Origin and geological significance of mylonitic shear zones, northern Lucy Gray Range, Clark County, Nevada

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Origin and Geological Significance of Mylonitic Shear Zones, Northern Lucy Gray Range, Clark County, Nevada

by

Clinton H. Christensen

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

Master of Science in

Geology

Department of Geology
University of Nevada, Las Vegas December 1994
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May 1994
ABSTRACT

The Beer Bottle Pass pluton, at the northern end of the Lucy Gray Range, Nevada, is part of a continent-scale belt of 1.4 Ga intrusive rocks that extends from California to Labrador. These granites are conventionally interpreted as anorogenic; however, recent work has documented that some of these plutons may have been deformed during or after emplacement. In the Lucy Gray Range, a series of mylonite zones is spatially associated with the Beer Bottle Pass pluton. An integrated study involving field and laboratory work, was used to distinguish between three possible scenarios for the origin of the mylonites: (1) intrusion into an active shear zone, (2) post-emplacement ductile deformation, and (3) mylonitization during and as a consequence of forcible pluton emplacement. Observations made during this study indicate that forcible intrusion is unlikely and the mylonites are a result of late synkinematic or post emplacement deformation.
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CHAPTER 1
INTRODUCTION

The Beer Bottle Pass pluton is in the Lucy Gray Range, Clark County, Nevada (Fig. 1). It is a 1.4 Ga potassic, megacrystic granite that is spatially associated with major zones of ductile deformation as indicated by the presence of mylonite. Thick zones of mylonitization occur not only at the pluton contact, but also within both the granite and the gneissic wall rock. The origin of the mylonite zones and how they relate to the pluton is the subject of this study.

The Beer Bottle Pass pluton is part of a continent-scale zone of large-volume, granitic intrusions that extends from southern California to Labrador (Fig. 2). This belt of intrusive rocks is restricted to Proterozoic accreted terranes and occurs locally at the Proterozoic-Archean boundary. The granites are considered to be anorogenic, meaning that they were emplaced in the absence of regional deformation (Anderson, 1983). However, recent work on individual plutons within the continent-scale belt indicates possible syn-intrusive regional deformation (Thompson, 1991; Thompson and Karlstrom, 1993). This observation raises the possibility that the anorogenic interpretation of the granites may need to be re-evaluated.

The spatial association of the mylonite and megacrystic granite can be explained in one of three ways. First, the granite may have been emplaced synkinematically into an active shear zone during a yet undocumented period of deformation. Second, the forcible intrusion of the granite produced the mylonites. Third, the deformation that produced the mylonite zones may have occurred after emplacement of the granite. If the first explanation is correct, the granite is not
Figure 1 Location of the Lucy Gray Range in Clark County, southern Nevada. The range is located on the 1:100,000 scale Mesquite Lake topographic map (adapted from Schmidt, 1987).
Figure 2  Distribution of Proterozoic anorogenic granite complexes of North America, and location of the Beer Bottle Pass pluton within this complex (adapted from Anderson, 1983).
anorogenic in the strict sense. If the second explanation is correct, this result would challenge widely held views on granite emplacement mechanisms, particularly those involving forcible intrusion or ballooning mechanisms (Paterson and others, 1991). In the third case, the deformation must post date the 1.4 Ga age of the granite. This would be the first documentation of post 1.4 Ga, pre-Phanerozoic deformation in the southern Nevada.

**Purpose, Problem, and Methods**

The purpose of this study is to determine the origin of the mylonites in the northern Lucy Gray Range. An integrated study involving both field and laboratory work was conducted to examine the structural relationships between the mylonites and the granite. The structural relationships were studied at the macroscopic, mesoscopic, and microscopic scales. Laboratory work focused dominantly upon thin section analysis, but also included X-Ray Fluorescence Spectrometer analysis of several mylonitic and non-mylonitic samples, and a K/Ar biotite date on a mylonitic sample from the pluton.

The three possibilities mentioned above were evaluated in the context of three models: (1) synkinematic emplacement of the granite into an active shear zone (Fig. 3a), (2) emplacement-related deformation (Fig. 3b), and (3) post-emplacement deformation of the granite (i.e., post 1.4 Ga) (Fig. 3c).

Mapping was completed on a 1:6000 scale topographic base that was enlarged from the 1:24,000-scale Desert 7.5' quadrangle. Two areas totaling 28 km² were mapped during the fall-winter-spring of 1991, and fall-winter of 1992 (Fig. 4). The southern boundary of the northern study area is 1 km south of the Beer Bottle Bottle Pass road and the area is bound on all other sides by Quaternary
Figure 3 Three possible models to explain the deformation spatially associated with the Beer Bottle Pass pluton: (a) synkinematic emplacement of the granite into an active shear zone, (b) emplacement-related deformation, and (c) post-emplacement deformation of the granite.
Figure 4  Location of the northern study area at the northern end of the Lucy Gray Range, and the location of the southern study area in the central portion of the range. XGn = quartzofeldspathic gneiss, BBPP = Beer Bottle Pass Pluton, Tv = Tertiary volcanic rocks, $\ominus$ = Mylonite zones.
alluvium (Fig. 5). The southern study area contains a major northeast striking shear zone that transects the range. The northern boundary of this study area is 1 km north of the relay tower, and its southern boundary is the major wash near the southern end of the shear zone (Fig. 6).

Seventy oriented samples were collected for petrographic and microstructural study, and 6 additional bulk samples were collected for major and trace element analysis. Microscopic kinematic indicators were used to determine shear sense in the thin sections. The thin sections were used to determine degree of annealing of deformational fabrics and types of synkinematic minerals present. These observations were used to place qualitative constraints on temperature conditions during deformation. Mineral percentages were determined by visual estimation.

X-Ray Fluorescence Spectrometer analysis included a major and trace element scan of six samples that traversed one of the major shear zones of the Lucy Gray Range. The geochemical study was used to determine if the mylonitization was isochemical with little or no mixing of protoliths across the contact.

A K/Ar biotite date on a sample of Beer Bottle Pass pluton was determined by the Geochronology Laboratory at the University of Arizona for the purpose of attempting to constrain the age of mylonitization. The biotite used for the date is from mylonitic granite in the northern Lucy Gray Range.

The principal conclusion of this paper is that the mylonites are not directly related to pluton emplacement, and therefore are probably related to a previously unrecognized Proterozoic deformational event.
Figure 5 Location of the major shear zones in the northern study area. XGn = quartzofeldspathic gneiss, BBPP = Beer Bottle Pass Pluton, ◇ = Mylonite zones.
Figure 6 Location of the major shear zones of the southern study area. XGn = quartzofeldspathic gneiss, Tv = Tertiary volcanic rocks, \( \bigtriangledown \) = Mylonite zones.
Previous Work

Previous work conducted within the Lucy Gray Range is minimal. Longwell and others (1965) completed the preliminary mapping of Clark County which includes the Lucy Gray Range, but the mapping was not detailed and did not differentiate Proterozoic units. Anderson and Bender (1989) conducted a whole-rock geochemical study on three samples from the Lucy Gray Range near Beer Bottle Pass. The three samples are of undeformed granite, mildly foliated granite, and strongly mylonitized granite. Anderson and Bender (1989) concluded that the samples compared well with the pluton chemically which indicates that the mylonitization was isochemical with limited to no mixing with the wall rock.

The gneiss and granite were dated at 1,740 +/- 25 Ma, and 1,425 +/- 25 Ma respectively using the U/Pb zircon method (L.T. Silver, oral communication to Stewart and Carlson, 1978).
CHAPTER 2
REGIONAL GEOLOGIC SETTING
Precambrian of the Southwestern United States

Amalgamation of Archean microcontinents between 2.0 and 1.8 Ga formed a relatively large North American continent. The mechanism for the accretion was the collision of the Archean microcontinents and intervening arc systems (Hoffman, 1988). A 1200 km-wide orogenic belt consisting of juvenile arc and back-arc material was added to the northern continental nucleus between 1.8-1.6 Ga. This belt includes all middle Proterozoic rocks exposed in southern Wyoming, Colorado, New Mexico, Arizona, Nevada, and southeastern California.

Three accreted crustal provinces have been distinguished in the southwestern United States by Nd and Pb isotopic characteristics and crystallization ages of plutonic rocks (Bennett and DePaolo, 1987; Wooden and Miller, 1990; Chamberlain and Bowring, 1990). These three provinces, the Yavapai, Mazatzal, and Mojave, are terranes that include smaller tectonic blocks that are bound by various shear zones (Karlstrom and Bowring, 1988). The Yavapai province consists of at least five tectonic blocks that were assembled by about 1700 Ma (Karlstrom and Bowring, 1988). The Mazatzal province consists of three tectonic blocks that were assembled and juxtaposed with the Yavapai province between 1695 and 1630 Ma (Fig. 7) (Karlstrom and Bowring, 1988). The Mojave province is characterized by Nd model ages of 2.3-2.0 Ga (Bennett and DePaolo, 1987) and higher radiogenic initial Pb isotopic compositions than the Arizona provinces and therefore reflects an origin independent of the Arizona terranes. The two terranes were contiguous by between 1.74 Ga (Wooden and DeWitt, 1991) and 1.70 Ga.
Figure 7 Distribution of early Proterozoic rocks in Nevada, California, and Arizona. Tectonostratigraphic blocks: MO-Mojave block; HB-Hualapai-Bagdad block; G-Green Gulch block; B-Big Bug block; A-Ash Creek block; M-Mazatzal block; S-Sunflower block; P-Pinal block. Major Proterozoic shear zones: CH-Chaparral fault zone; SH-Shylock fault zone; MG-Moore Gulch fault; SC-Slate Creek movement zone. Lineaments on the Colorado Plateau: SI-Sinyala fault system; BA-Bright Angel fault system; MB-Mesa Butte fault system; G-northwest boundary of gravity high; HO-Holbrook lineament. Other boundaries: Pb-isotope provinces; Sm/Nd-boundary between Sm/Nd provinces; C-geochemical boundary (from Karlstrom and Bowring, 1988).
(Karlstrom and Bowring, 1988) and both show evidence for a major 1.71-1.70 orogeny. The Lucy Gray Range lies within the Mojave province. Transcontinental anorogenic magmatism occurred at about 1.4 Ga in the southwestern United States.

**Brief Geological History of the Lucy Gray Range**

The north-south trending Lucy Gray Range of southern Nevada is composed dominantly of Proterozoic crystalline rocks overlain locally by Miocene volcanic rocks. The oldest rocks in the Lucy Gray Range are 1.7 Ga orthogneisses, and are among the oldest rocks found in southern Nevada. Similar orthogneisses are exposed in the adjacent McCullough and New York Mountains (Wooden and Miller, 1990). In the northern and central portions of the range, the gneiss complex is intruded by a 1.425 +/- 0.025 Ga megacrystic granite of the Beer Bottle Pass Pluton (L.T. Silver, oral communication to Stewart and Carlson, 1978). Rocks equivalent to the 2300-1800 Ma supracrustal rocks in the Turtle, Ivanpah, and New York Mountains (Wooden and Miller, 1990) have not been recognized in the Lucy Gray Range. Diabase dikes of the 1200-1100 Ma suite, widely distributed throughout the southwestern United States have not been recognized in the Lucy Gray Range.

The crystalline rocks of the Lucy Gray Range are overlain nonconformably by Cambrian Tapeats Sandstone near Sheep Mountain, just 2 km north of the study area. Presence of mylonites, which require deformation at temperatures greater than 300°C, near the contact with the unmetamorphosed Tapeats Sandstone indicates that the deformation that produced the mylonites is pre-Middle Cambrian in age.
The Lucy Gray Range lies in the foreland of the Mesozoic fold and thrust belt, and east of the easternmost limit of plutons associated with the Mesozoic magmatic arc. The location of the range relative to the eastern limit of significant Mesozoic deformation at this latitude, combined with the fact that the Cambrian Tapeats sandstone near the northern end of the Lucy Gray Range shows no evidence of thrust-related deformation, eliminates the possibility of Mesozoic ductile deformation in the range.

In the Las Vegas region, Cenozoic extension began during mid-Miocene time (Wernicke and others, 1987). The magnitude of Cenozoic extension in the Lucy Gray Range is uncertain; however, the range does not appear to be internally extended. The presence of probable Beer Bottle Pass pluton at the west margin of the McCullough Range argues against significant lateral translations between the two ranges, and demonstrates that the ranges form a structurally coherent block.

In the center of the valley between the Lucy Gray and the McCullough ranges is an outcrop of tuff that macroscopically resembles the tuff of Bridge Spring. Its presence is important in that it precludes a significant thickness of Quaternary or late Tertiary alluvial valley fill between the two ranges. This observation supports the suggestion that the two ranges have not been significantly displaced by normal faulting.

The Cambrian section of Sheep Mountain and the Tertiary volcanic rocks in the study area dip approximately 20-25° to the east suggesting that the effects of Cenozoic deformation within the Lucy Gray Range are modest.

1.4 Granitoids

Most North American anorogenic granites were emplaced during three different magmatic events (Fig. 2). The oldest occurred between 1.41 and 1.49 Ga,
and the second event occurred between 1.34 and 1.41 Ga. The youngest episode occurred between 1.03 and 1.08 Ga (Anderson, 1983).

The 1.41 to 1.49 Ga anorogenic belt is approximately 600 to 1000 km wide, includes 70% of all Proterozoic anorogenic granites, and seems to be restricted to North America (Anderson, 1983). The Beer Bottle Pass pluton was emplaced during this episode. The oldest plutons of this group occur in the northern midcontinent, and plutons become younger to the northeast and the southwest (Fig. 2).

The 1.4 Ga granites are more potassic, iron-enriched, and depleted in Ca, Mg, and Sr than are typical orogenic granitoids (Anderson and Bender, 1989). The granites formed near the 7-10 Kb minima, implying a middle- to lower-crustal source (Anderson, 1983). The plutons have been defined as anorogenic based on an apparent lack of deformation associated with the 1.4 Ga plutons, and on the observation that nowhere in the zone of 1.4 Ga transcontinental magmatism has Proterozoic orogenic deformation and metamorphism younger than 1.65 Ga been documented (Anderson and Bender, 1989). Several models have been proposed to explain the anorogenic generation and emplacement of the 1.4 Ga granitoids. These include: (1) mantle diapirism in an extensional regime (Anderson and Cullers, 1978; Emslie, 1978); (2) heating due to tectonic crustal thickening by previous orogenic episodes (Bickford and others, 1981; Van Schmus and Bickford, 1981); and (3) an early manifestation of the Grenville Orogeny (Nelson and DePaolo, 1985).
CHAPTER 3
DISCUSSION OF POSSIBLE MODELS OF MYLONITE ZONE DEFORMATION

Synkinematic Intrusion of the Beer Bottle Pass Pluton

If the Beer Bottle Pass pluton had been emplaced synkinematically with respect to deformation within an active shear zone, a 1.4 Ga deformational event is indicated. Recognition of a 1.4 Ga deformational event would be inconsistent with a strictly anorogenic setting for pluton emplacement. This result would call into question previous interpretations of anorogenic emplacement of at least one of the 1.4 Ga granitoids. Granites emplaced within actively deforming shear zones should show: (1) parallelism of mylonitic foliation inside and outside of the pluton, and the mylonitic foliations can be oblique to the pluton-wall rock contact, (2) high temperature mylonites near the pluton that grade to lower temperature mylonites away from the pluton, both along and across strike of the shear zone, (3) mylonites that locally diverge from the pluton-wall rock contact, and (4) a consistent sense of simple shear in all mylonite zones (Paterson and others, 1991).

Post-emplacement Deformation

If the granite had been deformed after emplacement and cooling, the following observations would be expected: (1) microstructures and synkinematic mineral assemblages should indicate approximately uniform temperatures of deformation throughout the shear zone, (2) mylonite zones may diverge markedly from the pluton contact and possibly cut the pluton-wall rock contact at high angles, and (3) an overall unidirectional shear sense would be recorded in the mylonites (Paterson and others, 1991). Development of a post-emplacement shear zone would not rule out an anorogenic origin of the granite, but would document a
Proterozoic deformational event not widely recognized in the southwestern United States.

Emplacement-related Deformation

If the mylonites were produced by forcible intrusion of the Beer Bottle Pass pluton, the anorogenic interpretation for the origin of the granites is permissible. Forcible intrusion accompanied by ballooning of the pluton would result in: (1) mylonites that are areally restricted to the contact, (2) mylonites that show evidence for high-temperature deformation near the pluton margin and low-temperature deformation away from the pluton, (3) an overall pattern of flattening strains, and (4) variable or bi-directional shear sense indicators (Paterson and others, 1991).

The Papoose Flat pluton, located in the White Mountains of California, was cited as a classic example of pluton emplacement by ballooning (Sylvester and others, 1978; Holder, 1979; Law and others, 1993). However, Paterson and others (1991) recently suggested that the mylonites adjacent to the Papoose Flat pluton are a result of post-emplacement regional deformation. This example shows that the presence of mylonites adjacent to a pluton does not necessarily imply or require a genetic relationship between plutonism and deformation.

Age of Deformation

Two lines of evidence establish that the age of mylonitization must be post-1.42 Ga, but pre Phanerozoic. First, the presence of mylonites directly beneath the Cambrian nonconformity indicates that the mylonites were exposed at the surface at that time. If the mylonites were exposed at the surface during Cambrian time, while the Tapeats Sandstone was being deposited, mylonitization must have occurred sometime during the Precambrian. Second, a biotite K/Ar date of 1399 +/- 32 Ma (Table 1) was obtained on mylonitic granite from the northern study
area (Plate 1) (M. Shafiquallah, personal communication, 1992). Biotite has a closure temperature, with respect to Ar loss, of 280-300° C, which is at the lower end of thermal conditions required for mylonitization. The date, if valid, indicates a minimum age for mylonitization, and places a Precambrian time constraint on the deformation.
Table 1: Reported analytical data on a K-Ar biotite date completed by the University of Arizona December 30, 1992 on a sample of mylonitic Beer Bottle Pass granite collected from the Lucy Gray Range.

Analytical Data:

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CHAPTER 4
Description of Map Units

1.7 Ga Gneiss (all types, XGn)

The Lucy Gray Range contains a heterogeneous assemblage of metamorphic rocks. The most abundant rock type in the northern Lucy Gray Range is a light gray to pink, fine- to medium-grained quartzofeldspathic gneiss with undulating foliation defined by the alignment of biotite (Fig. 8). Microcline (35-50%), plagioclase (20-35%), quartz (10-25%), and biotite (2-7%) are the common minerals, with minor traces of sphene. Sericitic alteration of feldspars is common. The quartzofeldspathic mineralogy and the presence of xenoliths of non-foliated amphibolite indicate that the gneiss is an orthogneiss. Lack of aluminous or pelitic protoliths precludes a more precise determination of conditions of metamorphism.

Small pods and elongate bodies of mafic gneiss occur at various locations at the northern end of the Lucy Gray Range. The size of the mafic gneiss bodies vary, but most are generally less than 100 m at their widest point. Major minerals are plagioclase, quartz, microcline, biotite, and hornblende suggesting an intermediate or locally mafic plutonic rock as the protolith. Sphene is an accessory mineral. The presence of hornblende indicates metamorphism at amphibolite facies conditions.

At the northern tip of the Lucy Gray Range, pods, on the scale 10-100 m, of a garnet-bearing gneiss occur. The gneiss is felsic in composition and contains coarse garnet and biotite. Major minerals are microcline, plagioclase, quartz, and biotite. Garnet is an accessory mineral, and chlorite and sericite are secondary alteration products. Depletion halos surround the garnets, and foliation is weak and deflects around the garnet halos.
Figure 8 Photograph of the most common type of 1.7 Ga gneiss in the Lucy Gray Range. The photo is an outcrop of gneiss showing a distinct foliation defined by alternating light and dark compositional layering.
1.4 Ga Granite

The Beer Bottle Pass pluton is mineralogically and texturally uniform with the exception of a marginal facies exposed at the eastern contact on the western flank of the McCullough Mountains along the McCullough Pass road. At this contact the granite is more mafic and finer grained than the typical Beer Bottle Pass granite.

The Beer Bottle Pass pluton is a coarse-grained, porphyritic hornblende-biotite granite that contains feldspar megacrysts up to 4-5 cm in length (Fig. 9). Magmatic foliation occurs locally near the wall rock contact and at various locations well within the pluton. Locally the magmatic foliation is overprinted by solid state foliation. Magmatic foliation within the Beer Bottle Pass pluton is distinguished from solid state foliation by the presence of aligned euhedral feldspar crystals surrounded by non-deformed quartz grains. During solid state deformation the feldspar crystals become rounded and reduced in size and surrounding quartz grains are ductilely deformed (Paterson and others, 1989). Mafic and felsic dikes occur sparsely within the granite. The orientation of the mafic dikes is random, and they are typically 1 m thick and up to 50 m in length. The felsic dikes are pegmatites on the order of 3 m wide and 50 m long (Fig. 10).

Primary minerals within the granite are microcline (40-50%), plagioclase (20-30%), quartz (10-15%), biotite (2-5%), and hornblende (< 1%). Accessory minerals are sphene, apatite, Fe-Ti oxides, and zircon. Sericitic alteration of feldspars is common. Hornblende, partially altered to biotite and chlorite, is present in some thin sections collected near the contact. Rapakivi texture is present in several samples, but appears to be only partially developed.
Figure 9 Photograph of undeformed 1.4 Ga Beer Bottle Pass granite. The feldspar porphyroclasts euhedral with little or no rounding of the crystal corners. (Pencil for scale)
Figure 10  Felsic dike from the northern study area. (Gatorade bottle used for scale)
Other Rock Types

The rocks south of the southern study area differ from the typical Lucy Gray gneisses present in the northern half of the range. The two dominant rock types are a banded gneiss of intermediate composition, and a mafic megacrystic granite. The gneiss consists of strongly folded alternating light and dark bands (Fig. 11). The granite differs from the Beer Bottle Pass pluton in that it is more mafic and contains markedly smaller potassium feldspar megacrysts. It should be noted that work done in the area south of the southern study area was reconnaissance in nature.

Several dikes and pods of pegmatitic leucogranite occur within both study areas. These bodies are small, typically less that 40 m long, and consist of coarse-grained, white to pink, garnet-bearing leucogranite or pegmatite.

The Cambrian Tapeats sandstone is present just 2 km north of the Lucy Gray Range, south of Sheep Mountain. At this location it is a red to pink, fine- to medium-grained subarkose. A Tertiary andesite unit is present in the central Lucy Gray Range within the southern study area (Fig. 6).

Description of the Wall Rock-Pluton Contact

The mapped contact represents only the western margin of the pluton; however, the eastern contact is exposed at the western edge of the McCullough Mountains along McCullough Pass road. The eastern contact is non-mylonitic and is poorly exposed. Large xenoliths of gneiss, on the order of 5 m wide and 20 m long, occur within the granite along portions of the eastern and western contacts. Numerous dikes and sills of granite occur within the gneiss along the eastern contact.
Figure 11 Photograph of thickly banded gneiss from the south end of the southern study area. (Rock hammer for scale)
Only 16% of the mapped contact between the granite and the gneiss is appreciably mylonitized. Where the contact is oriented northeast-southwest it is commonly mylonitic, it is less commonly mylonitic in other orientations (Fig. 4). Where the contact is non-mylonitic, it is typically knife sharp, and lacks any microscopic or macroscopic evidence for deformation (Fig. 12). The granite intrudes the gneiss in a lit-par-lit fashion at various locations along the contact. Xenoliths are present at some locations along the western contact, and are typically composed of gneissic wall rock. In the southern study area, the contact is offset by a major mylonitic shear zone (Fig. 6).
Figure 12 Photograph of non-mylonitic contact between granite (bottom) and gneiss (top) along the western contact north of Beer Bottle Pass road. At this location the granite interfingers with the gneiss. The gneiss foliation is parallel to the contact (N-S) and dips 50° to the west. The rock hammer is located at the first of two tabular bodies of granite.
CHAPTER 5
STRUCTURE

General Structure

Wall rock foliation, defined by mineral alignment, is variable in strike and
dip along the western margin of the pluton, but generally is north-northeast and
subvertical (Fig. 13). Foliation development is probably unrelated to the pluton
emplacement as it is equally well developed regardless of proximity to the pluton.
The foliation is broadly parallel with the intrusive contact but in some locations it
strikes at a high angle to the pluton margin. Wall rock foliation in the southern
study area is truncated at a high angle by a shear zone.

Several large mylonite zones are spatially associated with the Beer Bottle
Pass Pluton. The mylonite zones commonly strike northeast-southwest and dip
moderately to steeply to the west. For convenience, mylonitic shear zones in the
northern and southern study areas will be discussed separately below. In the equal-
area plots and the discussion that follows, all orientation data are presented in
present day coordinates; i.e., they are not corrected for the 25° of Phanerozoic
eastward tilt. The tilting does not affect the conclusions of this study.

Several brittle faults are present in both the northern and southern study
areas. The large shear zone in the southern study area is truncated by a brittle fault
near its southern end (Fig. 6; Fig. 14). Breccia zones along these faults range from
0.5 m to 8 m thick. Two of the brittle faults in the northern study area contain
mylonitic fragments indicating prior ductile deformation suggesting that the ductile
shear zones could be zones of weakness that accommodated later brittle
deformation.
Figure 13 Equal-area lower hemisphere projection of wall rock foliation in the northern study area. The Kamb method was used for this plot which considers statistical deviation from an expected standard. C.I. = contour interval.
Figure 14 Photograph of the truncation of the southern shear zone. The pen near the top of the rock hammer is parallel to mylonitic foliation, and the pen at the bottom of the photo defines the strike of the brittle fault. The bottom of the rock hammer handle is the location where brittle deformation begins.
Mylonitic Shear Zones of the Northern Study Area

The dominant structural features in the northern study area are thick ductile shear zones that occur near the wall rock-pluton contact in section 18, T. 26 S., R. 60 E. (Fig. 5; Plate 1). Individual mylonite zones range in width from 0.5 m to 20 m. The largest shear zone in the northern study area splits into two separate branches. One branch of the major shear zone is deflected around the northern end of the pluton; another strikes approximately N50°E, dips 40°W, and continues west away from the contact, wholly within the wall rock. Strain intensity, based on field interpretation and thin section analysis, within the northern shear zones is very heterogeneous, with rocks ranging from protomylonite to ultramylonite. Very abrupt transitions between these types of fault rocks indicate that strong strain gradients existed during deformation.

The mylonites of the northern study area are LS tectonites, with a mean mineral elongation lineation that trends 266° and plunges 45°. Mylonitic foliation and lineation data from the northern and southern study areas were combined on lower-hemisphere equal area projections (Fig. 15). Mesoscopic and microscopic kinematic indicators used to evaluate shear sense were asymmetrical augen, S-C fabrics, oblique foliations in quartz aggregates, hornblende fish, and mica fish (Simpson and Schmid, 1983; Passchier and Simpson, 1986) (Figs. 16, 17, 18, and 19). Of the 39 thin sections made from hand samples collected in the northern study area 24 are mylonitic. Of those 24 mylonitic thin sections, 13 show that the pluton moved down relative to the wall rock, 4 show that the pluton moved up relative to the wall rock, and 7 were ambiguous. Combined with orientation data on mylonitic foliation and lineation, kinematic analysis at the mesoscopic and microscopic scales indicate that the shear zones represent reverse-slip faults with a
Figure 15 Lower-hemisphere equal area projections of mylonitic foliation and lineation data from both north and south study areas. Foliation is more variable than the lineation. (N=number of data points, C.I.=2 Sigma)
Figure 16 Photomicrograph of asymmetrical feldspar augen in an ultramylonite from the northern study area. Plane light was used and the field of view is 3.5 mm across. Shear sense is dextral (shown by arrows).
Figure 17 Photomicrograph of oblique foliations in quartz ribbons. The sample is from the northern study area. Polarized light was used and the field of view is 3.5 mm across. Sense of shear in this view is dextral. Q = fabric defined by quartz subgrains and new grains, M = mylonitic foliation.
Figure 18 Photomicrograph of hornblende fish (labeled N) in mylonitic Beer Bottle Pass Pluton from the northern study area. Plane light was used and the field of view is 3.5 mm across. Shear sense is dextral.
Figure 19  Mylonite from the northern study area. A dextral shear sense was indicated by asymmetrical augen (shown by arrows) at the outcrop.
dextral component of movement. This result is unchanged by restoring 25° of Phanerozoic eastward tilt.

**Mylonitic Shear Zones of the Southern Study Area**

The dominant structural feature of the southern study area is a large mylonitic shear zone that strikes variably to the northeast, dips from 30° to 60° to the west and can be traced discontinuously for 2.8 km from section 4 to section 8, T. 27 S., R. 60 E. To the northeast, the shear zone is offset by a series of brittle faults, but can be traced discontinuously northward until buried beneath alluvium. To the southwest, the shear zone is truncated by a brittle fault (section 8, T. 27 S., R. 60 E.) (Plate 2), and its offset extension was not found. Ductile fault rocks within the southern shear zone range from protomylonite to ultramylonite and strain is homogeneous with gentle gradations between the different degrees of mylonitization, based on thin section analyses and field observations.

The shear zone truncates an intrusive contact between granite and gneiss at a high angle (Plate 2), and offsets the contact by approximately 800 m right-laterally in map view (Fig. 6). Mylonitic foliation within the shear zone is oblique (87°) to the wall rock foliation. Where the shear zone places granite against gneiss it varies in width from 20 m to 80 m. As it passes entirely into the granite to the northeast, the shear zone becomes more protomylonitic and much wider (> 100 m). There are two explanations for the widening of the shear zone as it passes into the granite. The first is that the pluton was still hot during deformation, resulting in more distributed but lower-magnitude strain. The second is that perhaps the mechanical differences between the wall rock and the pluton localized shear strain along a relatively narrow zone.
The mylonites of the southern shear zone are LS tectonites, with mineral elongation lineation that has an average trend of 275°, and an average plunge of 43°. Macroscopic and microscopic kinematic indicators, including asymmetrical augen, S-C fabric, oblique foliation, mica fish, were examined to determine sense of shear in the southern shear zone (Figs. 20, 21, 22, and 23). Of the 25 thin sections made from hand samples collected in the southern study area, 17 are mylonites. Of those 17 mylonitic thin sections, 10 show that the pluton moved down relative to the wall rock, 3 showed pluton moved up relative to the wall rock, and 4 were ambiguous. Shear indicators record top-to-the-east sense of shear which corresponds to reverse-slip movement with a dextral component. These observations are consistent with the map pattern that shows right-lateral separation of the northwest striking granite-gneiss contact across the southern shear zone (Plate 2).

Wall rocks north of the southern shear zone are similar to orthogneisses of the northern study area. The wall rock types appear to be different south of the southern shear zone. The different rock types south of the shear zone possibly indicate a different protolith and may reflect substantial displacement along the southern shear zone prior to intrusion of the Beer Bottle Pass pluton (Plate 2). The significant amount of displacement could represent a pre-pluton deformational event that was reactivated during pluton emplacement, or synkinematic emplacement during a single event.

There are several mylonite zones south of the southern shear zone, but these are not considered likely candidates for the offset extension of the main shear zone because they show markedly different foliation and lineation orientations than the
Figure 20  Asymmetrical δ porphyroclast in a mylonitic sample from the southern study area. Polarized light was used and the field of view is 3.5 mm across. Sense of shear is dextral (shown by arrows).
Figure 21 Oblique foliations in quartz aggregates in a mylonitic sample from the southern study area. Polarized light was used and the field of view is 3.5 mm across. Shear sense is sinistral in this view. Q=fabric defined by quartz subgrains and new grains, M=mylonitic foliation.
Figure 22 Stable biotite (labeled B) in a mylonitic sample from the southern study area. This occurrence indicates that mylonitization occurred under conditions corresponding to the biotite stability field. Plane light was used and the field of view is 3.5 mm across.
Figure 23  Field photograph of protomylonitic 1.4 Ga granite. The photo is from the southern study area, and the pencil points to the east. Shear sense determined at the outcrop is top-to-the-east by evaluation of asymmetrical porphyroclasts (shown by arrows) and S-C relationships (shown by lines).
main zone (Plate 2), and they are developed in rock types that are unlike the rocks present in the central and northern portions of the Lucy Gray Range. A more extensive examination of these shear zones is needed, but is beyond the scope of this study.

Discussion of Structure

The orientations of mylonitic lineation and foliation are remarkably similar for both study areas (Fig. 15). The combined mean mylonitic foliation strikes N51°E and dips 50°W, and the mylonitic lineation for both areas trends 269° and plunges 49°. Mylonitic foliation is more variable in orientation than mylonitic lineation as shown by contoured stereonet plots (Fig. 15). This relationship is inconsistent with forcible intrusion. If the mylonites were formed by forcible intrusion, then variability in both mylonitic lineation and mylonitic foliation would be expected due to reorientation of early formed fabrics during successive intrusive pulses. The observed relationship is best explained by processes that involve uniform elongation or tectonic transport direction along variably oriented shear surfaces.

The prominence of LS fabrics in both study areas is suggestive of bulk non-coaxial deformation. These rocks do not exhibit the flattening fabrics expected with forcible intrusion. The abundance, well-developed character, and consistency of kinematic indicators corroborates this interpretation.
CHAPTER 6
THERMAL CONDITIONS AND CHEMISTRY

Thermal Conditions of Deformation

To constrain qualitatively the thermal conditions of deformation, synkinematic minerals were identified in thin section and microstructures in quartz and feldspar were examined. The requisite mineral assemblages for thermobarometry are not present in any of the rocks studied. Biotite is the most abundant ferromagnesian mineral in the mylonites indicating its stability during deformation. Hornblende, where present is commonly but not completely converted to biotite and chlorite. This synkinematic mineralogy indicates deformation at upper-greenschist to lower-amphibolite facies conditions.

Quartz is deformed into elongate ribbons in all mylonitic samples indicating plastic deformation. Feldspars show evidence for brittle, transitional, and plastic deformation (Figs. 24, 25, and 26). The onset of plastic deformation in feldspars is generally considered to occur at 450° C, a temperature that corresponds approximately with the greenschist-amphibolite facies transition (Tullis and Yund, 1985). This temperature is consistent with the synkinematic mineral assemblages observed in thin section.

To evaluate the possibility of any thermal effects associated with the pluton during mylonitization, I plotted the degree of annealing of quartz ribbons in each sample relative to the contact for both the northern study area (Fig. 27), and the southern study area (Fig. 28). If the pluton produced the mylonites by forcible intrusion heating would outlast deformation and the samples nearest to the pluton should be strongly annealed. The other two scenarios for mylonite formation do not require that thermal effects outlast deformation. The criteria used to evaluate the degree of annealing are: (1) Weak Annealing - quartz ribbons show no evidence
Figure 24 Brittle deformation of a feldspar (shown by arrow) in a mylonite from the northern study area. Polarized light was used and the field of view is 3.5 mm across.
Figure 25 Transitional deformation of a feldspar showing both brittle deformation (labeled 1) and dynamic recrystallization (labeled 2). Polarized light was used and the field of view is 3.5 mm across.
Figure 26 Dynamic recrystallization (shown by arrows) of a feldspar in a mylonite from the northern study area. The large porphyroclasts are remnants of an optically continuous microcline grain. The intervening material consists of very finely recrystallized microcline grains. There is no evidence for microfracturing in this sample. Polarized light was used and the field of view is 3.5 mm across.
Figure 27  Map showing the degree of annealing in mylonite samples relative to the pluton contact in the northern study area. There is no distinct pattern of strongly annealed textures near the contact grading to progressively less annealed textures away from the contact.
Figure 28  Map showing the degree of annealing in mylonite samples relative to the pluton contact in the southern study area. There is no distinct pattern of strongly annealed textures near the contact grading to progressively less annealed textures away from the contact.
for recovery or recrystallization. The quartz ribbons exhibit undulatory extinction (Fig. 29), (2) Moderate Annealing - quartz ribbons show subgrain development (i.e. low-angle boundaries between extinction domains), but the grain margins are serrated and irregular indicating incipient recrystallization (Lister and Snoke, 1984) (Fig. 30), and (3) Strong Annealing - the quartz ribbons display well developed new grains with 120° angles between adjacent grains (Fig. 31). The margins of the individual grains are straight and show little or no serration.

The two maps show that there is no relation between the degree of annealing of a sample and its position relative to the pluton, suggesting that there was no temperature gradient away from the pluton. Forcible emplacement would produce a distinct pattern of strongly annealed fabrics near the pluton grading to weakly annealed fabrics away from the pluton. I observed in some locations strong annealing away from the pluton, and weak annealing within a few meters of the wall rock contact. It is apparent that there is no distinct pattern to the degree of annealing adjacent to the Beer Bottle Pass pluton.

Feldspar and quartz microstructures are most consistent with lower amphibolite facies conditions for mylonitization and not higher as would be expected if the mylonites formed during forcible intrusion. The degree of annealing in mylonites from both the northern and southern study areas shows no systematic distribution with respect to the pluton. These observed microstructures along with upper greenschist-lower amphibolite facies synkinematic mineral assemblages are not consistent with formation of mylonites due to forcible emplacement of the Beer Bottle Pass Pluton.
Figure 29 Non- to weakly annealed quartz grains (shown by arrow) in a mylonitic sample from the southern study area. Notice brittle deformation of feldspar porphyroclast and unrecovered quartz. Polarized light was used and the field of view is 7 mm across.
Figure 30  Moderately annealed quartz grains (shown by arrow) from a mylonitic shear zone in the northern study area. Polarized light was used and the field of view is 3.5 mm across.
Figure 31  Strongly annealed quartz grains (shown by arrow) in a mylonitic sample from the northern study area. Polarized light was used and the field of view is 3.5 mm across.
Chemistry of the Mylonites

The purpose of this part of the study is to determine the elemental content of a series of rock samples from a mylonitic shear zone from the northern study area of the Lucy Gray Range to evaluate the possibility of chemical mixing during mylonitization. Previous geochemical analyses of variably mylonitized granite showed that the mylonitization was isochemical with limited or no mixing of the country rock with the pluton (Anderson, 1989); however, this study was limited to three samples. In addition it is not clear that these samples were taken systematically across a zone of mylonitization.

Channel samples BR-1, BR-2, BR-3, BR-4, BR-5, and BR-6 were analyzed using a Rigaku model 3030 X-Ray Fluorescence Spectrometer. The samples were analyzed for both major elements using fusion disks and trace elements using pressed pellets. Sample BR-1 is undeformed gneiss and BR-6 is undeformed granite. The other samples are all mylonitized (Table 2). Sample locations are shown on the base map in the northern study area (Plate 1).

Trace elements are; Ni, Rb, Sr, Zr, and Ba (Table 3). Major elements that were analyzed are; Si, Al, Ti, Fe, Ca, K, P, Na, Mg, and Mn (Table 4). Standardization was done using sample M2. Sample M2 is from the McCullough Pass rhyolite tuff and has been developed as a multi-element rock standard at the University of Nevada, Las Vegas. Sample standard M2 was used as an unknown for major and trace element scans to determine analytical accuracy. The results are very close to previous scans done on sample M2. PHA was checked before operation of the XRF and standardization was done at three-sample intervals.
Table 2  Field descriptions, and relative locations of the samples used for chemical analysis.

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Table 3 Results of trace element analysis of the six samples across a shear zone in the northern study area.

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Table 4 Results of major element analysis of the six samples across a shear zone in the northern study area.

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<td>0.528</td>
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<td>1.543</td>
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<td>0.65</td>
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<td>BR-6</td>
<td>70.52</td>
<td>14.25</td>
<td>0.65</td>
<td>5.42</td>
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</table>

<table>
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<th>Na2O</th>
<th>MgO</th>
<th>MnO</th>
<th>%Totals</th>
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<td>3.887</td>
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<td>2.64</td>
<td>0.558</td>
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<td>98.5</td>
</tr>
<tr>
<td>3.605</td>
<td>0.07</td>
<td>3.464</td>
<td>0.528</td>
<td>0</td>
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<tr>
<td>3.776</td>
<td>0.048</td>
<td>3.113</td>
<td>0.577</td>
<td>0</td>
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<tr>
<td>3.83</td>
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<td>0.48</td>
<td>0</td>
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<tr>
<td>3.806</td>
<td>0.077</td>
<td>2.3</td>
<td>0.765</td>
<td>0</td>
<td>97.0</td>
</tr>
<tr>
<td>3.83</td>
<td>0.03</td>
<td>2.68</td>
<td>1.3</td>
<td>0</td>
<td>100.7</td>
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</tbody>
</table>
Interpretation of the Chemical Analysis

Bar graphs were made for all elements in the six samples. Several of the elements show a very distinct chemical contact between the granite and the gneiss between samples BR-3 and BR-4. Ni, Sr, Zr, Ba, Si, Ti, Fe, Ca, and Na show a definite compositional contact between the two rock types (Fig. 32; Fig. 33). These graphs suggest that there was no mixing of the country rock with the granite.

Si, Al, and K show no change in elemental percent throughout the shear zone. These results could be due to homogenization of mobile elements throughout the shear zone. Sample BR-3 appears to show mobilization of some elements. The elements are Ba, Sr, and Ca.

These geochemical data support the conclusion of Anderson (1989) that mylonitization was fundamentally isochemical, but suggest that limited migration of the more mobile elements did occur. The data also suggest that, where shear zones occur at the pluton-wall rock contact, mylonitization occurs within both rock types.
Figure 32  Bar graphs showing trace element percent in rock samples taken across a shear zone in the northern study area. The pluton-wall rock contact occurs between BR-3 and BR-4.
Figure 33 Bar graphs showing major elements in ppm from rock samples collected from a shear zone in the northern study area.
CHAPTER 7
RESULTS AND CONCLUSIONS

Discussion of Results

The purpose of this section is to evaluate each of the three models for mylonite formation in the context of the data and observations presented above. These observations are summarized in Table 5. Previous studies have shown that no single observation or criterion can be used alone to establish the relative timing of pluton emplacement and regional deformation (Paterson and Tobisch, 1988). Each of the three models will be discussed, using the observations made during this study.

The 1399 Ma K/Ar biotite date is consistent with each of the three models for mylonite formation. The uncertainties of the K/Ar and U/Pb zircon dates overlap, permitting contemporaneous magmatism and deformation as predicted by the ballooning pluton or synkinematic intrusion models. If the extreme limits of uncertainties in age data are considered, deformation could have post dated intrusion by 83 Ma; consistent with the post-emplacement deformation model.

The observation that shear zones locally conform to the contact is consistent with all three models. The ballooning pluton model requires that shear zones parallel the pluton-wall rock contact. In the synkinematic intrusion model, shear zones might form preferentially adjacent to the granite due to thermal weakening of the wall rock. In the post-emplacement deformation model, strain could be localized adjacent to the pluton if the intrusion acted as a rigid body during deformation. It is important to note that deformation conforms to the pluton-wall rock contact only in the northern study area along 400 m of the contact. This locality is the only area of major deformation that does not have a NE-SW orientation.
The relatively uniform top-to-the-east sense of shear is more consistent with mylonite development in a zone of unidirectional shear than adjacent to a ballooning pluton. A ballooning pluton would produce either symmetrical fabrics, ambiguous shear sense indicators, or conjugate shears that show opposing shear senses. This criterion is most consistent with either syntectonic intrusion or post-intrusion deformation.

The shear sense indicators are suggestive of bulk non-coaxial deformation typical of uniform sense shear zones rather than coaxial deformation that would be expected with a ballooning pluton. This observation is most consistent with either synkinematic intrusion or post-intrusive deformation.

Nearly all of the pluton contact that is mylonitic has a NE-SW orientation. Forcible intrusion of the pluton should result in a more random orientation of mylonites around its margin, and not show a preference to a specific orientation. This observation argues against the ballooning model and is consistent with either synkinematic intrusion or post-intrusive deformation.

The high angle relationship between the wall rock-pluton contact and the major shear zone in the southern study area is consistent with both of the shear zone models and cannot be explained satisfactorily by a ballooning pluton (Fig. 6). This observation indicates that a significant portion of the pluton margin must have cooled enough to act as a coherent body at the time of mylonite formation. Along the strike of the shear zone, the pluton has an estimated maximum width of 13 km, if the eastern contact represents the pluton's side and not its top. The pluton margin has been offset by a minimum of 800 m (approximately 1 km). The shear zone can be traced for 2 km into the pluton where it is buried underneath alluvium. The significant amount of offset at the pluton margin suggests that 800 meters of the
outer pluton had cooled prior to the last episode of deformation. This observation is inconsistent with the ballooning pluton model but can be accommodated by either the synkinematic or post-emplacement models.

Shear sense indicators from both the northern and southern study areas indicate that the pluton moved down relative to the wall rock. Although this situation may occur locally as a pluton intrudes wall rock, it is unlikely to characterize a large portion of the margin of an ascending pluton. This observation is most consistent with either synkinematic intrusion or post-intrusion deformation.

Only 16% of the exposed pluton-wall rock contact is mylonitic. The overwhelming majority of the contact is clearly intrusive, with little or no deformation of wall rock. It is unlikely that forcible intrusion of a pluton would result in such localized deformation. The local coincidence of mylonite zones with the contact can be explained by strain localization of the pluton margin due to the mechanical contrast between the pluton and wall rock.

Mylonitic foliation is more variable in orientation than mylonitic lineation (Fig. 13). As discussed above, this relationship is inconsistent with forcible intrusion because forcible intrusion should reorient foliation and lineation equally. This relationship is more consistent with uniform shear sense along variably oriented surfaces, as in an anastomosing shear zone or as the zones of deformation wrap around the pluton margin, while maintaining a consistent lineation trend. This observation is consistent with syntectonic intrusion or post-intrusive deformation.

Mylonites adjacent to the pluton do not show a transition from high temperature deformation to low temperature deformation away from the contact.
This observation requires that the pluton must have been cooled at least partially prior to deformation; a situation unlikely to occur if intrusion of the pluton was responsible for the formation of the mylonites. Lack of a transition from high temperature deformation to low temperature deformation could occur in the synkinematic intrusion model as long as deformation continued well below the solidus temperature of the granite. The thermal variation is difficult to explain with the post emplacement model.

The observed lower amphibolite-upper greenschist facies mineral assemblages and microstructures that suggest deformation at temperatures lower than 450°C are consistent with deformation of a significantly cooled pluton. This constraint is incompatible with the ballooning pluton model because the mylonites adjacent to the contact should contain and preserve evidence for development at higher temperatures. Deformation at upper-greenschist to lower-amphibolite facies conditions is most consistent with post-intrusive deformation but could occur in a synkinematic intrusion as long as deformation continued long after the pluton cooled.

The above discussion shows that forcible intrusion may be ruled out as the cause of the deformation. I therefore conclude that this scenario is not a valid explanation for the deformation associated with the Beer Bottle Pass pluton. The observations supporting the other two scenarios are numerous and indicate that either of the two solutions is possible.

All of the observations listed in Table 5 are equally consistent with both the synkinematic intrusion and post-intrusion deformation models and cannot be used to distinguish between the two. The apparent lack of a thermal transition in mylonites away from the contact and the relatively low-grade conditions under which mylonitization occurred imply either a late synkinematic or post emplacement
deformation. The temperature conditions indicated by microstructures are more consistent with post emplacement deformation, but cannot rule out a late synkinematic deformation because deformation could have outlasted thermal effects associated with plutonism.

The high angle relationship between the southern shear zone and the pluton indicates that at least the margin of the pluton had cooled prior to being offset by the shear zone. This observation seems most consistent with post-intrusive deformation, however, it does not negate the possibility of continued intrusive activity after the onset of deformation. Similarly, the pluton could have been emplaced synkinematically, but if deformation continued after emplacement of the pluton, evidence for that syn-intrusive deformation could be destroyed or overprinted. While favoring post-intrusive deformation, this observation is also consistent with late-synkinematic intrusion.
Table 5  Observations used to evaluate the three possible models for deformation.

<table>
<thead>
<tr>
<th>Observations</th>
<th>Post Emplacement</th>
<th>Synkinematic Emplacement</th>
<th>Forcible Intrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1399 Ma Date</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Deformation Conforming to Contact</td>
<td>Possible</td>
<td>Possible</td>
<td>Yes</td>
</tr>
<tr>
<td>Consistent Sense of Shear</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Dominant Simple Shear</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Dominant NE-SW Orientation of Mylonites</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>High Angle Relationship Between Shear Zones and the Pluton</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Pluton Side Down</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>16% of Contact Mylonitic</td>
<td>Yes</td>
<td>Yes</td>
<td>Unlikely</td>
</tr>
<tr>
<td>Mylonitic Foliation More Variable than Lineation</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>No Temperature Transition Away From the Pluton</td>
<td>Yes</td>
<td>Yes</td>
<td>Possible</td>
</tr>
<tr>
<td>Lower Amphibolite Conditions of Deformation</td>
<td>Yes</td>
<td>Possible</td>
<td>No</td>
</tr>
</tbody>
</table>
Conclusion

The principal conclusions of this study are: (1) forcible intrusion of the Beer Bottle Pass pluton did not cause the deformation observed in mylonite zones throughout the Lucy Gray Range. (2) Deformation associated with formation of mylonite zones occurred at upper greenschist-lower amphibolite facies conditions and represents either regional shortening or transpression. (3) The mylonites formed during the Proterozoic sometime between 1450 and 1367 Ma.

It is not possible to distinguish definitively between the synkinematic emplacement and post-emplacement deformation models, because synkinematic mineral assemblages and feldspar microstructures indicate that some deformation did occur after the pluton had cooled. However, the K/Ar biotite date, annealing patterns, and microstructures best fit the synkinematic model with deformation outlasting the heating effects of the pluton. I believe that the deformation associated with the Beer Bottle Pass pluton is synkinematic in origin and that the deformation continued after the pluton cooled.

I recognize that plutons are commonly very large and that I may be seeing only a small portion of the Beer Bottle Pass pluton. This problem of exposure exists in almost all pluton studies and must always be considered. However, I feel that my conclusions are the most simple solutions possible for the observations made. It is not possible to determine exactly when the pluton cooled, and therefore a distinction between the two models is not possible. The solutions are significant in that they propose a previously unrecognized deformational event that occurred during the Proterozoic.
REFERENCES


PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17\" x 23\") are available for an additional charge.
CONTOUR INTERVAL 10 METERS

PLATE 1
NORTHERN STUDY AREA

MAP UNITS

Qal  Alluvial deposits that may locally be as old as Tertiary

Tv   Tertiary andesite and basalt.

YGr  1.4 Ga granite that is coarse-grained, porphyritic hornblende granite that contains feldspar megacrysts up to 5 cm in length. Age is unknown.

XGb  Banded gneiss, light gray to dark gray, fine grained. Northern study area only.

XGg  White to pink, garnet bearing, coarse-grained granite.

XGn  1.7 Ga light gray to pink, fine- to medium-grained quartz gneiss with undulating foliation defined by the alignment of feldspar megacrysts up to 2 cm in length. Age is unknown.

Gh   Hornblende bearing, black to dark gray, coarse-grained feldspar megacrysts up to 2 cm in length. Age is unknown.
STUDY AREA

cally be as old as Tertiary.

gained, porphyritic hornblende-biotite
megacrysts up to 5 cm in length.
dark gray, fine grained.
g, coarse-grained granite.

e- to medium-grained quartzofeldspathic
don defined by the alignment of biotite.
dark gray, coarse grained granite with
om in length. Age is unknown.
Northern study area only.

XGn: 1.7 Ga light gray to pink, fine- to medium-grained gneiss with undulating foliation defined by the a
Hornblende bearing, black to dark gray, coarse feldspar megacrysts up to 2 cm in length. Age

SYMBOLES

Wall rock foliation
Mylonitic foliation and lineation
Magmatic foliation
Contact
Vertical lineation

DECLINATION DIAGRAM

CONTOUR INTERVAL 10 METERS
SCALE 1:6000

Beer Bottle Pass
Hornblende bearing, black to dark gray, coarse grained granite with feldspar megacrysts up to 2 cm in length. Age is unknown.

**SYMBOLS**

- ▲ Wall rock foliation
- ▲ Wall rock foliation and lineation
-  ▪ Magmatic foliation
-  ▪ Contact
-  ▪ Vertical lineation

**Contact located approximately**

**Location of shear zones**

**Sample locations**

**XOXOXOXO** Mafic and felsic dikes

**DECLINATION DIAGRAM**

**CONTOUR INTERVAL 10 METERS**

**SCALE 1:6000**
blende bearing, black to dark gray, coarse grained granite with par megacrysts up to 2 cm in length. Age is unknown.

SYMBOLS

Contact located approximately
Location of shear zones
Sample locations
Mafic and felsic dikes

MILS

LUCY GILAY RANGE

VAL 10 METERS
6000

2-529
Beer Bottle Pass
PLEASE NOTE:

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Black and white photographic prints (17" x 23") are available for an additional charge.
Alluvial deposits that may localize 1.4 Ga granite that is coarse-grained granite that contains feldspar megacrysts and hornblende bearing, black to dark gray gneiss with undulating foliation. Age is unknown.

Tertiary andesite and basalt

Banded gneiss, light gray to dark gray, hornblende bearing, black to dark gray gneiss with undulating foliation. Age is unknown.

White to pink, garnet bearing, light gray to pink, gneiss with undulating foliation. Age is unknown.

Hornblende bearing, black to dark gray gneiss with undulating foliation. Age is unknown.
MAP UNITS

Qal  Alluvial deposits that may locally be as old as Tertiary.
Tv   Tertiary andesite and basalt.
YGr  1.4 Ga granite that is coarse-grained, porphyritic hornblende-biotite granite that contains feldspar megacrysts up to 5 cm in length.
XGb  Banded gneiss, light gray to dark gray, fine grained.
   Age is unknown.
XGg  White to pink, garnet bearing, coarse-grained granite.
   Northern study area only.
XGn  1.7 Ga light gray to pink, fine- to medium-grained quartzofeldspathic gneiss with undulating foliation defined by the alignment of biotite.
Gh   Hornblende bearing, black to dark gray, coarse grained granite with feldspar megacrysts up to 2 cm in length. Age is unknown.

SYMBOLS

Wall rock foliation
Mylonitic foliation and lineation
Migmatite foliation
Contact
Vertical lineation

DECLINATION DIAGRAM

Contact located approximately
Location of shear zones
Sample locations
Mafic and felsic dikes

CONTOUR INTERVAL 10 METERS
SCALE 1:6000
PLATE 2
SOUTHERN STUDY AREA

MAP UNITS

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<td>Hornblende bearing, black to dark gray, coarse-grained granite with feldspar megacrysts up to 2 cm in length. Age is unknown.</td>
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SYMBOLS

- Wall rock foliation
- Mylonitic foliation and lineation
- Magmatic foliation
- Contact
- Vertical lineation
- Contact located approximately
- Location of shear zones
- Sample locations
- Mafic and felsic dikes

DECLINATION DIAGRAM

CONTOUR INTERVAL 10 METERS
SCALE 1:6000