatures.

Overall, the microstructural studies indicate deformation conditions ranging from moderately high temperature (450-550 °C) to low temperature (< 300 °C) conditions. There is microstructural evidence for deformation during decreasing temperature conditions. Quartz shows evidence for both relatively high temperature and low temperature deformation (compare Figs. 17A and 31A). Near the top of the shear zone, quartz is entirely recrystallized showing well developed straight to irregular (lobate) grain boundaries (regime to 3 of Hirth and Tullis, 1993), indicating recovery dominantly by grain boundary migration recrystallization (Fig. 17A). On the other hand, quartz also shows deformation lamellae and undulose extinction, indicating deformation at low temperature conditions (< 300 °C) (Fig. 32C). The presence of core-and-mantle structure and new recrystallized crystals at boudin necks in K-feldspar show a relatively high temperature condition of deformation (450-500 °C) whereas the presence of deformation twins (kink?), flame perthite, and extension fractures filled by muscovite and quartz indicate a lower temperature deformation condition. Extension fractures cutting across new K-feldspars grains and myrmekite
Figure 33. Microstructures showing deformation of the porphyry dikes within the shear zone. (A) and (B) Deformed quartz ribbons from central part of the shear zone, showing recrystallization of the old quartz into new grains at their grain boundaries and at the two ends of the ribbons. (C) Deformed quartz grains showing a typical grain boundary migration recrystallization. The grains with higher dislocation density (gray) were consumed by bulging of grain with low dislocation density (light). The bulge eventually developed into independent grains. (D) Deformed quartz ribbon showing undulose extinction, subgrains and dynamically recrystallized fine grained quartz developed parallel to the old quartz ribbon.
were noted, indicating superposition of lower on higher temperature deformation. This superposition of lower temperature on higher temperature deformation probably occurred during the progressive unroofing of the footwall block.
CHAPTER 6

$^{40}\text{Ar}/^{39}\text{Ar}$ THERMOCHRONOLOGY

Different minerals close to argon diffusion at different temperatures, as a result, cooling ages for different minerals can be combined to reconstruct the cooling histories of the rocks. The thermal histories for the hanging wall and footwall rocks of the Pinto shear zone were constructed by modeling of K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (Lovera, 1993), together with muscovite and biotite cooling ages. Additionally, this approach was used to approximate the age range for ductile deformation at temperature conditions of mylonitization.

The mineral separates of the five samples collected from the footwall, hanging wall, and within the shear zone (Fig. 34) were analyzed by $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology in the Nevada Isotope Geochronology Laboratory, University of Nevada Las Vegas. With the exception of the two samples collected from the center of the shear zone, muscovite, biotite, and K-feldspar were analysed in each sample. Due to the hydrous nature of muscovite, biotite, and hornblende, they are unstable in vacuum furnace. As a result we must use generic (hydrothermal) diffusion parameters.

The results of each analysis for mica are presented below according to their transect location.

**Mica ages, central transect**

Muscovite (MW98NY-1M) is from the hanging wall of the Pinto shear zone. This sample shows a stair-stepped age spectrum with increasing ages from $63.0 \pm 0.4$
Figure 34. Study area showing the map area, sampling transects for microstructural studies (open bar), and sample sites for dating (dark circle).
Ma to 74.4 ± 0.4 Ma. The total gas age is 72 ± 0.4 Ma (Fig. 35A). The isochron age is 70.1 ± 0.6 Ma (Fig. 35A) zone (Fig. 34). The Ca/K ratio is low (0.3), indicating there is no significant Ca-derived argon in the system (Fig. 35C), suggesting there are no Ca bearing phases in the mineral separate. Coexisting biotite (MW98NY-1B) yields a discordant age spectrum with a slight saddle at intermediate temperature steps. The first step produced an age of 67.8 ± 0.4 Ma whereas the last step is 72.3 ± 0.5 Ma (Fig. 35D). The total gas age for this sample is 71.2 ± 0.4 Ma, younger by 0.78 Ma than the total gas age of the coexisting muscovite (MW98NY-1M). This probably reflects the difference in closure temperature for muscovite (350-400 °C) and biotite (300 °C). The Ca/K ratio for this sample is small (< 0.35), indicating there is no significant Ca-derived argon in the system (Fig. 35F), suggesting the mineral separate is pure (no Ca-bearing phase).

Muscovite (MB99NY-25) was analyzed from a quartz vein filling a NW oriented fracture within the shear zone (Fig. 34). This sample produced a flat age spectrum, with a plateau age of 71.82 ± 0.3 Ma, similar to the total gas age of 71.9 ± 0.4 Ma (Fig. 36A). A plateau age is here defined by contiguous steps with a minimum of 50 % gas released. The isochron age is 72.2 ± 0.5 Ma and shows a good fit with a MSWD of 1.7 (Fig. 36B). The Ca/K ratio is 0.1, indicating there is no significant Ca-derived argon (Fig. 36C).

Muscovite (MB99NY-26) was collected from the footwall of the Pinto shear zone (Fig. 34). The muscovite occurs most dominantly in randomly oriented, very thin (< 0.5 millimeter) and long fractures (1-2 millimeters), indicating it is hydrothermal muscovite. The sample yields a slight age gradient from 68.9 ± 0.4 Ma to 72.4 ± 0.4 Ma (Fig. 37A). The total gas age of this sample is 70.4 Ma. Unless fracturing occurred at temperatures higher than muscovite closure for argon, the age of
Figure 35. $^{40}\text{Ar}/^{39}\text{Ar}$ apparent age spectra and the corresponding isochron and K/Ca ratio for hanging wall biotite and muscovite.
Figure 36. $^{39}\text{Ar}/^{39}\text{Ar}$ age spectrum and the corresponding isochron and K/Ca ratio for muscovite from the central part of the Pinto shear zone.
the muscovite should be the age of mineral growth in the fracture. Biotite suitable for analysis from the footwall in the northern transect was only found in the porphyry dikes that intrude the Mid Hills adamellite. Biotite (MB99NY-40) was analyzed from a fresh, undeformed porphyry dike (Fig. 34). The biotite is clearly igneous in origin, and the age of the biotite probably indicates a cooling age following crystallization. Excluding the first step, this sample produced a flat age spectrum, with a plateau age of 71.0 ± 0.3 Ma, similar to the total gas age of 70.90 ± 0.4 Ma (Fig. 37D). The isochron age for all steps is 71.4 ± 0.4 Ma, with MSWD of 1.35 (Fig. 37E). The Ca/K ratio is far below 0.2, indicating there is no Ca-derived argon in the system (Fig. 36F). The difference of the total gas age of the footwall biotite and the hanging wall biotite is insignificant (hanging wall is older by 0.22 Ma).

Mica ages, eastern transect

In this part of the shear zone, no Mid Hills adamellite is exposed in the hanging wall because it is covered by Cenozoic sedimentary and volcanic rocks. Samples were collected for thermochronology from within the shear zone and from the footwall. Muscovite within the shear zone (MB99NY-49) is from an ultramylonitic aplitic dike. A second sample of muscovite and biotite was collected from the Mid Hills adamellite (MB99NY-2) in the footwall.

Microscopic studies show that shear zone muscovite is clearly of igneous origin because it does not occur in fractures and also forms the mylonitic foliation. Excluding the first two steps, the sample yields a plateau age of 72.3 ± 0.3 Ma (Fig. 38A). The total gas age for this sample is 72.4 ± 0.4 Ma (Fig. 38A) which is similar
Figure 37. $^{40}$Ar/$^{39}$Ar age spectra and the corresponding isochron and Ca/K ratio of the muscovite and biotite from the footwall of the Pinto shear zone.
with the plateau age within one σ error. The isochron age is $72.8 \pm 0.4$ Ma and shows a good fit of points with a MSWD of 1.07 (Fig. 38B).

Similar to MB99NY-26 (from the NW footwall), the muscovite from MB99NY-2 occurs within randomly oriented, generally thin and long fractures. This sample produced an age spectrum ranging from $66.3 \pm 0.8$ Ma to $71.7 \pm 0.6$ Ma. The isochron age of this sample is $68.8 \pm 0.8$ Ma and shows good fit of all heating steps with a MSWD of 1.86 (Fig. 39B). Coexisting biotite (MB99NY-2) is clearly igneous biotite. All heating steps with the exception of the first, are between 72 and 74 Ma. The total gas age of this sample is $72.8 \pm 0.4$ Ma (Fig. 39D). The ages obtained at the sixth and seventh step are significantly higher (74.6 Ma), and may indicate the presence of excess argon. The isochron (Fig. 39E) suggests excess argon, however, excess argon is most commonly experienced in the first and last few heating steps. The absence of a corresponding hanging wall sample in this part of the shear zone did not allow a comparison of ages between the footwall and the hanging wall.

**K-feldspar ages**

In contrast to other minerals commonly used for $^{40}$Ar/$^{39}$Ar dating (e.g., biotite, muscovite, and hornblende), alkali feldspar is stable during long vacuum heating below the melting temperature.

The three K-feldspar separates from the hanging wall and the footwall were analyzed and modeled to construct thermal histories. The total gas age of the hanging wall K-feldspar is $70.9 \pm 0.4$ Ma whereas the two footwall K-feldspars have total gas ages of $70.8 \pm 0.4$ Ma (MB99NY-26) and $70.1 \pm 0.4$ Ma (MB99NY-2) (Fig. 40).
Figure 38. $^{40}$Ar/$^{39}$Ar age spectra and the corresponding isochron and Ca/K ratio of the muscovite from the eastern part of Pinto shear zone.
Figure 39. $^{40}$Ar/$^{39}$Ar age spectra and the corresponding isochron and K/Ca ratio of Muscovite and biotite from the footwall of the eastern part of the Pinto shear zone.
Table 1. Summary $^{40}\text{Ar}^{39}\text{Ar}$ of mica ages

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total gas Age (Ma)</th>
<th>Plateau age (Ma)</th>
<th>$^{39}\text{Ar}_p$ %</th>
<th>Isochron age</th>
<th>$^{39}\text{Ar}$ %</th>
<th>$^{40}\text{Ar}^{39}\text{Ar}$</th>
<th>MSWD</th>
<th>Field relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW98NY-1 Bi (ig)</td>
<td>71.2±0.7</td>
<td>-</td>
<td>72.3±2.2</td>
<td>100</td>
<td>277.6±13</td>
<td>37.2</td>
<td></td>
<td>Hanging wall MDA</td>
</tr>
<tr>
<td>MW98NY-1 Mu (ht + ig)</td>
<td>72.0±0.7</td>
<td>-</td>
<td>70.1±1.2</td>
<td>99.2</td>
<td>437.4±10.9</td>
<td>33.8</td>
<td></td>
<td>Footwall MDA in the eastern part of the shear zone</td>
</tr>
<tr>
<td>MB99NY-2 Bi (ig)</td>
<td>72.8±0.7</td>
<td>-</td>
<td>73.1±3.7</td>
<td>91.1</td>
<td>339.7±43.9</td>
<td>25.0</td>
<td></td>
<td>From the center of the shear zone</td>
</tr>
<tr>
<td>MB99NY-2 Mus (ht)</td>
<td>69.9±0.7</td>
<td>-</td>
<td>70.2±1.6</td>
<td>100</td>
<td>293.6±13.9</td>
<td>1.8</td>
<td></td>
<td>Undefomed porphyry dike in the footwall MDA in the footwall</td>
</tr>
<tr>
<td>MB99NY-49 Mus (ig)</td>
<td>72.4±0.8</td>
<td>72.3±0.3</td>
<td>72.8±2.2</td>
<td>100</td>
<td>288.6±6.7</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB99NY-25 Mu (vein)</td>
<td>71.9±0.8</td>
<td>71.8±0.3</td>
<td>97.1</td>
<td>97.1</td>
<td>282.2±12.7</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB99NY-40 Bi (ig)</td>
<td>70.9±0.8</td>
<td>71.0±0.3</td>
<td>96.0</td>
<td>71.4±0.1</td>
<td>284.9±4.8</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB99NY-26 Mu (ht)</td>
<td>70.38±0.8</td>
<td>-</td>
<td>69.1±0.8</td>
<td>96.6</td>
<td>342±13.2</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For sample with low MSWD, the best apparent age is the isochron age whereas for sample with high MSWD, the best age is the total gas age. Mu, Muscovite; Bi, Biotite; ig, igneous; ht, hydrothermal; MDA, Mid Hills adamellite. The percentage $^{39}\text{Ar}_p$ of the total $^{39}\text{Ar}$ in the sample that was released in the heating steps included in the plateau are shown. The $^{39}\text{Ar}_p$ column shows the percentage of the $^{39}\text{Ar}$ in the heating steps used for regressions. All uncertainties are quoted at 2σ confidence level. MSWD, mean square of weighted deviates.
Figure 40. Age spectra of K-feldspars from the hanging wall and footwall of the Pinto shear zone.
Modeling of K-feldspar age spectra

The stability of K-feldspar during vacuum heating makes possible the calculation of diffusion parameters (activation energy and frequency factor). Several authors (Berger & York, 1981a; Harrison & McDougall, 1982) used the measured $^{39}$Ar loss from irradiated K-feldspar during vacuum extraction to calculate argon diffusion coefficients. When diffusion coefficient was plotted against absolute temperature of the heating step, Arrhenius relationships were obtained. Results of these experiments generally produced a linear array for low temperature gas fractions. It is believed (Lovera, 1989; Harrison & McDougall, 1982) that the smallest sized diffusion domains are the ones that produce the initial linear array of the curve (low-temperature portion of the Arrhenius curve). The departure from linearity in the Arrhenius plots is explained by a distribution of diffusion domain sizes in the sample. Activation energy ($E$) is calculated from the slope of the initial linear segment. Assumption of the same activation energy for all domains is supported by a number of Arrhenius plots from recent experiments (Lovera, 1993) and is adopted here.

**Hanging wall K-feldspar (MW98NY-1K)**

The log ($D_0/r_0^2$) vs temperature and log ($t/r_0$) vs % $^{39}$Ar released plots of the sample and the model produced an excellent fit (Fig. 41A & B), indicating that the diffusion properties determined in the laboratory data are the same as those acting in a sample when in the geological environment.

Different models were run by varying the maximum input plateau age and the number of models. Overall, 15 cooling curves were produced by the program that fulfilled the criteria set by Lovera (1993) (Fig. 41D).
Figure 41. Multiple diffusion domain models for the hanging-wall K-feldspar (MW98NY-1). A single activation energy was assumed to best represent all diffusion domains, and was determined by linear regression of the lower temperature steps of the experiment on an Arrhenius diagram. The activation energy, frequency factor, volume fraction, and number of domains are determined by the autoarr. program. Closure temperatures for each domain are calculated iteratively using the activation energy and frequency factor. Using the diffusion parameters produced by autoarr., the thermal histories (D) and their corresponding ages (C) are produced by the autoage program.
Closure temperatures for the different domains were calculated iteratively using the activation energy (E) and frequency factor \( (D_0/r_0^2) \) (table 2), and assuming constant cooling rate. The closure temperatures range from 190 °C (smallest domain) to 348 °C (largest domain) and bound the upper and the lower ends of the steepest and overlapping segments of the 15 cooling curves produced by the program (Fig. 41D). The age of the steepest part of the cooling curves ranges from 64.0 to 71.1 Ma (Fig. 41D). Calculation of the slope of the steepest curve produced a cooling rate of 23° C/m.y. from 71.1 to 64.0 Ma. This is a fairly rapid cooling rate for the hanging wall block (Fig. 41D). The model age spectrum corresponding to the best fit cooling curves reproduce well the measured age spectrum of the sample (Fig. 41 C).

**Footwall K-feldspar (MB99NY-26K)**

This sample was taken from the footwall of the Pinto shear zone, along an azimuth parallel to the transport direction from the hanging wall sample. Manual fits to the Arrhenius data were conducted to get the best linear fit among the initial points. The best fits are obtained from points 3-6, which produced an \( r^2 = 1 \). Activation energy from the slope of these points is 55.8 kcal/mol. The activation energy and the Y-intercept of this graph were used as input data to run the autoarr program. The autoarr program produced a very nice fit of the log \( (D_0/r_0^2) \) vs temperature and log \( (r/r_0) \) vs % \(^{39}\)Ar released plots of the actual sample and the model (Fig. 42). The model was evaluated up to 50% \(^{39}\)Ar released.

Overall, the autoage program produced 10 best-fit cooling curves and corresponding age spectra (Fig. 42C & D). Using the calculated activation energy and frequency factor, closure temperatures were calculated iteratively for each domain. The closure temperatures range from 218 °C (smallest domain) to 412 °C (largest...
Figure 42. Multiple diffusion domain models of footwall K-feldspar (MB99NY-26). Manual fit to Arrhenius plot were performed and a linear array with $r^2 = 1$ was taken to calculate the activation energy.
domain) (Table 2). Table 2 shows the diffusion parameters and calculated closure temperatures for the different domains. The range of closure temperatures shows that this sample was more retentive for Ar than the footwall sample in the eastern part of the shear zone. The retentivity of this sample is also supported by the high activation energy of this sample, 55.8 kcal/mol. The range of the closure temperature coincides with the upper and lower ends the steepest part of the cooling curves. This part of the curve is interpreted as the cooling path of the footwall. The upper and lower age limits of the curve bounded by the closure temperature range in age from 67-71 Ma (Fig. 42C). The slope of the steepest curve gives a cooling rate for the footwall of 44 °C/m.y. (Fig. 42D).

**Footwall K-feldspar (MB99NY-2K)**

This sample was taken from the footwall of the eastern part of the shear zone. The sample shows a good fit of the log \( \log \left( \frac{D_0}{r_0^2} \right) \) vs temperature and log \( \log \left( \frac{r}{r_0} \right) \) vs \%\(^{39}\)Ar released plots of the actual sample and the model (Fig. 43A & D). The model goes up to 55-60\% \(^{39}\)Ar released. Diffusion parameters and calculated closure temperatures for the different domains are shown in table 2.

Twelve best fit cooling curves and corresponding age spectra are shown in Fig. 43D and C. The calculated closure temperature ranges from 200 °C (smallest domain) to 354 °C (largest domain). The upper and lower age limits of the steepest part of the cooling curves bounded by the closure temperature range in age from 65.6-70.2 Ma (Fig. 43D). The slope of the steepest curve gives the cooling rate of the footwall (44 °C/m.y.) (Fig. 43D).

Although the cooling curves produced are acceptable, only those curves that have the smallest chi-square values (with inflection at lower temperature part of the curve) are used to calculate the cooling history of the footwall K-feldspars.
Figure 43. Multiple diffusion domain models of footwall K-feldspar (MB99NY-2).
Table 2. Table showing diffusion parameters and calculated closure temperatures for the hanging wall and footwall K-feldspars

<table>
<thead>
<tr>
<th>Diffusion Parameters</th>
<th>MW98NY-1 (Hanging wall)</th>
<th>(MB99NY-26) (Footwall)</th>
<th>(MB99NY-2) (Footwall)</th>
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<td>E, kcal/mol</td>
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ρ, volume fraction of each domain

E, activation energy, D is diffusion coefficient

Tc, closure temperature

r^1, r^2, r^3.....r^7, relative domain sizes

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Discussion and interpretation of mica ages

*Interpretation of mica ages, central transect*

The stair-stepped age spectrum of the hanging wall muscovite may indicate either slow cooling of the hanging wall block or a mixture of argon from hydrothermal and igneous muscovites.

Muscovite from within the center of the shear zone (MB99NY-25) is from a 20-25 centimeter thick quartz vein filling a W-NW oriented fracture. Field observation from this particular locality and other areas within the shear zone show there are two sets of fractures within the shear zone. The first are W-NW oriented fractures, mostly filled by deformed quartz veins. The second set of fractures are developed parallel to the stretching lineation and are in most cases open and in some places filled by muscovite-bearing thin quartz veins. The quartz vein from which this sample came is barely deformed and can be grouped with the N-NW oriented quartz veins. The random orientation of the muscovite in thin section indicates that this quartz vein might have been undeformed (postdeformational) or little deformed (late deformational), so that the age of the muscovite from this sample may indicate either the age of cooling age during unroofing of the footwall or hydrothermal mineral growth.

The age of muscovite from within the center of the shear zone (MB99NY-25) is older than the footwall muscovite, particularly for the first 30% of degassing. Presumably, the difference in age of the muscovites may reflect the time span in which hydrothermal mineralization was active. For instance, fractures filled by muscovite (MB99NY-26) (70.4 ± 0.3 Ma) are developed only in feldspar porphyroclasts.

Ductile deformation in K-feldspar requires a minimum temperature of 450-500 °C (Simpson and De paor, 1991). In the Pinto shear zone, the presence of ductile...
deformation features suggests a minimum temperature of 450-500 °C. This implies fractures in feldspar porphyroclasts could be developed at temperatures less than 450 °C. On the other hand, quartz microstructures indicate that quartz was deformed ductilely throughout the shear zone, implying a minimum temperature of 250 °C. In this broad temperature range (400-250 °C), argon in muscovite could record either cooling or growth ages. However, the coexisting biotite from the porphyry dike (MB99NY-40B) is a bit older than the muscovite age, suggesting the footwall muscovite age is a mineral growth age.

The total gas age of the footwall muscovite (MB99NY-26) is 69.9 ± 0.4 Ma (Fig. 39A) which is the same within analytical error as the other footwall muscovite in the eastern part of the shear zone (70.4 ± 0.4 Ma), indicating either a cooling age of hydrothermal muscovite (if fracturing occurred at temperature higher than muscovite closure for argon) or nearly synchronous hydrothermal mineral growth within fractures formed during the unroofing event.

The random occurrence of the biotite grains and phenocrysts and their morphology, and absence of biotite in fractures are clear evidences that show biotite in the hanging wall and in the footwall are igneous biotites and their age represents cooling ages through ~ 300 °C for the footwall and hanging wall blocks respectively. The total gas age of footwall biotite is 70.9 ± 0.4 Ma whereas the hanging wall biotite is 71.22 ± 0.3 Ma (Fig. 37D and 44B), indicating the difference between the hanging wall and footwall biotite ages is insignificant (0.23 m.y.). Based on the biotite age of the footwall, the Pinto shear zone might have cooled through about 300 °C at about 70.9 Ma. The plots of biotite and muscovite apparent age spectra along this transect show to some extent overlapping age spectra (Figs: 44 and 45). This indicates that Ar-
Figure 44. $^{40}$Ar/$^{39}$Ar age spectra along a transect across the central part of Pinto shear zone. (A) Muscovite age spectra of the hanging wall, shear zone, and the footwall. Note the stair-stepping age spectra of the hanging wall muscovite. (B) Biotite age spectra from the hanging wall and the footwall.
Figure 45. Comparison of $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of muscovites and biotites along the transect across the central part of Pinto shear zone.
closure for igneous biotites both in the hanging wall and footwall, and hydrothermal mineral growth in the fractures within the shear zone and footwall had occurred in a very short time interval. On the other hand, the hanging-wall muscovite age may represent a mixture of igneous and hydrothermal origin because both are seen in thin section. Thus, the hanging-wall block may have either cooled slowly or the hanging wall muscovite age may record a mixture of gas from both igneous and hydrothermal muscovites.

Interpretation of mica ages, eastern transect

The muscovite from the center of the shear zone (MB99NY-49) is igneous in origin and the age of this sample (72.4 ± 0.4 Ma) represents a cooling age due to unroofing of the footwall block. In the high temperatures degassing steps (> 60% $^{39}$Ar release), the analyses for hydrothermal muscovite (MB99NY-2) in the footwall and igneous muscovite in the shear zone show plateau ages (Fig. 46A). The difference in the plateau age is 2.4 Ma that is greater by 1.0 Ma than the difference between the footwall and the shear zone hydrothermal muscovites in the northwestern part of the shear zone.

Comparison of the best ages (total gas ages) of the footwall biotites, MB99NY-2B (72.8 ± 0.4 Ma) in the eastern part of the shear zone and MB99NY-40B (70.9 ± 0.4 Ma) in the northwestern part of the shear zone shows that the eastern footwall biotite is older by 1.9 Ma than the northwestern footwall biotite (Fig. 46C). This may indicates that there had been a progressive unroofing of the footwall towards the northwest direction. If this interpretation is correct, the eastern part of the shear zone
Figure 46. $^{40}$Ar/$^{39}$Ar muscovite and biotite age comparison. (A) $^{40}$Ar/$^{39}$Ar muscovite and biotite age spectra along the transect in the eastern part of the shear zone. (B) $^{40}$Ar/$^{39}$Ar age of footwall biotites from the northwestern and eastern part of the shear zone. (C) $^{40}$Ar/$^{39}$Ar age of footwall muscovites from the northwestern and eastern part of the shear zone. (D) $^{40}$Ar/$^{39}$Ar muscovite ages of samples collected from the eastern and northwestern part of the shear zone.
was at a higher structural level at all stages of shearing. Miller et al. (1996) dated muscovite from a deformed quartz vein in the central part of the shear zone and reported a total gas age of 69.74 ± 0.16 Ma. However, the present dating of muscovite from a quartz vein (MB99NY-25) in the same area (structurally below) yields a total age of 71.9 ± 0.4 Ma. Muscovite from a deformed aplitic dike in the southeastern part of the shear zone yield an age of 72.4 ± 0.4 Ma which is a bit older (0.5 Ma.) than the new muscovite age in the northwestern part of the shear zone.

Comparison of the previously dated muscovite age from the northwestern part of the shear zone with the present muscovite age from the eastern part of the shear zone shows that the eastern muscovite age is older by 2.0 Ma. This difference in age between the shear zone muscovites in the eastern part of the shear zone and in the northwestern part of the shear zone (2.0 Ma) is almost equal to the difference between the footwall biotite in the eastern part of the shear zone and northwestern part of the shear zone (1.9 Ma), supporting the interpretation that progressive unroofing of the footwall occurred towards northwest direction.
CHAPTER 7

DISCUSSION

Does the Pinto shear zone record extension or contraction?

One of the principal research questions addressed is whether the Pinto shear zone records contraction or extension. Previous workers have suggested that the Pinto shear zone is a Mesozoic thrust (Beckerman, 1982). Several lines of evidence taken together, provide a compelling case for the reinterpretation of the Pinto shear zone as an extensional shear zone. The Pinto shear zone in New York Mountains is interpreted to record late Cretaceous extension based on evidence summarized below:

(1) All the shear zone indicators (oblique grain-shape fabrics, S-C fabrics, biotite fish, winged feldspar porphyroclasts, shear bands, and quartz C-axis preferred orientation studies) consistently demonstrate top-to-the-S-SW, generally down-dip shear sense. This down dip, top-to-the-S-SW movement within the Pinto shear zone suggests a normal-sense motion.

(2) The geometrical relationship between the main shear zone that records top-to-the-south shearing and the high-angle dike margin faults within the hanging wall that record top-to-the-north shearing is most compatible with normal faulting, rather than thrusting. The antithetic high-angle normal sense shear zones that extended the hanging wall of the Pinto shear zone merge downward with the top of the main shear zone, and are interpreted as developing synchronously with the main shear zone.
(3) The footwall has a higher cooling rate (44 °C/m.y.) than the hanging wall (23 °C/m.y.). Rapid cooling of the footwall of normal faults has been documented by numerous studies of Cenozoic core complexes in the western United States but has not been documented in the footwalls to thrust faults.

Age of Pinto shear zone

The timing and thermal history of deformation is constrained by a combination of $^{40}$Ar/$^{39}$Ar thermochronology of biotite, muscovite, and K-feldspar and microstructural studies. Since the cooling rate of the two footwall K-feldspar cooling curves are identical (Fig. 47), the cooling curves are considered together, and compared with the hanging-wall cooling curve (Fig. 48). The cooling rate of the hanging wall (23 °C/m.y.) is significantly slower than the cooling rate of the footwall (44 °C/m.y.) (Fig. 48).

Composite cooling curves for coexisting minerals (K-feldspar, muscovite, and biotite) are plotted for each sample from the hanging wall and the footwall. The biotite and muscovite in the hanging wall nicely overlap with the K-feldspar cooling curves, and the muscovite age is older than the biotite age (Fig. 49A). However, biotites in the footwall are a little older than the coexisting muscovite, compatible with the interpretation that the muscovite ages in the footwall are growth ages. Nevertheless, mixing of hydrothermal muscovites with igneous muscovite can't be ruled out. The overlapping of the muscovite and biotite ages with the larger domain parts of the K-feldspar cooling curves indicates the relatively high retentivity of K-feldspar in the study area.
Figure 47. Combined K-feldspar cooling curves of the footwall (MB99NY-26 and MB99NY-2).
Figure 48. Thermal histories of the footwall and hanging wall from multiple diffusion domain modelling of K-feldspar.
Figure 49. Comparison of K-feldspar model cooling curves to coexisting muscovite, and biotite thermochronology from the hanging wall and the footwall of the Pinto shear zone.
The similarity between footwall muscovite (69.9 & 70.4 ± 0.3 Ma) and biotite (70.9 ± 0.4 Ma) ages indicate rapid cooling. The two K-feldspar multidomain analyses suggest rapid cooling of the footwall at 44 °C/m.y., from 354 °C at 70 Ma to 200 °C at 65 Ma for MB99NY-2 (Fig. 43), and from 412° at 71 Ma to 218 °C at 66 Ma, for MB99NY-26 (Fig. 42). However, plastic fabrics in K-feldspar indicate that deformation began at temperatures of about 500°C.

The age of deformation of the Pinto shear zone is well constrained by a combination of U-Pb crystallization ages, the thermal history of footwall rocks derived from ⁴⁰Ar/³⁹Ar thermochronology, and microstructural studies (Fig. 50). The shear zone deforms porphyry dikes that yielded an U-Pb age of 80 ± 2 on zircon (Wells and Walker, unpublished data). This data provides a maximum age of deformation. Microstructural studies indicate that the bulk of the distributed deformation occurred at upper and middle greenschist facies conditions, with temperatures decreasing during deformation, as shown by kinematically compatible brittle deformation features overprinted on early plastic deformatonal features. The thermochronology well defines a moderately rapid cooling rate for footwall rocks of 44 °C/m.y., from 410 °C to 200 °C, over the time interval 71 to 66 Ma. An abrupt reduction in cooling rate at 66-65 Ma (corresponding temperature of 200 °C) most probably indicates the end of motion on the Pinto shear zone system (Figs. 42 & 43). This reduction in cooling rate may postdate the actual reduction or termination of slip due to the time lag for the attainment of thermal equilibrium of the advected isotherms. Much of the upper to middle greenschist facies ductile fabric was probably acquired between 74 and 70 Ma. The similarity of the hydrothermal muscovite (from the microfractures in feldspar porphyroclasts and within quartz veins) and igneous biotite ages indicates hydrothermal mineralization had been occurred synchronously or immediately after
Figure 50. Date of deformation of the Pinto shear zone. Cooling curves of the footwall and temperature of deformation (from microstructural studies) are combined to infer the age of shearing.
shearing. The hanging-wall mica ages (71.2 ± 0.5 Ma, biotite; 72.0 ± 0.4 Ma, muscovite) are slightly older than the footwall mica ages (70.9 & 72.8 ± 0.4 Ma, biotite; 69.9 & 70.4 ± 0.4 Ma, muscovite). Hanging-wall K-feldspar shows a cooling rate of 23 °C/m.y. from 71 to 64 Ma.

The relatively rapid cooling of the hanging wall and the lack of significant discordance in mica ages between hanging wall and footwall suggests several possible explanations: (a) hanging wall cooling is related to an unrecognized structurally higher normal fault; (b) hanging wall cooling is related to denudation resulting from upper plate thinning by antithetic normal faults; (c) Laramide refrigeration; or (d) the hanging wall was advectively heated by the hot footwall and underwent sympathetic but slower cooling than the footwall. The difference in age between cooling path convergence and reduction in cooling rate are compatible with the latter explanation.

The presence of another low-angle fault structurally above the study area can not be excluded. With the exception of the minor shear zones along the porphyry dike margins, which record top to the north and northwest shearing, no major structure was observed in the close proximity of the hanging wall nor has been recognized in the larger area by previous studies. However, it can not be excluded that a structure is concealed beneath the Cenozoic deposits in Ivanpah valley. Thinning of the hanging wall by antithetic faulting probably did not result in sufficient extension to cause the measured hanging wall cooling.

Dumitru et al. (1991) developed the hypothesis of Laramide refrigeration in the western Cordillera. They suggested that the shift from normal to shallow-angle subduction proposed by many after 75 Ma and would have caused widespread refrigeration of the lithosphere in the western Cordillera. This shift from a warm to a cold lithosphere could have very important thermal and rheological effects in the
western Cordillera. The authors concluded that the western Cordillera should have developed a much colder, forearc-like thermal structure due to the refrigeration of the lithosphere by the underlying cold subducting slab. In contrast, Hodges and Walker (1992), Livaccari (1991) and many others argue that the continental crust thickened during the Sevier-Laramide orogeny within the orogen interior uplifted and extended synchronously with foreland-thrust deformation in the orogen exterior. The above authors and many others have suggested that Mesozoic crustal thickening during the Laramide-Sevier orogeny was followed by a period of gradual crustal heating and weakening that ultimately led to gravitational collapse and extension. On the other hand, refrigeration would cause strengthening of the lithosphere and impede deformation, suggesting that extension and refrigeration can’t occur at the same time. Therefore, it is unlikely that the hanging wall K-feldspar cooling rate in the Pinto shear zone, is related to Laramide refrigeration.

The similarity of the footwall and the hanging wall mica ages supports the interpretation that the hanging wall was heated by juxtaposition against a hot footwall, perhaps aided by fluid advection during Pinto shearing, which lead to subsequent relatively rapid cooling of the hanging wall.

Correlation of the Pinto shear zone with other similar structures in the eastern Mojave Desert

Beckerman et al. (1982) mapped the Pinto shear zone as a thrust fault, and suggested that the shear zone may be correlated to the Morning Star thrust in the southern Ivanpah Mountains. However, the down-dip, top-to-the southwest and west
movement within the Pinto shear zone suggests a normal-sense movement, and calls into question the previously proposed correlation between these faults.

The Old Woman Mountains area to the south and Funeral Mountains of the Death Valley region to the north are two areas in the northeastern Mojave Desert and adjacent Great Basin which have documented latest Cretaceous extensional features (Fig. 2). The metamorphic and plutonic rocks in the Old Woman Mountains underwent rapid cooling between 73 and 65 Ma, implying rapid tectonic denudation (Howard et al., 1987, Carl et al., 1991; Foster et al., 1992). The Funeral Mountains of the Death Valley region underwent extension at ~ 72 Ma (Applegate et al., 1992; Hodges and Walker, 1992; Hoisch and Simpson, 1993; Applegate and Hodges, 1995) bracketed by intrusion of pre- and post-kinematic dikes. In both regions, extension was accommodated by normal-sense movement along west-dipping shear zones.

The Pinto shear zone in many aspects is similar to the western Old Woman Mountains shear zone. Rocks within the 1-km-thick western Old Woman Mountains shear zone show ductilely deformed quartz and ductilely and brittly deformed feldspar, indicating greenschist to lower amphibolite facies mylonitization. Foliation measured in 73 Ma mid-crustal granitoids generally dips west-southwest, and sense-of-shear indicators demonstrate top-to-the-west sense of movement parallel to gently southwest-plunging lineation. The Pinto shear zone shows ductilely deformed quartz ribbons, ductilely and brittly deformed feldspar, and myrmekite developed on the margins of feldspar porphyroclasts, indicating greenschist to lower amphibolite facies conditions of shearing. With the exception of few places in the western end of the shear zone
(domain 6), the foliation dips west and southwest. The lineation is down-dip in the eastern, southeastern, and well-exposed central part of the shear zone and oblique in the northwestern part of the shear zone. The sense-of-shear indicators show top-to-the-southwest sense of movement parallel to the southwest and south-southwest plunging lineation. The other common feature to these shear zones is the increase of deformation towards higher structural levels. In both shear zones the granitoids near the top of the shear zone are strongly mylonitic and record considerable grain-size reduction and modest to strong S-C fabrics, particularly true for the Pinto shear zone which has a 7-15 meter thick ultramylonite capping the strongly mylonitic Mid Hills adamellite.

Thermochronologic studies indicate a similar timing of extensional denudation between the Pinto and western Old Woman Mountains shear zones. The 73-66 Ma deformation age of Pinto shear zone is similar to the 73-65 Ma age range of unroofing in the Old Woman Mountains. Therefore, there was a close kinematic and timing concordance between these two shear zones.
CHAPTER 7

CONCLUSIONS

The following conclusions are drawn:

(1) The base of the Pinto shear zone is gradational and the top is sharp, and strain generally increases upwards, from undeformed footwall granitoids beneath the shear zone to protomylonite, mylonite, and ultramylonite near its top.

(2) Foliation in the Pinto shear zone generally dips 20-65° S and SW, and lineations plunge to the SSW.

(3) Kinematic studies within the shear zone consistently demonstrate top-to-the SSW shearing, suggesting normal-sense movement.

(4) The hanging wall of the Pinto shear zone was extended along antithetic north-dipping normal-sense shear zones that were localized along the margins of porphyry dikes. Structural relationships between these antithetic shear zones and the main shear zone indicate that they were simultaneously active.

(5) Rapid cooling (44°C/m.y.) of footwall rocks from ~410 to 200°C over the time interval ~71-66 Ma is constrained by muscovite, biotite, and K-feldspar $^{40}$Ar/$^{39}$Ar thermochronology.

(6) Deformation of ~80 Ma porphyry dikes within the shear zone together with evidence of rapid cooling during deformation indicate that the Pinto shear zone was active from <80 to 66 Ma. Microstructural considerations suggest that temperatures were no higher than 500°C; if correct, this tightens the brackets on deformation to 74 to 66 Ma.
(7) A reduction in cooling rate at 65-66 Ma (corresponding $T \sim 200$ °C) may mark the
termination of rapid cooling related to tectonic denudation.

(8) Hydrothermal muscovite filling microfractures in feldspar porphyroclasts and within
quartz veins yield similar ages as igneous biotite, implying hydrothermal
mineralization during shearing.

(9) The preferred model for the relatively rapid cooling of the hanging wall and the lack
of significant discordance in mica ages between hanging wall and footwall is that
the hanging wall was advectively heated by the hot footwall and underwent
sympathetic but slower cooling than the footwall. The difference in age between
cooling path convergence and reduction in cooling rate are compatible with this
explanation.

(10) The Pinto shear zone is similar in kinematics and age with other late Cretaceous
extensional structures in the eastern Mojave Desert including the Old Woman
Mountain shear zone to the south and the Monarch Canyon and Chloride Cliff shear
zones of the Funeral Mountains to the north. The similarity in timing between the
shear zones suggests that late Cretaceous extension may have been widespread in
the southern Sevier orogen.
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APPENDIX A

Description of thin sections for deformation mechanism studies

Thin sections used for deformation mechanism studies are described below for each domain.

Domain 1:
MB99NY-8- This sample is collected from strongly deformed mylonite beneath the carbonate hanging wall in the eastern part of the shear zone. It shows strongly deformed quartz ribbons internally recrystallized into new grains. The new grains in most cases show: oblique grain shapes, well-defined grain boundaries, and similar grain shape and sizes (Fig. 18A). The grain boundaries of most grains are straight to slightly irregular, implying recovery was by grain boundary migration recrystallization. Rims of K-feldspar porphyroclasts facing the incremental shortening direction are characterized by the development of mushroom-shaped lobes of myrmekite, whereas the tail region is recrystallized into new polygonal k-feldspar grains (Fig. 27A). The myrmekite (intergrowth of oligoclase and quartz) is developed on the sides facing the S plane. Myrmekite is not developed on the long ends of the feldspar grain that faced the incremental stretching mineral lineation (Fig. 27A and B). After staining for both K-feldspar and plagioclase, it is clear that mantles around the K-feldspar porphyroclast
are composed of very fine grained, recrystallized plagioclase and quartz, most probably derived from the deformation of the myrmekite itself.

MB99NY-34- This sample is taken from weakly deformed Mid Hills adamellite, close to the footwall. The quartz at places forms a weak shape preferred fabric defining a foliation. The quartz grains show patchy undulose extinction and are crystallized into very fine grains along grain boundaries (regime 2 of Hirth and Tullis, 1992). Feldspars seem undeformed and there are no significant fracturing and associated alteration minerals.

MB99NY-12- The sample is collected from the center of the shear zone, about 2 kilometers west of MB99NY-8 (plate 1). The quartz shows two mutually perpendicular, well-developed deformation lamellae (Fig. 27D). The presence of the deformation lamellae indicates deformation under low temperature conditions (Tullis and Yund 1987).

Domain 2:

MB99NY-31 and MB99NY-30- These samples are collected from the mylonite in the center of the shear zone. They show strongly stretched and flattened quartz ribbons that wrap around cores of feldspar grains. In most places, the quartz ribbons are oriented obliquely to C surfaces and show minor recrystallization along grain boundaries, indicating a recovery by grain boundary migration recrystallization (Fig. 31A and B). The K-feldspar porphyroclasts exhibit myrmekite along the direction of shortening, and dynamic recrystallization into new feldspar grains in the direction parallel to the extension direction (parallel to the S surfaces) (Fig. 28C). Feldspar
porphyroclasts are in most cases altered to muscovites and white micas along cleavage planes, grain boundaries, and fractures developed across the cleavages. The tensile fractures are filled dominantly by muscovite and subordinate quartz, and are localized only in a core of K-feldspar augens. At one place it is found that myrmekite is developed on grain boundaries facing the shortening direction but the myrmekite is partially replaced by fine-grained muscovites (Fig. 28D). The intensity of muscovitization at places is manifested by a complete break down of feldspars into fine-grained muscovite aggregates (Fig. 28E).

Flame-perthite is very common on the K-feldspar porphyroclasts, tapering towards the center of the grain (Fig. 28F).

MB99NY-32- This sample is collected from a quartz vein in the same area as the above samples. The thin section shows stretched and flattened quartz ribbons crystallized at ribbon margins probably by grain boundary migration recrystallization. Some of the quartz ribbons show undulatory extinction and minor subgrain formation, indicating deformation by dislocation creep (regime 2 of Hirth and Tullis, 1992) (Fig. 28A and 28B). Note the irregular flattening effect in the enlarged (Fig. 31A) part of figure 28A. There are also undeformed fracture filled quartz stringers, which cut the deformed quartz ribbons (Fig. 28A). The undeformed fracture filled quartz crystals are bounded on both sides by muscovites.

Domain 3:

MB99NY-24- This sample is collected from a quartz vein from the top of the mylonite. The thin section shows irregularly stretched and flattened quartz ribbons.
recrystallized into extremely fine-grained quartz along their grain boundaries. The flattened quartz ribbons also show undulose extinction. The fine grained recrystallized quartz along the grain boundaries of these irregularly flattened quartz ribbons and the associated patchy undulose extinction probably indicate the rapid cooling condition of the shear zone.

MB99NY-25- This sample is collected from a quartz vein at about 1-kilometer east of the above sample. The thin section shows irregular grain boundaries and bulging structure. The bulging direction is the same throughout the thin section, indicating the movement direction of a migrating grain boundary during dynamic recrystallization. Poorly developed subgrains are also noted along the grain boundaries of high dislocation and low dislocation density grains (Fig. 29A).

MB99NY-29- This sample is taken from a well-exposed part of the Pinto shear zone, northwest of the above three samples (plate.1). Like the samples (MB99NY-31 and -32) in the south, ribbons of quartz are oriented obliquely to C surfaces and wrap around feldspar porphyroclasts. The quartz ribbons show minor recrystallization at grain boundaries similar to the above samples. The feldspar porphyroclasts are recrystallized at grain boundaries and tails forming a core and mantle structure. The grain size of the mantle is the same as the matrix and composed of plagioclase + quartz + minor K-feldspars (after staining). The staining also show myrmekites developed on the side of K-feldspar porphyroclasts facing the shortening direction and are composed of plagioclase and quartz. K-feldspar cores connected by strings of
fine-grained feldspar are very common in this thin section. Cores of feldspar grains also show tensile fractures filled by muscovite and quartz.

MB99NY-27- This sample is collected from a mylonite in the same area as the above sample. New recrystallized quartz crystals define an oblique grain-shape foliation internal to an old quartz ribbons. As in the other thin sections in the southeastern part of the shear zone, feldspar porphyroclasts show mushroom-shaped myrmekites on the sides facing the incremental shortening direction where as the porphyroclast is recrystallized into new feldspar crystals on the direction facing the incremental extension direction (Fig. 29B). In addition, flame perthites and myrmekites are found developed roughly in different quadrant (Fig. 29C). The flame-perthite was grown in the direction parallel to the extension direction (parallel to S surfaces) whereas myrmekite was developed on the sides of the feldspar porphyroclast facing the incremental shortening direction (Fig. 29C).

Domain 4 and 5:

MB99NY-20A, 20B and 46- These samples were collected from ultramylonite outcrop which are overprinted by mild brittle deformation. The old, elongated, and flattened quartz ribbons are recrystallized at grain boundaries into relatively fine-grained quartz grains (Fig. 30B). In addition, locally the old quartz ribbons show undulose extinction. Overall, the features noted for quartz in this area indicates that quartz deformed by dislocation creep and recovery by grain boundary migration recrystallization.
Feldspar shows both ductile and brittle deformation features. However, most of the features depict the domination of brittle deformation and concealed the earlier ductile features. Feldspar porphyroclasts are deformed by network fractures (Fig. 30C). For instance, in one of the thin section (Fig. 21D), a feldspar porphyroclast is found sliced by antithetic micro fractures into bookshelf fragments. Due to the brittle overprinting on the top of the shear zone, it is not clear whether the fractures are related to the earlier ductile fault or the latter brittle deformation. Grain size reduction is a common feature along the conjugate joints and grain boundaries. A thin section from the same area shows a strong cataclastic fabric (crushed and powdered materials).

MB99NY-33- This sample is collected from a mylonite on the top of the shear zone, structurally underneath the ultramylonite. About 60 % of the flattened and strained quartz ribbons are recrystallized at grain boundaries into new grains (regime 2 of Hirth and Tullis, 1992) (Fig. 30B). The new quartz grains have extremely irregular grain boundaries and are aligned at a small angle to the main ribbon orientation. Some of the old ribbons show undulose extinction. The style of grain boundaries of the ribbons and new grains, and the presence of undulose extinction in few of the remnant ribbons indicates that deformation was by dislocation creep and recovery by grain boundary migration recrystallization, probably with little subgrain rotation recrystallization. Although, feldspar porphyroclasts are complicated by fracturing and grain size reduction, at places they show a very fine-grained recrystallized mantle around the grain boundaries. The plagioclase feldspar in most cases are brittlely deformed, and at
places have undergone grain size reduction along fractures and grain boundaries. The matrix is extremely fine and powdery in appearance, indicating the intensity of brittle deformation towards the top of the shear zone.

Alteration (sericitization) is mostly concentrated along grain boundaries and cleavages of feldspar phenocrysts.

MB99NY-37- This sample is taken from the center of the shear zone, close to the boundary of domain 3 and 4. The quartz shows irregular grain boundaries and almost the same size, indicating grain boundary migration recrystallization (Fig. 31). K feldspars show a strong well-developed core-and mantle structure (Fig. 31B). The thickness of the mantles developed around the cores of K-feldspars is variable but the grain size is more or less the same. Staining for plagioclase and K-feldspars reveals that the grain size and composition of the mantle is the same as the matrix (plagioclase and quartz), probably indicating that the mantles might have contributed a lot to form the matrix.

MB99NY-39- This sample was collected about a kilometer northwest of MB99NY-37. Quartz has entirely undergone recrystallization and the grains have irregular grain boundaries, indicating recovery by grain boundary migration recrystallization. K-feldspars show a well-developed core-mantle structure. The mantles are much wider and finer than the mantles of MB99NY-37. Feldspars show grain size reduction along fractures and grain boundaries. The matrix is extremely fine grained, suggesting a further grain size reduction had occurred, presumably during brittle overprinting of the
northwest striking brittle fault on the top of the ductile fabrics. At one place in this
thin section, a fracture filled by quartz is found cut by a fracture which underwent
grain size reduction. This can be an evidence for a latter overprinting of the brittle
fault on the ductile fabric and associated fractures.

Domain 6:

MB99NY-45- This sample was collected from ultramylonitic quartz vein, near the top
of the shear zone shows a cataclastic features, indicating a clear brittle deformation
overprints which entirely obliterated the former ductile deformation features (Fig.
32D). Development of fractures and grain size reduction along them, grain
boundaries, and preexisting fractures (in most cases show synthetic, micro scale
displacement) are most probably related to the brittle overprinting episode.
Plagioclase porphyroclasts have suffered more from brittle overprinting than K-
feldspar porphyroclast. At places in the thin sections, cores of plagioclase feldspar
porphyroclast are altered to muscovites.

MB99NY-43- This sample was collected in the same area as the above sample.
Quartz shows only ductile deformation features. It is characterized by recrystallized,
nearly uniform quartz grains, probably recovered dominantly by grain boundary
migration recrystallization. In the same thin section, biotite fibers are grown in
pressure shadows at the long ends of the plagioclase feldspar, indicating their
syntectonic development (Fig. 32A and B). The plagioclase feldspar porphyroclasts
have undergone grain size reduction along fracture networks. The fractures extend
beyond the boundaries of the porphyroclast into the matrix and surrounding small
feldspar augens. Overall, brittle failure seems a dominant visible deformation mechanism for feldspars, however, in some places feldspar porphyroclasts recrystallized at the margins and tails to form σ-type feldspar grains.

MB99NY-44- This sample was collected from a strongly deformed mylonitic rock close to the footwall. Quartz is flattened and stretched and shows recrystallization at grain boundaries. The quartz ribbons are variably recrystallized along grain boundaries and show evidence of grain boundary migration recrystallization and undulose extinction (Regime 2 of Hirth and Tullis, 1992). There are two foliations. One is defined by newly recrystallized quartz oriented at an angle to the ribbons (S-surfaces) and the other one is defined by the ribbon itself (C surfaces). K-feldspars show a recrystallized mantle around the rims, forming a core and mantle structure (Fig. 32C). The cores of the porphyroclast at places exhibit tensile fractures, which are filled by muscovite and quartz. At places in this thin section, augens of K-feldspars are found connected with recrystallized fine-grained feldspars.

**Description of thin sections from porphyry dikes**

**within the Pinto shear zone**

MB99NY-19- This sample was collected from the porphyry dike in the northwestern part of the shear zone, just beneath the carapace-forming ultramylonite. The thin section shows deformed quartz ribbons with undulose extinction, subgrains, and insignificant recrystallization at ribbon and deformation bands boundaries (Fig. 33D).
MB99NY-21 - This sample was collected from a deformed dike within the center of the northwestern part of the shear zone. The thin section shows an ideal example of dynamic recrystallization (grain boundary migration recrystallization). The grain boundary with low dislocation density bulged into the grain with the high dislocation density and formed new crystals sitting within the center of the high dislocation grains (Fig. 33C). Passchier and Trouw, (1996) mentioned that along a grain boundary in a crystal with high dislocation density can be displaced slightly so that they fit to the lattice of the crystal with low dislocation density. This allows local displacement of the grain boundary and growth of the less deformed crystal at the cost of the more deformed crystal.

MB99NY-22 - The sample is collected from a deformed margin of a porphyry dike in the center of the shear zone. A big quartz-ribbon recrystallized into new fine grained quartz at grain boundaries and tails forming a core-and mantle structure (Fig. 33A and B), indicating deformation by dislocation creep and recovery by subgrain rotation recrystallization and probably little grain boundary migration recrystallization.
APPENDIX B

Ar Isotopic Analysis of dated Samples

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<th>Temp °C</th>
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MW98NY-1B biotite, 2.87 mg, J = 0.0011888 +/- 0.5
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**MB99NY-2M muscovite, 3.65 mg, J = 0.0011893 +/- 0.5%**

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<th>(^{36}\text{Ar}/^{39}\text{Ar})</th>
<th>(^{40}\text{Ar}/^{39}\text{Ar}_k) (mole x yield %)</th>
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**MW98NY-49 muscovite, 2.58 mg, J = 0.001187 +/- 0.5%**
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<th>Radiogenic yield (%)</th>
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*MW98NY-25 M muscovite, 3.65 mg, J = 0.0011893+/− 0.5%*
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* MW98NY-1K K-spar, 10.17 mg, J = 0.001183 +/- 0.5%
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**MB99NY-2K K-spar, 11.00 mg, J = 0.001190 +/- 0.5%**

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VITA

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Geological Society of America, Award and outstanding mention in the annual Bulletin, (Summer 1999).
University of Nevada, Las Vegas, Geoscience Department Summer Research Grant, 1999.
University of Nevada Las Vegas, Graduate Student Association Research Grant, 1999
University of Nevada, Las Vegas, Geoscience Department Summer Research Grant, 1998.

Publications:


**Mengesha Assefa**, 1996, Progress report on the Sirkole Primary Gold & Base Metal exploration, License area of St. Genevieve Resources Ltd. Company, P. O. Box 4360, Addis Ababa, Ethiopia

**Ayele Kebede, Eshetu Assefa, Mengesha Assefa et. al.**, 1994, The Geology of Megado-Serdo Primary Gold Prospect, Shakisso, P.O. Box- 17, Tel. 33, Sidamo, Ethiopia.
Ayele Kebede, Eshetu Assefa, Mengesha Assefa et. al., 1993/94, Geology on the Primary Gold Prospect of Bore Area, P. O. Box 17, Tel. 33, Shakiso, Ethiopia.

Mengesha Assefa, 1993, Report on the Geology of Serdo Primary Gold Prospect Area, Shakiso, P.O.Box – 17, Tel., 33, Sidamo, Ethiopia.

Mengesha Assefa, 1991/92, Report on the Geology of Bedadessa area, Shakiso, P.O. Box 17, Tel. 33, Sidamo, Ethiopia.

Thesis Title: Kinematics and Timing of the Pinto shear zone, New York Mountains, northeastern Mojave Desert, California.

Thesis Examination Committee:
Chairperson, Dr. Michael Wells, Associate Professor, Ph.D.
Committee Member, Dr. Gene Smith, professor, Ph.D.
Committee Member, Dr. Terry Spell, Assistant Professor, Ph.D.
Committee Member, Dr. Barbara Luke, Professor, Ph.D.
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UMI
ar zone and its surrounding area
Symbols

Quaternary deposits

Cenozoic volcanic rock

Pinto shear zone

Cretaceous porphyry dikes

Mesozoic Mid Hills adamellite

Cambrian marble

Contact. Dashed where approximately located; dotted where inferred under quaternary alluvium

Fault zone boundary in the hanging wall. Dashed where approximately located.

Brittle fault

Domain boundary

Profile line

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Quaternary deposits

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Mesozoic Mid Hills adamellite

Cambrian marble

Cambrian quartzite

Precambrian gneiss

Profile line
Strike and dip
Lineation
Microstructural sample sites
Dating sample sites

outside of the author map area from D.M. Miller, Unpublished Pinto Valley Geologic Quadrangle

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Domain boundary

Profile line

Strike and dip

Lineation

Microstructural sample sites

Dating sample sites

M. Miller, Unpublished Pinto Valley Geologic Quadrangle

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Plate 2: Cross section along A-A'

Scale:
Horizontal 1:12,000
Vertical 1:6,000

- Hanging wall dated sample (MW99NY-1)
- Shear zone dated sample (MB99NY-25)
- Footwall dated sample (MB99NY-26)

- Quaternary deposits
- Pinto shear zone
- Mild Hill adamellite
- Fissure