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Date
NEW STRATIGRAPHY, POLYPHASE DEFORMATIONAL HISTORY AND BASEMENT-INVOLVED THRUST BELT MODEL FOR THE PROTEROZOIC UNCOMPAHGRE GROUP AND VALLECITO CONGLOMERATE NEEDLE MOUNTAINS, COLORADO

BY

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B. A. EARTH AND ENVIRONMENTAL SCIENCES
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2002

THESIS
Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
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The University of New Mexico
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ABSTRACT

The nature and timing of deposition and deformation of Proterozoic siliciclastic metasedimentary cover sequences in the southwestern U.S is important for understanding Paleoproterozoic and Mesoproterozoic tectonism in the context of crustal accretionary episodes. These thick, ultramature siliciclasite successions are important orogenic markers that record regional sedimentation events that occurred between orogenic pulses. Their tectonic connections to these orogenic events remains an important issue. New geologic mapping and structural analysis of the siliciclastic Uncompahgre Group and the Vallecito Conglomerate in the Needle Mountains, southwestern Colorado, provide insight into the depositional and deformational history of one of the best exposed of these Paleoproterozoic cover successions. This study documents a gradational contact between the basal Vallecito Conglomerate and the overlying Uncompahgre Group and offers a transgressive depositional model for regional basin evolution. This new stratigraphic connection also helps elucidate deformatonal geometry. The succession is interpreted to be ~ 1.70 Ga based on new detrital zircon data. Structural analysis indicates that the two cover units underwent a similar polyphase deformation sequence involving D1 north-directed thrusting, D2 macroscopic folding and south-directed thrusting and D3 macroscopic folding associated high-temperature low-pressure metamorphism of ~ 500° C and 2-3 kbars. D1 thrusting is interpreted to be related to the Mazatzal orogeny and resulted distributed shearing along the basement-cover contact and duplexing of basement and cover. D2 deformation, the main folding event in the quartzites, is interpreted to be synchronous with andalusite growth throughout the area but is undated and could be related to either ~1.65 or ~1.43 Ga events. This event is associated with ~
50% shortening of the cover sequence via south-vergent folding and south-directed shearing. D3 deformation is interpreted to be temporally related to 1.43 Ga plutonism and resulted in doming and broad refolding of earlier structures. This structural synthesis reconciles previous models by reinforcing some aspects of each: early north-directed thrusting and multiple shear directions, south-directed shear zones and related macroscopic folds as the main structural elements of the Uncompahgre synclinorium, partial basement-cover detachment, and basement-cored thrust duplexes. Our interpretations do not strongly support the previous cuspate-lobate basement-cover infolding model.
# TABLE OF CONTENTS

List of Figures .............................................................................................................. xi
Introduction ..................................................................................................................... 1

**Geologic Setting and Description of Rock Units** ......................................................... 7
  - Basement Units ........................................................................................................... 8
  - Basement-Cover Contact ........................................................................................... 9
  - Siliclastic Cover Sequence ....................................................................................... 10
  - 1.4 Ga Plutonic Rocks .............................................................................................. 15

**Stratigraphic Relations of the Vallecito Conglomerate and Uncompahgre Group** ... 17
  - Results 1: New Stratigraphy ..................................................................................... 17
  - Basin Interpretation and Evolution ......................................................................... 18
  - Evaluation of possible tectonic settings ................................................................... 22

**Structural Geology** .................................................................................................... 26
  - Previous Work and Remaining Problems ................................................................ 26
  - Deformation of the Basement .................................................................................. 29
  - Metamorphism: Previous Studies ............................................................................ 29
  - Results 2: Structural Geology ................................................................................... 30
    - First Generation Structures .................................................................................. 33
    - Second Generation structures .............................................................................. 39
  - Results 3: Andalusite porphyroblast-fabric relations ............................................... 42
  - Results 4: Ductile Shear zones ............................................................................... 51

**Discussion and Interpretations** .................................................................................. 62
  - D1 Deformation ....................................................................................................... 62
  - D2 Deformation ....................................................................................................... 67
  - D3 Deformation ....................................................................................................... 72

**Summary and Conclusions** ....................................................................................... 75

**Suggestions for Additional Work** ............................................................................... 76

**Appendix 1: Description of fold and fabric elements by sub-area** ............................... 78
  - Table Mountain sub-area ....................................................................................... 78
  - Vallecito Creek sub-area ......................................................................................... 78
  - Pine River sub-area ................................................................................................. 79
  - Emerald Lake sub-area ........................................................................................... 80
  - Moon Lake sub-area ............................................................................................... 82
  - Western Needle Mountains ..................................................................................... 83

**Appendix 2: Data CD** .................................................................................................. 85

References ...................................................................................................................... 86
LIST OF FIGURES

Figure 1 Regional tectonic map ............................................................. 3
Figure 2 Simplified geologic map of the Needle Mountains .................... 6
Figure 3 Stratigraphic column of siliclastic units in the Needle Mountains ..... 11
Figure 4 Photographs of siliclastic metasedimentary rock ........................ 13
Figure 5 Block diagrams depicting basin evolution .................................. 20
Figure 6 Map of southeastern needles showing major structural features ... 32
Figure 7 Photographs of F1 folds .......................................................... 35
Figure 8 Stereonets ........................................................................... 36
Figure 9 Photographs of S2 crenulations ................................................. 41
Figure 10 Photomicrographs of pre-tectonic andalusite ............................. 44
Figure 11 Photomicrographs of syntectonic andalusite .............................. 45
Figure 12 Photomicrographs of syntectonic andalusite .............................. 46
Figure 13 Photomicrograph of conjugate crenulation cleavages ............... 47
Figure 14 Photomicrograph of syntectonic andalusite .............................. 49
Figure 15 Photomicrographs from the Pine River syncline ....................... 50
Figure 16 Photomicrograph of foliated dike in Pine River ....................... 52
Figure 17 Shear sense indicators: Vallecito Creek shear zone .................... 54
Figure 18 Shear sense indicators: Moon Lake shear zone ....................... 57
Figure 19 Shear sense indicators from the southern basement-cover contact ... 59
Figure 20 Shear sense indicators: pelites in Animas Canyon ..................... 61
Figure 21 Block diagram depicting D1a ................................................. 64
Figure 22 Block diagram depicting D1b ................................................. 65
Figure 23 Block diagram depicting D2 ................................................. 68
Introduction

Siliciclastic metasedimentary rocks in the Needle Mountains of Colorado, and other Paleoproterozoic quartzite sequences of the southwestern U.S. are key for understanding the history of formation and stabilization of juvenile continental lithosphere in southwestern Laurentia. In southern Colorado, thick successions of mature quartz arenite sands were deposited within domains in the accretionary orogen during the latest stages of the 1.78-1.70 Ga Yavapai orogeny (Condie, 1982; Grambling et al., 1988; Karlstrom and Bowring, 1993), and were subsequently deformed during both the ~1.65 Ga Mazatzal orogeny (Karlstrom et al. 2004; Magnani et al., 2004) and 1.45-1.35 intracratonic deformational event (Anderson, 1983; Nyman et al. 1994; Karlstrom et al. 2004). Sedimentary and volcanic supracrustal rocks were deposited on exhumed Yavapai basement prior to deformation during the ~1.65 Ga Mazatzal orogeny (Karlstrom et al. 2004; Hill and Bickford, 2002) and thus offer an excellent opportunity to distinguish deformation associated with the Mazatzal orogeny from that related to the Yavapai orogeny. Available age constraints for these supracrustal sequences suggest that many quartzites are possibly time-correlative and may represent both a regional 1.70 Ga succession within Colorado, northern New Mexico and central Arizona, and a regional 1.65-1.60 Ga succession in New Mexico and southern Arizona (Luther et al, in prep). These successions serve as important marker units that separate Yavapai and Mazatzal accretionary events and offer insight into rapid exhumation-deposition-thrust-burial cycles characteristic of regional crustal evolution during this period (Jessup et al., in press).
The Uncompahgre Group and Vallecito Conglomerate, in the Needle Mountains of southwestern Colorado (Figure 1) are thick and well exposed sequences of dominantly siliciclastic metasedimentary rocks that are possibly contemporaneous with other quartzite successions in the region, including the Cebolla Creek and Blue Ridge quartzites in Colorado (Hill and Bickford, 2002; Jessup et al., *in press*), the Ortega quartzite in northern New Mexico (Bauer and Williams, 1994), and the Mazatzal quartzite in Arizona (Cox et al. 2002). The stratigraphy (Barker, 1969; Burns et al. 1989; Ethridge et al., 1984; Harris and Eriksson, 1990) and deformational history (Tewksbury, 1981; 1985; 1986; 1989; Harris et al. 1987; Gibson and Simpson, 1988; Harris, 1990; Gibson, 1990; and Gonzales, 1997) of metasedimentary units in the Needle Mountains have been the foci of numerous studies but the relation of the two units to one another and the correlation of their respective deformational histories are still poorly understood. Resolving the depositional and deformational history of quartzite successions in the southwest, including those in the Needle Mountains, is important for testing conflicting models for orogenic history centering on the significance of the Paleoproterozoic "quartzite phenomenon" (Karlstrom and Williams, 2006), the relative importance of ~1.65 vs. ~1.4 Ga deformation (e.g. Pedrick et al., 1998; Daniel, 2005), middle crustal rheology (Karlstrom and Williams, 2006), and the origin and location of orogenic segmentation in the Proterozoic crust of the Southwest (Karlstrom et al., 2005).

The Needle Mountains are located within the zone of foreland deformation associated with the Mazatzal orogeny and were also effected by the ~1.4 Ga thermal event. The relative roles of these two events in the tectonic evolution of the region are a subject of continued controversy. It was initially believed that 1.4 Ga plutons were
Figure 1: Map of the southwestern United States showing distribution of Precambrian provinces, Proterozoic rocks, and localities of ~1.7 Ga Paleoproterozoic quartzite successions including 1) Needle Mountains, 2) Mazatzal Quartzite, 3) Ortega Quartzite, 4) Cebolla Quartzite, 5) Blue Ridge Quartzite. The Needle Mountains (1) are located within the zone of foreland deformation associated with docking of the Mazatzal Province ~1.65 Ga shown as Yavapai-Mazatzal transition. Its’ southern margin is marked by the Jemez lineament.
"anorogenic" and that most regional deformation occurred prior to their emplacement during the Mazatzal orogeny (Anderson, 1983; Condie, 1982; Cox et al., 2002), but subsequent work suggests that the plutons have chemical and structural features characteristic of synorogenic emplacement (Nyman et al. 1994; Collier, 1989; Kirby et al., 1995; Karlstrom and Humphreys, 1998) and that the thermal event associated with the magmatism caused widespread regional metamorphism to 350-500+ C (Karlstrom et al., 2004; Shaw et al., 2005). Various "reconciliation papers" have postulated that both 1.7-1.6 and 1.45-1.35 Ga deformation are variably expressed in the fabrics of Paleoproterozoic rocks of the Southwest (Pedrick et al. 1998, Read et al., 1999, Williams et al., 1999). In New Mexico, the present state of the debate suggests that the dominant fabric development and the triple point metamorphism was at 1.45 to 1.35 (Williams et al., 1999, Shaw et al., 2005; Daniel, 2006), in some regions, but that the 1.4 Ga ductile event may have been superimposed on both ductile and brittle thrust belt-related deformation (Williams et al., 1999). Deciphering the roles of Mazatzal vs. 1.4 Ga deformations in each area is important for improving regional tectonic models for the Proterozoic, which ultimately provide insight into long term crustal evolution. Southern Colorado is an important area because metamorphic temperatures reached at ~1.4 Ga here were lower than in northern New Mexico (Shaw et al., 2005), hence the chance to distinguish Mazatzal thrust-related deformation from 1.4 Ga structures and fabrics.

The first goal of this study is to document the nature of the stratigraphic association of the Vallecito Conglomerate and Uncompahgre Group in order to improve our understanding of evolution of the Needle Mountains depocenter and ultimately gain insight into the regional “quartzite phenomenon.” A second goal of this project is to
correlate and constrain the timing of the various deformations that affected the two units. Relative to the western and central Needle Mountains, very little has been published regarding cover-sequence deformation in the eastern Needle Mountains. Interestingly, north-south fold trends in the Vallecito conglomerate are nearly orthogonal to trends of macroscopic folds within the Uncompahgre Group. The resulting overall map pattern for the traces of foliation and fold axial planes (Figure 2) shows a broad "horseshoe" centered around the Eolus granite. Determining the history of development of this structural pattern, and its relation to regional deformation events is a main aspect of this study.
Figure 2: Proterozoic rocks in the Needle Mountains. Geology of the Basement units in the western Needle Mountains is from Gibson and Simpson (1988) and Gonzales (1997). Geology of the Uncompahgre Group in the western and central Needles is from Harris et al. (1987) and Tewksbury (1981). The remainder is modified from new mapping and Barker (1969), including basement-fabric trends.

Uncompahgre Group
Quartzite and metapelites

Vallecito Conglomerate
Quartz-pebble-conglomerate

Vallecito Conglomerate
Foliated conglomerate

Bakers Bridge Granite ~1.896 Ma

Tennille and Whitehead Granites
~1.715 & 1.700 Ma

Twilight Gneiss ~1.77-1.75 Ga

Irving Formation ~1.8-1.78 Ga

~1.4 Ga plutonic suite

Trimble Granite ~1.350 Ma

Quartz Diorite of Pine River

Eolus Granite ~1.435 Ma

Electra Lake Gabbro ~1.435 Ma

Contacts
Faults
Geologic setting and description of rock units

The Needle Mountains were uplifted in the Laramide orogeny and contain one of the most extensive exposures of Proterozoic rocks in southwestern Colorado (Cather, 2004). Proterozoic rocks in the Needle Mountains form a domal core to shallowly dipping Paleozoic sedimentary units to the east, south, and west, and are bounded by Oligocene rocks of the San Juan volcanic field to the north and northeast. Contacts between Proterozoic units and younger strata are generally major unconformities or Phanerozoic faults. Prior to Laramide reactivation, the Needles were a southeast continuation of the Pennsylvanian Uncompahgre Ancestral Rocky Mountain uplift (Cather, 2004).

Following convention of previous workers, Proterozoic rocks will be discussed in terms of “basement” units, the siliciclastic Uncompahgre Group and Vallecito Conglomerate “cover” successions and the 1.4 Ga plutonic suite. High grade gneisses of the Needle Mountains basement complex are some of the oldest rocks in Colorado and are exposed throughout the western and southeastern Needle Mountains (Figure 2). Siliciclastic metasedimentary cover in the Needle Mountains forms a 30 km long arcuate synclinorium that trends east-west in the western Needle Mountains and southeast to south in the southeastern Needle Mountains and includes quartzites of the Uncompahgre Group and conglomerates of the Vallecito Conglomerate. The Uncompahgre Group is commonly bounded by underlying basement along its southern and northern contacts, except where intruded by the Eolus Granite or unexposed. The basement-cover contact is generally a shear zone but is locally depositional. Bimodal magmatism in the Needle Mountains resulted in the emplacement of numerous ~1.43 Ga plutons including the
Eolus Granite (300 km$^2$) and Electra Lake Gabbro, as well as later granitic 1.35 Ga plutons. Following sections briefly summarize the age and tectonic setting of each major Proterozoic rock unit.

**Basement units**

Basement to the Uncompahgre Group consists of a felsic to mafic metavolcanic succession of gneiss and schist known as the Irving Formation, a suite of tonalitic to granodioritic intrusive orthogneisses of the Twilight Gneiss, and several masses of relatively less deformed granite of the Tenmile, Whitehead, and Bakers Bridge granites. The Irving Formation is the oldest lithologic unit in the Needle Mountains and consists of subaqueous mafic flows (with relict pillow basalt structures), mafic to felsic volcaniclastic rocks (with fragmental textures preserved), shallow level dikes and sills and thin horizons of banded iron formation (Barker, 1969, Gonzales, 1988, Gibson and Simpson, 1988). U-Pb zircon ages for the Irving Formation range from approximately 1.8 to 1.78 Ga (Gonzales, 1997). The Twilight Gneiss is considered an intrusive arc-related plutonic suite that intruded the slightly older but tectonically related volcanic rocks of the Irving Formation. These metaplutonic rocks yield crystallization ages of approximately 1770-1755 Ma (Gibson and Simpson, 1988; Gonzales, 1997). Both the Irving Formation and Twilight Gneiss underwent an early polyphase deformation sequence at amphibolite facies metamorphic conditions that resulted in macroscopic in-folding and transposition of the two units ($D_{B1}$ and $D_{B2}$ of Gibson and Simpson, 1988). The foliated Tenmile and Whitehead (1700 Ma) granites intrude the Irving Formation and have been widely interpreted as postdating deformation of the basement (i.e. Gibson and Simpson, 1988).
However, Gonzales (1997) reports ages of approximately 1735 to 1715 for the Tenmile granite and argues that it was deformed at approximately 1700 Ma, prior to deposition of metasedimentary cover sequence. This argument is based on new geochronology for the undeformed Baker’s Bridge granite which yields ages of $1698 \pm 4$ and $1695 \pm 2$ (Gonzales, 1997). Basement to the Vallecito Conglomerate and Uncompahgre Group in the southeastern Needle Mountains consists entirely of the Irving Formation.

The foliation pattern in the Irving-Twighlight basement forms a large north to northeast sigmoidal bend (Figure 2) of subvertical foliation and steeply plunging lineation that is truncated at the basement-cover contact. This foliation trend is similar to north-northeast and east trending foliation to the east in adjacent areas of the Yavapai province (Jessup et al, 2005). The present study did not concentrate on basement rock units, or basement deformations.

**Basement-Cover contact**

In many areas, the contact between the basal quartzite layer of the Uncompahgre Group or the Vallecito Conglomerate with the underlying basement is a shear zone, as discussed below (see also Barker, 1969; Tewksbury, 1981; Harris et al., 1987, etc.). In most areas, foliation in the basement is generally at a high angle to bedding in the cover units and becomes progressively transposed into the shear zone at the base of the Uncompahgre Group. The amount of displacement across the basement-cover shear zone, however, is unclear and the contact in many places has features that suggest it was initially a depositional nonconformable contact. For example, outcrops in the canyon of the Animas River and 3 km west of Snowdon peak have non-sheared Al-rich horizons at
the contact between the basement and overlying quartzite interpreted to be metamorphosed regoliths (Harris, 1990).

**Siliciclastic Cover Sequence**

In the Needle Mountains, the Uncompahgre Group is at least 3 km thick and consists of four 250-600m thick quartzite units and five, 200-300 m thick, inter-bedded metapelite units as shown in Figure 3, a composite stratigraphic column for the Needle Mountains (Harris and Eriksson, 1990). Primary sedimentary structures in the quartzite units include trough-cross stratification, parallel and cross lamination and thin lenses of quartz-pebble conglomerate. Pelitic units generally coarsen upward into quartzite units with the exception of the basal quartzite horizon which shows an overall fining upward trend. A conglomeratic horizon is present at the base of the Uncompahgre Group and contains abundant clast types that are not found matched to the local basement. The Uncompahgre Group is interpreted to have been deposited shallow marine and fluvial environments (Harris and Eriksson, 1990). Overall, long term facies variations are attributed to base level oscillations associated with pulsatory tectonic activity marginal to the basin (Harris and Eriksson, 1990). The Uncompahgre Group is also exposed 20 km to the north in the Ouray Gorge, near Ouray Colorado, and possibly correlates with quartzites 25 km to the west in Rico Colorado (Harris and Eriksson, 1990; Tweto, 1987), and small quartzite outcrops in Cebolla Creek to the east (Jesup et al., 2005).

The Vallecito Conglomerate is also about 3 km thick and is exposed in a 100 km² area in the southeastern Needle Mountains, primarily along the drainages of Vallecito Creek and Pine River. Burns (1980) and Ethridge et al. (1984) recognized four intervals
Figure 3. Generalized stratigraphic column for the Needle Mountains cover sequence showing stratigraphic subdivisions of the Uncompahgre Group and Vallecito Conglomerate. Sections are correlated based on laterally extensive pelitic horizon P2, which is equivalent to P1/P2 of Harris et al. (1987). Note thickening of the Uncompahgre Group and presence of additional pelitic units in the in the eastern Needles. Q1, Q2 and P1, P2 etc. denote to quartzite and pelite horizons in the Uncompahgre Group. Vc is the quartz-pebble-conglomerate facies of the Vallecito Conglomerate. Stratigraphic sections are adopted from Harris and Eriksson (1990) for the western Needle Mountains and Tewksbury (1981) for the central Needle Mountains. Columns for the Eastern Needle Mountains are from this study.
within the Vallecito Conglomerate that show an overall fining-upward trend. However, the units show lateral as well as vertical variations making the Vallecito conglomerate generally devoid of laterally extensive mappable units.

The basal foliated conglomerate facies within the Vallecito (the Fall Creek Conglomerate of Gonzales, 1988) is 0-500 m thick (Figure 3) and consists primarily of matrix to clast supported cobble to boulder conglomerates with thin, discontinuous siltstone horizons (Figure 4). Clasts are typically 2-10 cm in diameter but locally exceed over a meter. Clast types include schist, phyllite, amphibolite, vein quartz, chert, quartzite, banded iron formation and undeformed granite; rock types largely correlative to the Needle Mountains basement complex. The facies has a well developed foliation and tectonic lineation defined by stretched clasts and mineral lineations. Bedding shows both normal and reverse grading and rare cross stratification. Thickness of the foliated conglomerate facies varies from approximately 100 m in Vallecito Creek to over 300 m on Middle Mountain. The boulder conglomerate facies directly overlies the Irving Formation to the west of Emerald Lake and is characterized by clasts ranging from 18 cm to 1 m in diameter. This unit was mapped separately from the foliated conglomerate facies of Middle Mountain and Vallecito Creek by Burns et al. (1980) because it contains a large percentage of more resistant, quartz rich clasts. However, both the foliated conglomerate of Middle Mountain and the boulder conglomerate facies at Emerald Lake directly overly the Irving formation and contain locally derived basement clasts. Both units are also pervasively foliated and contain stretched clasts. This study refers to both units collectively as the foliated conglomerate facies of the Vallecito Conglomerate. Thickness of the basal foliated conglomerate facies therefore varies
**Figure 4.** Siliclastic metasedimentary rocks of the Needle Mountains. **A.** Stretched clasts in foliated conglomerate facies of the Vallecito conglomerate defining L1 near Table Mountain. **B.** Braided stream channel deposits typical of the quartz-pebble-conglomerate facies of the Vallecito Conglomerate, Vallecito Creek. **C.** Quartzite from uppermost Vallecito-lowermost Uncompahgre Group, east of Pine River.
considerably, from approximately 500 m at Middle Mountain to less than 100 m at Emerald Lake and along Vallecito Creek (Plate 2). The foliated conglomerate facies is absent on the east side of Emerald Lake and possibly pinches out. Overall, the abundance of locally derived clasts in the foliated conglomerate facies decreases from west to east between exposures in Vallecito Creek, the Table Mountain area and near Emerald Lake. This potentially represents varying degrees of mixing of locally and distally derived sediments throughout the unit.

The quartz pebble-conglomerate facies is the thickest and most widespread unit within the Vallecito Conglomerate. Along Vallecito Creek, the quart-pebble conglomerate facies is approximately 800 m thick and consists primarily of cross-trough stratified quartz-pebble conglomerate with thin, pebbly to coarse grain quartzite horizons (Figure 4b). The stratigraphic thickness of the quartz-pebble conglomerate facies increases to the south, from approximately 1 km near Emerald Lake to more than 3 km along southern Pine River (see Plate 2, section E-E’). Clast types include vein quartz, quartzite, chert and banded iron formation. Pebbles are generally less deformed than those in the basal foliated conglomerate facies and primary sedimentary structures are spectacularly preserved.

The quartzite facies is the uppermost unit of the Vallecito Conglomerate defined by Burns et al. (1980) and Ethridge et al. (1984). It is exposed east of Pine River and was described as consisting primarily of cross-stratified quartzite beds with thin pebble horizons and discontinuous pelitic layers (Figure 4). This study shows that the quartzite exceeds ~300 m in thickness and is interbedded with ~100 m of laterally extensive metapelite. This facies of the Vallecito is interpreted here to be the same as the basal
quartzite and pelite units of the Uncompahgre Group (see Plate 2, E-E’). These relationships are discussed in detail in the following section.

The contact between the Vallecito Conglomerate and the basement is preserved in exposures on Middle Mountain where the Vallecito Conglomerate is deposited on, and faces away from the Irving Formation (Burns et al., 1980; Gonzales, 1988; Ethridge et al. 1984; Tewksbury, 1989). The Vallecito Conglomerate was initially interpreted as the oldest unit in the Needle Mountains based on relationships along Vallecito Creek where the Irving formation is structurally above the Vallecito (Barker, 1969). Subsequent work has shown that this contact is faulted (Ethridge et al., 1984) and sheared (Gonzales, 1988; this study).

1.4 Ga Plutonic rocks

Batholiths of the Eolus Granite are the most widespread of the Proterozoic units in the Needle Mountains. The Eolus granite ranges from porphyritic to apilitic granite to monzodiorite. It intrudes parts of the Uncompahgre Group, the Vallecito Conglomerate, and the Irving Formation along sharp, generally steeply dipping contacts and clearly truncates structures in the country rocks (Figure 2). U/Pb ages for the Eolus Granite (1442 ± 3, 1435 ± 3, 1438 ± 9 Ma) indicate emplacement during the regional 1.45-1.35 Ga tectonostructural event (Gonzales, 1997). The Electra Lake Gabbro intrudes basement rocks in the southwestern Needle Mountains and has been dated at 1435±1 Ma (Gonzales, 1997). Melt-related deformation features within the aureole of the Electra Lake gabbro have been interpreted to record regional N-S shortening during its emplacement (Gonzales et al., 1996). The quartz diorite of Pine River was first described
by Barker (1969) and forms a 2 km² stock within the eastern batholith of the Eolus Granite. Although no radiometric ages are available for the diorite, it is interpreted as an earlier phase of the Eolus pluton (Barker, 1969). The Trimble granite is a small stock within the center of the western Eolus pluton and yields a Rb-Sr age of ~1350 Ma (Bickford et al. 1968).
Stratigraphic Relations of the Vallecito Conglomerate and Uncompahgre Group

Results 1: New Stratigraphy

The Vallecito Conglomerate and the Uncompahgre Group are both exposed in the southeastern Needle Mountains (Figure 2). The two units are mapped in close proximity to one another on the ridge east of Emerald Lake but were not previously recognized to be in anywhere in contact (Barker, 1969). Most workers consider the Uncompahgre Group to be slightly younger than the Vallecito, or possibly contemporaneous, (Burns, 1981; Ethridge et al. 1984; Tewksbury, 1989) but this relationship has remained ambiguous.

New mapping in the easternmost exposure of the Vallecito Conglomerate, east of Pine River, suggests that the quartzite facies of the Vallecito conglomerate is thicker and more widespread than previously interpreted and shows that the Vallecito Conglomerate is in gradational contact with the overlying Uncompahgre Group. Here, the Vallecito Conglomerate shows a general fining upward trend through approximately 400 m of section. On the ridge east of Granite Peaks Ranch, the Vallecito Conglomerate consists primarily of quartz-pebble conglomerate with thin (~10 cm) quartzite horizons. Average clast size is 1-3 cm and the unit is generally characteristic of the quartz-pebble conglomerate facies described by previous workers (Burns et al. 1980; Ethridge et al. 1984). Approximately 100 m up section, horizons quartz-pebble conglomerate averaging 50 cm-1 m thick are interbedded with horizons of purple to grey, trough cross stratified quartzite that average 20-30 cm thick. Clast size in the conglomerates is 5 mm-3 cm. Higher up section, gray to maroon quartzite is predominant (Figure 4c) with thin (<15 cm) conglomerate horizons. Clasts larger than 1 cm were not observed. In the vicinity of
The Notch, white, clean quartzite is interbedded with thick (30 m) horizons of aluminous mica-schist which can be traced along strike for over a kilometer to the north. The highest stratigraphic level of the Vallecito Conglomerate is within the hinge of a previously unmapped syncline located on a steep mountainside approximately 1 km southeast of the Pine River-Lake Creek junction. Here, the massive, homogenous quartzite facies grades abruptly into a >50 m thick pelitic unit with 2 -20 cm thick, continuous to lenticular horizons of fine grain quartzite. The quartzites and pelites are compositionally and texturally identical to those of the Uncompahgre Group and the quartzite-pelite pair is similar in thickness to the laterally continuous Q1, P1 pair of the Uncompahgre Group as shown in Figure 3.

Structural arguments also support the interpretation that the upper quartzites previously mapped as part of the Vallecito Conglomerate are instead, likely the basal unit of the Uncompahgre Group. As shown on the map (Plate 1), quartzites in the Vallecito Conglomerate are in close proximity (7 km) to and nearly along strike with those of the Uncompahgre Group but are separated by an intervening intrusion of Eolus granite. Cross sections C-C’ and D-D’ require that Uncompahgre quartzite overlies the Vallecito Conglomerate. Both units also contain similar fabrics and porphyroblast-matrix relationships, as discussed below.

**Basin Interpretation and Evolution**

Interpreting the depositional characteristics of the Proterozoic quartzites in the southwest is challenging due to incomplete preservation of strata in isolated synclinal "keels" surrounded by basement that are commonly intruded by younger granites, as in
the Needles. This makes correlation between outcrops uncertain and hence, the size, shape and nature of the original sedimentary basin are largely speculative. Adding further complexity, deformations involved more than one episode of thrusting capable of imbricating and repeating portions of the section making observed thicknesses in cross section dependent on correct identification of thrust geometries. Despite these uncertainties, the combined stratigraphic and structural relationships are interpreted as follows.

The Vallecito Conglomerate was previously interpreted to have originated as an alluvial fan complex consisting of proximal to distal gravelly river deposits (Burns et al., 1980; Ethridge et al. 1984). However, the term alluvial fan implies sedimentation caused by unconfinement of the feeder channel and a convex, fan-shaped geometry (Blair and McPherson; 1994). Instead, I interpret the Vallecito as gravelly river deposits, rather than an alluvial-fan system based on the dominance of braided stream channel deposits and presumably distal sediment provenance. Models presented by previous workers involve a sediment source area immediately north of the current exposure of the Vallecito and deposition in normal-fault bounded basins (Ethridge et al. 1984). However, much of the unit lacks metavolcanic clasts characteristic of the surrounding basement rocks and basin bounding faults have not been recognized. I propose that sediments of the Vallecito Conglomerate were derived from a more distal source area and deposited as gravelly river deposits which initially underwent mixing with locally derived alluvial fan deposits, as depicted in Figure 5a. Pending detrital zircon geochronology for the Vallecito will ultimately provide insight into the source region of the sediments, but the dominantly
Figure 5. Schematic block diagrams illustrating paleogeographic evolution of the Needle Mountains depocenter. **A.** Cartoon showing deposition of the Vallecito Conglomerate sediments as distally derived braided stream deposits mixing with locally derived alluvial fan deposits. Local material is derived from basement highlands, possibly fault controlled. **B.** Cartoon depicting deposition of laterally extensive Uncompahgre Group sediments in shallow marine environment after Vallecito Conglomerate fills in local paleotopography.
siliciclastic nature of the pebble conglomerate facies suggests distally derived, far
traveled sediments.

The up-sequence gradational contact between the Vallecito Conglomerate and the
Uncompahgre Group preserved east of Pine River also offers insight into the depositional
history of the Needle Mountains cover sequence. The Uncompahgre Group is exposed
over a wide region extending from the Needle Mountains to exposures in the Ouray gorge
approximately 15 km to the north. Individual quartzite-pelite shoaling sequences in the
Needles are correlated to those in the Ouray region (Harris and Eriksson, 1990)
suggesting that Uncompahgre deposition occurred synchronously over a large region. In
contrast, the Vallecito Conglomerate is only exposed in the southeastern Needle
Mountains and shows lateral thinning and facies variations. Paleocurrent indicators
within the Vallecito and alluvial facies of the Uncompahgre indicate south-directed
sediment transport (Burns et al. 1980; Ethridge et al., 1984; Harris and Eriksson, 1990).
The location of the Vallecito Conglomerate south of the Uncompahgre is therefore
inconsistent with the conglomerates being a more proximal facies of the Uncompahgre
Group quartzites. Instead, the Vallecito is most likely a localized, older, basal facies of
the Uncompahgre Group. This relationship is represented in the up-sequence gradational
contact between the two units preserved east of Pine River.

The fining-upward transition from the dominantly coarse, braided stream deposits
of the Vallecito into the shallow marine quartzites of the Uncompahgre Group is believed
to record a marine incursion associated with sedimentation over an increasingly
expansive region, as depicted schematically in Figure 5b. The basal, locally derived
facies of the Vallecito Conglomerate braided river system was likely derived from
basement highlands to the north of its current exposure, as suggested by Ethridge et al. (1984). As the river system aggraded, sedimentation became dominated by texturally and compositionally mature quartz-pebble conglomerates, which were likely derived from increasingly distal source regions and transported to the depocenter in gravelly rivers. This distally derived material was likely mixed with locally derived material to varying degrees, as is possibly represented in the east to west increase in the abundance of basement derived clasts within the basal foliated conglomerate facies of the Vallecito Conglomerate. Continued deposition of quartz pebble conglomerates eventually filled in local paleo-topographic relief in the region, which may have exceeded the >3 km thickness of the Vallecito Conglomerate. The upper four quartzite-pelite sequences of the Uncompahgre have fairly consistent thicknesses across the Needle Mountains but the basal quartzite unit is over 200 m thicker in the eastern Needle Mountains and contains additional pelitic units not seen in the western part of the range (Figure 3). Thickness variations of the basal quartzite unit suggest that its deposition filled in whatever topographic relief remained in the depocenter prior to deposition of the upper, laterally extensive quartzite units.

**Evaluation of possible tectonic settings**

Available age constraints for the Uncompahgre Group and other ultra-mature Paleoproterozoic quartzite successions suggests that these sequences were deposited relatively synchronously at ~1.7 Ga in basins situated along the juvenile Laurentian accretionary margin. The tectonic setting of these basins, although still enigmatic, is key to understanding the nature of this regional sedimentation event in the context of crustal
assembly and orogenic pulses. This section summarizes and evaluates proposed tectonic settings for Paleoproterozoic quartzite deposition in the southwestern U.S. in the context of the new stratigraphic framework for siliclastic sequences in the Needle Mountains.

A passive margin setting was proposed for deposition of the Ortega quartzite in northern New Mexico (Soegarrd and Eriksson, 1985). However, new geochronology suggests that some quartzite sequences in the southwest were deposited during periods of silicic volcanism, including the Ortega quartzite (Kopera et al., 2002) and the Mazatzal quartzite (Cox et al., 2002). This, coupled with improved understanding of the timing of accretionary episodes in the region suggests that quartzites were deposited in syn-tectonic basins along an active accretionary margin, rather than on a passive continental margin.

Some alternative tectonic settings for quartzite deposition include extensional intra-arc or back-arc basins, inter-montane basins and foreland basins. Cox et al. (2002) proposed an intra-arc depositional setting for the Mazatzal quartzite which is generally consistent with its location near the Yavapai-Mazatzal provincial boundary and the association of quartzites with metarhyolites. Absence of coeval volcanics in the Needle Mountains does not necessarily rule out an intra-arc setting, as the ~1.69 Baker’s Bridge Granite may represent an intrusive equivalent of the Vadito rhyolite below the Ortega quartzite. Deposition of the Needle Mountains cover sequence may also have occurred in extensional basins that formed during crustal uplift and stabilization following the 1.78-1.70 Ga Yavapai orogeny. This is consistent with new detrital zircon data that suggests Uncompahgre Group deposition shortly after ~1700 Ma (Jones, personal comm.). This setting is also consistent with facies variations in both the Vallecito Conglomerate and Uncompahgre Group which have been attributed to tectonic activity in the region (Burns
et al. 1980; Ethridge et al. 1984; Harris and Eriksson, 1990) and with paleo-topographic relief in the depocenter.

Deposition of the Needle Mountains cover sequence in inter-montane or foreland basins related to outboard-plate-margin tectonism is also plausible. The Jemez lineament, which is postulated to represent the suture between the Yavapai and Mazatzal provinces is located in northern New Mexico, approximately 125 km southwest of the Needle Mountains and was likely the location of a major orogen circa 1.65 Ga (Figure 1) (Magnani et al., 2004; Karlstrom et al., 2004). While quartzite basins could potentially have formed during this orogenic event as either collision related inter-montane or foreland basins, available age constraints suggest that quartzite deposition initiated approximately 50 Ma prior to the onset of the 1.65 Ga Mazatzal orogeny. A foreland basin setting for the Needle Mountains cover sequence is also inconsistent with the presence of coarse alluvial and fluvial conglomerates of the Vallecito Conglomerate which were derived from the north, as these sequences are commonly found near the proximal margins of nonmarine foreland basins and are typically derived from the orogen rather than the craton (Miall, 1995). However, shoaling sequences in the Uncompahgre Group are overall similar to those exhibited in inland parts of foreland basins where flexural basin accommodation is less than sediment supply rates and deposits show marine to fluvial progradation (Liu et al. 2005). It is also potentially possible that quartzites were deposited in collision-related inter-montane, Laramide style basins (Cather, 2004) that developed in response to early outboard tectonism as a predecessor to the main pulses of the Mazatzal orogeny. More work on these quartzite successions, and
their relation to regional tectonic events is necessary to further evaluate the tectonic setting and significance of regional Paleoproterozoic quartzite deposition.
Structural Geology

Previous Work and remaining problems

Structural studies of the Uncompahgre Group (Table 1) in the western Needle Mountains (Harris et al. 1987; Harris, 1990; Gibson, 1990) and the central Needle Mountains (Tewksbury, 1981) indicate that the region underwent polyphase deformation involving bedding parallel shear (D1), macroscopic folding (D2) and an additional deformation event of variable intensity and style (D3). D2 in both the central and western Needle Mountains involved macro and mesoscopic folding of bedding (S0) and bedding parallel cleavage (S1) and refolding of F1 folds with spatially restricted development of S2 axial planar cleavage (Tewksbury, 1985; Harris et al. 1987).

The main disagreement among the previous studies involves the timing and shear sense along basement-cover shear zones. Tewksbury’s (1985) deformation model for the central Needle Mountains involved south-directed, layer-parallel shearing along the basement-cover contact and within pelitic units followed by a macroscopic folding event. Macroscopic folds have northward dipping axial surfaces and are truncated by top-to-the south thrusts (Plate 2). Tewksbury (1985) shows that S2 fabrics in the central Needle Mountains dip moderately to the north or south and proposed that they developed synchronously as conjugate crenulation cleavages during the late stages of D2.

Tewksbury (1981) considered south-directed shearing of the Uncompahgre Group over the basement to be the direction of tectonic transport during D1. The deformation model presented by Harris et al. (1987) has a similar deformational sequence, with layer parallel shearing preceding macroscopic folding, but differs in that D1 shear sense is top-to-the north. D1 shear zones with top-to-the north shear sense are folded by F2 macroscopic
Table 1. Summary of previous structural studies in the Needle Mountains for the Uncompahgre Group showing fold and fabric designations used by previous workers. Results of this study are also included.

<table>
<thead>
<tr>
<th>Structural studies</th>
<th>D1 deformation</th>
<th>D2 deformation</th>
<th>D3 Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tewksbury (1981; 1985; 1986)</td>
<td>South directed layer parallel shearing</td>
<td>F1 and S1</td>
<td>Macroscopic folding and south directed thrusting. Development of conjugate S2 crenulation cleavages.</td>
</tr>
<tr>
<td>Harris et al. (1987), Gibson and Simpson (1988), Gibson (1989), Harris (1990)</td>
<td>North directed layer parallel shearing and local stratigraphic duplication</td>
<td>F1 and S1c</td>
<td>Macroscopic folding and south directed thrusting.</td>
</tr>
<tr>
<td>This study</td>
<td>North directed layer parallel shearing progressive into basement-involved, north directed thrusting</td>
<td>F1 and S1</td>
<td>Macroscopic folding and south directed thrusting synchronous with growth of andalusite</td>
</tr>
</tbody>
</table>
folds. D3 of Harris et al. (1987) involved reactivation of basement-cover contacts with south-directed shearing along the southern contact and north-directed shearing along the northern contact. Movement of the Uncompahgre Group up and out relative to the basement during D3 was attributed to tightening of D2 macroscopic folds during cuspate infolding of the basement. Conjugate strike-slip shear zones were also active at this time. D3 resulted in the development of minor folds and crenulations that trend northerly in the western Needle Mountains and northeasterly in the central Needle Mountains. The only macroscopic D3 structure reported by these previous workers is a north-plunging syncline in Lime Creek that refolds a F2 syncline.

In contrast to the Uncompahgre Group, the Vallecito Conglomerate has not been the focus of detailed structural analysis. Previous work has recognized south-trending macroscopic folds within the Vallecito Conglomerate but it is unclear how these structures correlate to macroscopic folds within the Uncompahgre Group (Burns, 1980; Ethridge et al. 1984; Tewksbury, 1989). Gonzales (1988) was the first to document shearing within the foliated conglomerate facies in Vallecito Creek. The foliated conglomerate facies forms a thin horizon (>50 m thick) between the Irving Formation to the west and the Vallecito Conglomerate to the east. Stratigraphic facing in the Vallecito Conglomerate is to the west such that the Irving Formation is structurally above the Vallecito Conglomerate (Plate 2, E-E’). Elongated clasts within the foliated conglomerates plunge moderately to steeply to the south. Gonzales documented asymmetric porphyroclasts indicating west-side-up shearing along this contact and noted rare sedimentary structures indicating eastward-younging of the foliated conglomerate facies towards the westward facing siliclastic Vallecito Conglomerate. This shear zone is
nearly orthogonal to shear zones along the basement-cover contact in the western Needle Mountains but oblique shear sense is somewhat consistent with north-directed thrusting during D1 documented by Harris et al. (1987).

**Deformation of the Basement**

The Irving Formation and Twilight gneiss, of the Needle Mountains basement complex underwent polyphase deformation and amphibolite facies metamorphism prior to deposition of the cover sequence (Gibson and Simpson, 1988). Deformation involved an early isoclinal folding event followed by a second event resulting in formation of easterly trending macroscopic folds (D B 1 and D B 2 of Gibson and Simpson, (1988)). D3 deformation in the basement resulted in infolding of the Tenmile granite and the Irving formation and is correlated to D2 macroscopic folding of the Uncompahgre Group. This suggests that the Uncompahgre Group was initially decoupled from the basement along the basement-cover shear zone during D1 layer parallel shearing but this shear zone was subsequently folded to its present geometry during D2 in the Uncompahgre Group (Gibson and Simpson, 1988).

**Metamorphism: Previous Studies**

Previous workers reported that metamorphism in the Needle Mountains involved at least three temporally distinct metamorphic events. Regional amphibolite facies metamorphism of the basement complex is attributed to effects of the Yavapai orogeny and is believed to have occurred mainly prior to emplacement of the ~1700 granites. Gonzales (1997) argued for an additional tectonometamorphic episode at approximately
1700 Ma, synchronous with emplacement of the Tenmile and Bakers Bridge granites but prior to deposition of the cover sequence. Lower to middle greenschist facies metamorphism accompanied D1 and D2 deformation of the Uncompahgre Group in much of the western Needle Mountains (Barker, 1969; Tewksbury, 1985; Harris et al. 1987, Harris, 1990) but the timing of this event is not known. Barker (1969) reported the progressive appearance of chloritoid, biotite, garnet, staurolite, plagioclase and sillimanite moving southeastward across the range but subsequent work suggested that high temperature assemblages record regional contact metamorphism associated with the Eolus Granite (Gonzales, 1997), in agreement with $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology data (Shaw et al., 2005).

Results 2: Structural Geology

Reconnaissance geologic mapping and detailed structural analysis of the Vallecito Conglomerate and Uncompahgre Group were conducted in the southeastern region of the Needle Mountains. The goal of this study was to document and correlate the deformation histories of these two units. Work on shear zones within the Uncompahgre Group in the canyon of the Animas River in the western Needle Mountains was also conducted in order to characterize the timing and nature of shearing relative to metamorphism (Plate 1). Polyphase deformation of the metasedimentary units resulted in development of multiple generations of mesoscopic folds and tectonic fabrics and resulted in activation and reactivation of shear zones along the basement-cover contact as documented below. The following sections discuss new data on the macroscopic structural features of the southeastern Needle Mountains in conjunction with outcrop and petrographic
observations. Fold terminology is from Ramsey (2000) and that for fabrics and shear zones is from Simpson and Schmid (1983). The following section describes relationships depicted on the map and in cross section (Plates 1 and 2).

In the southeastern Needle Mountains, the cover units are well exposed in an area covering approximately 120 km$^2$ that is flanked by batholiths of the Eolus Granite to the west and east. Figure 6 is a simplified map of the southeastern Needle Mountains showing the location of major structures. The Eolus Granite truncates bedding within the metasedimentary units along intrusive and fault bounded contacts. The Vallecito Conglomerate forms a broad south-trending anticline (the Middle Mountain anticline) with opposite limbs in Vallecito Creek and along Pine River (Plate 2, E-E’). The basal foliated conglomerate facies of the Vallecito is exposed in the central part of the study region on Middle Mountain within the core of this anticline. The Uncompahgre Group is characterized by macroscopic folds of bedding that define the regional Uncompahgre synclinorium. In the southeastern Needle Mountains, the entire section of Uncompahgre Group is within the southern limb of a syncline with hinge in the central Needle Mountains. Shear zones are present along the southern and western margins of the Uncompahgre Group, the western margin of the Vallecito Conglomerate in Vallecito Creek and between the Vallecito Conglomerate and the Irving Formation west of Emerald Lake. These shear zones are discussed in detail in subsequent sections.

Similarly, the Uncompahgre Group in the western Needle Mountains forms a broad synclinorium that is commonly bounded by basement along its northern and southern contacts (Plate 2). The southern limb of the synclinorium has a convex-up geometry, bending from subvertical in canyon of the Animas River (8900’) to gently
Figure 6. Generalized geologic map of the southeastern Needle Mountains showing locations of major structural features and places referred to in the text.
north dipping in the vicinity of Snowdon Peak (13,077’). The synclinal hinge and the southern and northern basement-cover contacts are cut by Pennsylvanian reverse faults that also displace the Proterozoic-Paleozoic unconformity. Shear zones, or ductile fault zones, are developed within pelitic units of the Uncompahgre Group and along the basement-cover contact. These zones are generally parallel to bedding but result in local stratigraphic repetition and have also accommodated thrusting of the cover units over the basement to both the north and south.

The following two sections describe the mesoscopic structures observed in the field as first- and second-generation features. These structures have been correlated between sub-areas on the basis of local overprinting relations which were verified in thin section when possible. This correlation step has inherent uncertainty, especially in thrust-fold systems where: 1) progressive deformation can result in several generations that are part of a single protracted event, for example in a shear zone, and 2) where deformation partitioning results in development of fabrics in some horizons (e.g. pelites) but not others (e.g. conglomerates). The following discussion tries to make clear distinctions between local overprinting and more speculative regional correlations. For additional information, the reader is referred to Appendix 1, a detailed description of mesoscopic structures by sub-area, and Plate 3, a sample location map.

**First Generation Structures**

D1 structures consist of F1 folds, S1 bedding parallel foliation, L1 lineations and basement-cover shear zones with top-to-the north shear sense. These D1 structures, as
described below, are interpreted to have formed in the deep (5-10 km) portions of a fold-thrust belt.

F1 folds in the Vallecito Conglomerate and Uncompahgre Group fold bedding (S0) and have S1 axial planar cleavage. S1 is generally parallel to bedding except in the hinge regions of F1 folds. Geometry and amplitude of F1 folds varies considerably throughout the Vallecito Conglomerate, as shown in Figure 7, but F1 folds generally have west to south-southwest, shallowly to moderately plunging fold axes and are overturned to the north. Axial surfaces and S1 are generally sub-parallel to bedding and plots of S1 and S0 show similar great circle distributions within particular sub-areas (Figure 8). Mesoscopic F1 folds are present within largely siliclastic units as small scale crenulations of S0 and as flexural slip folds associated with small scale brittle thrust ramps. F1 folds are particularly well developed within the upper Vallecito Conglomerate near Dollar Lake. Here, sandy horizons interbedded with conglomeratic material contain a strong south-southwest plunging stretching lineation defined by stretched clasts and 1-3 m open to tight folds overturned to the north (Figure 7a). S1 is locally deflected into S0 indicating north directed slip along bedding.

The relationship between F1 folds and the L1 stretching direction within the foliated conglomerate facies on Middle Mountain is key for understanding the variable geometries of F1 throughout the study area. These folds consist of mesoscopic folds with S1 axial planar cleavage and macroscopic folds of the basement-cover unconformity (Plate 2, C-C’, D-D’). Stereonets for this area show that both S0 and S1 have similar great circle distributions defining folds with moderately south-southwest plunging axes, parallel to L1 stretching lineations defined by stretched clasts and mesoscopic fold axes
Figure 7. F1 mesoscopic folds in the Vallecito Conglomerate and Uncompahgre Group, southeastern Needle Mountains. A. Broad fold overturned to the north with S1 axial planar cleavage near dollar lake. B. Locality near the hinge zone of macroscopic fold of basement-cover nonconformity near Table Mtn. where S1/L1 in the foliated conglomerate facies are at a high angle to folded bedding. C. Small fold in quartzite facies of Vallecito Conglomerate. D. Isoclinal fold of sandy horizon within Uncompahgre group pelitic unit P2 near Rock Lake. Fold axis is parallel to L1.
Figure 8. Lower hemisphere equal area projections of structural elements from the eastern Needle Mountains. Crosses: S0, filled triangles: S1 or Sm, inverted open triangles: L1, filled circles: F1 fold axes, open triangles: S2, open circles: S1-S2 intersection lineations.
Figure 8 continued. Lower hemisphere equal area projections of structural elements from the southeastern Needle Mountains. Crosses: S0, filled triangles: S1 or Sm, inverted open triangles: L1, filled circles: F1 fold axes, open triangles: S2, open circles: S1-S2 intersection lineations.
However, S1 and L1 are locally at a high angle to S0 in the hinge regions of macroscopic folds of the basement-cover contact (Figure 7b), suggesting that deformation associated with folding of bedding and formation of S1 may have been progressive into folding of S1. The parallelism of F1 fold axes and L1 stretching lineations suggests that folds were rotated into L1 during D1 deformation, as discussed below. Other well expressed F1 folds occur within pelitic units of the Uncompahgre Group and quartzite facies of the Vallecito Conglomerate and generally consist of small, tight to isoclinal folds of bedding (Figure 7c, d). F1 folds locally have interfolial geometries and are sometimes associated with bedding parallel detachments. F1 folds in the Uncompahgre Group have axes parallel to the steeply south-southwest plunging L1 stretching lineation (Figure 8c), similar to relationships on Middle Mountain.

Shear zones with stretching lineations parallel to L1 in the basal foliated conglomerate facies are considered D1 shear zones. This correlation is based on the similarity between the stretching direction in the foliated conglomerate facies and stretching lineations in shear zones. These shear zones include segments of the Vallecito Creek shear zone, the Dollar Lake shear zone and the basement-cover contact. Movement direction determined from stretching lineations along these shear zones and within both the Vallecito Conglomerate and Uncompahgre Group is consistently north-northeast to northeast throughout the study area as shown in stereonets from both units (Figure 8) and is interpreted as the direction of thrust transport. Clasts within the basal foliated conglomerate facies of the Vallecito are highly stretched, whereas the siliciclastic units of the quartz-pebble conglomerate facies are largely unstrained. This suggests that the basal, rheologically weak facies of the Vallecito was a wide zone of distributed strain that
served as a decollement surface during D1 thrusting. Parallelism of macroscopic F1 fold axes with L1 in the Middle Mountain area suggests rotation of these folds into the stretching direction during progressive shearing and fabric development which is commonly observed in high strain zones (Hobbs et al. 1976). The amount of total displacement of the Vallecito is unknown, but preservation of depositional contacts in the Middle Mountain area suggests that the unit is parautochthonous rather than allochthonous and total translation of the unit did not exceed a few kilometers. This is consistent with sheared, but originally nonconformable basal contacts of the Uncompahgre Group in the western Needle Mountains, as reported by Harris et al. (1987).

**Second Generation Structures**

Second generation structures are the dominant regional structures of the Uncompahgre Group and the Uncompahgre synclinorium. They consist of macroscopic upright F2 folds, a spaced S2 axial planar cleavage and associated F2 crenulations and mesoscopic folds. Upright to shallowly plunging macroscopic F2 folds within the Uncompahgre Group are the regional shortening structures and trend parallel to the map trace of pelitic units within the Uncompahgre Group (Figure 2). In the central Needle Mountains, these structures trend east to south-southeast and have upright to moderately north-dipping axial surfaces. Folds are cut by north-dipping thrust faults parallel to F2 axial surfaces (Plate 2, section A-A’) which are interpreted as D2 structures.

Macroscopic fold hinges within the Uncompahgre Group are only exposed in the western and central Needle Mountains. In the eastern study area, the entire section of...
Uncompahgre Group is within the southern limb of a macroscopic syncline mapped in the central Needle Mountains by Tewksbury (1981). Bedding and S1 within the Uncompahgre Group dip moderately to steeply to the northeast and are locally overturned to the southwest near the southern basement-cover contact. Plots of Pi poles to bedding define a moderately northwest plunging macroscopic fold axis (Figure 8b).

Mesoscopic D2 structures consist of gentle F2 crenulations of S1 with weak S2 axial planar cleavage and S1-S2 intersection lineations parallel to F2 crenulation axes (Figure 9). In outcrop, S2 generally strikes northwest and dips steeply to moderately northeast or southwest (Figure 8c). Axes of F2 crenulations plunge shallowly to the southeast. The overall northeast trend of S2 is consistent with its formation as the axial planar fabric to macroscopic D2 folds within the Uncompahgre Group. In thin section, andalusite porphyroblasts generally overgrow one spaced to strongly developed S2 crenulation cleavage, as is discussed in detail in the following section.

In addition to F1 folds near Table Mountain, macroscopic folds within the Vallecito consist of the south-southeast plunging Pine River syncline and the south-southwest plunging Middle Mountain anticline (Figure 8h). These folds are nearly orthogonal to macroscopic F2 folds within the Uncompahgre Group (Figure 8b). The Pine River syncline refolds S0 and S1 within the quartzite facies of the Vallecito Conglomerate and is locally a D2 structure based on overprinting relations. However, it is believed that this structure formed during D3 deformation because parasitic mesoscopic folds within the hinge region are texturally associated with high-temperature, low-pressure metamorphic assemblages suggesting that the structure may have formed during contact metamorphism associated with the 1.43 Ga Eolus Granite. These fabrics and their
Figure 9. S2 crenulations of S0/S1 typical of those in pelites of the Uncompahgre Group. S2 is the northwest striking axial planar cleavage of F2 macroscopic folds. A. S2 crenulations in pelite unit near Half Moon lake, eastern Needle Mountains. B. S2 crenulations in aluminous quartzite ~2 km NNW of Mt. Garfield, western Needle Mountains.
significance are discussed in detail in the following sections. In some pelitic units of the Vallecito east of Pine River, S1 is weakly crenulated and overgrown by andalusite and biotite porphyroblasts. This is the only locality within the Vallecito that shows evidence for D2 deformation prior to andalusite growth.

The macroscopic, easterly trending upright F2 folds that accommodated significant shortening of the Uncompahgre Group were not recognized within Vallecito Conglomerate. The macroscopic south plunging folds that do fold the Vallecito are believed to be D3 structures for reasons outlined in the subsequent section. The axis of the D3 macroscopic Middle Mountain anticlinorium plunges approximately 20° along much of its length but shows somewhat variable plunge, from subhorizontal to moderately south-southwest in the vicinity of Emerald Lake. If the plunge of this fold axis is used as a proxy for D2 folding, it suggests that broad easterly trending folds may be present within the northernmost Vallecito Conglomerate, although this is somewhat uncertain. Generally, S2 cleavages and easterly trending macroscopic folds similar to those in the Uncompahgre do not occur within the Vallecito Conglomerate.

Results 3: Andalusite porphyroblast-fabric relations

A major aid in deciphering fold generations in this study is the use of porphyroblast-matrix relationships. It was noted that andalusite porphyroblasts across the area overgrow two fabrics (S1 and S2) and are sometimes folded and/or rotated by a later fabric/deformation. Previous studies suggest that metamorphism of the Uncompahgre Group involved two metamorphic events: (1) Regional metamorphism at greenschist facies conditions, and (2) contact metamorphism associated with the 1.43 Ga Eolus
Granite. In spite of the fact that the absolute timing of andalusite growth, which is key for placing deformation events into a regional context, is somewhat ambiguous and could potentially be related to either regional 1.65 metamorphism or 1.44 Ga contact metamorphism (as discussed below), these fabric relationships are invaluable for placing fabrics into a relative chronology based on overprinting.

Pelitic schists typically contain greenschist facies assemblages of quartz + white mica ± andalusite ± biotite ± chlorite. In pelitic units in close proximity to the Eolus Granite, assemblages of quartz + white mica + sillimanite ± andalusite ± chloritoid are common. In most thin sections from the Uncompahgre Group, andalusite porphyroblasts generally appear post-tectonic and overgrow S1 and S2 (Figure 10). However, some thin sections suggest that S2 cleavage formation may have continued after porphyroblast growth and that andalusite is syn-tectonic with respect to D2. These include samples from the western Needle Mountains where S1-S2 crenulations occur within ~1 mm thick andalusite horizons but S2 extends into the matrix where it offsets andalusite horizons and rotates andalusite grains containing S1-S2 (Figure 11). Sections from the Uncompahgre Group in the eastern Needle Mountains contain multiple crenulation cleavages at different orientations, one within andalusite horizons and a second within the matrix fabric (Figure 12). S2 within andalusite is at a high angle to S1 and generally dips to the north. These fabrics are folded by a second, weakly developed moderately south dipping crenulation cleavage that is at a high angle to S2 fabrics within andalusite porphyroblasts. While this overprinting relation could represent two distinct deformation events, some samples from the western Needle Mountains contain both north and south dipping S2 cleavages that developed synchronously, suggesting that S2 cleavages
Figure 10. Andalusite prophyroblasts overgrowing weakly crenulated S1. A. Sample KEP-3 from the western Needle Mountains. Andalusite overgrows weakly crenulated S1 and is generally aligned in S2. B. Sample ZEP-3 from the western Needle mountains containing andalusite overgrowing an S1-S2 spaced crenulation cleavage. Porphyroblast fabric relationships in which andalusite overgrows both S1 and S2 are common in pelitic units of the Uncompahgre Group throughout the Needle Mountains.
Figure 11. Sample KNO2-10, showing syntectonic andalusite. A. plain light, B. polarized light, C. sketch. Andalusite in this sample overgrows a spaced S2 crenulation cleavage. S2 also extends into the matrix where it offsets andalusite horizons and rotates individual andalusite grains. Sample was collected from sheared aluminous horizon within pelitic unit P2 in the western Needle Mountains, approximately 1 km south of the northern basement cover contact in the canyon of the Animas River. Sinistral offset of andalusite grains is consistent with evidence for top-to-the south shear in other samples from this outcrop (KN02-11).
Figure 12. Sample ZML-6, eastern Needle Mountains. Andalusite horizons in this sample overgrow a spaced S2 crenulation cleavage, typical of porphyroblast-matrix relations in the Uncompahgre Group throughout the Needle Mountains. S1 and S2 within andalusite horizons are weakly folded around a second crenulation fabric that is only present in the matrix. Both S2 cleavages strike NW, parallel to F2 fold axes, but dip in opposite directions. This secondary crenulation is locally considered S3, but is most likely regionally S2 and possibly developed a conjugate crenulation cleavage set, as reported in the central Needle Mountains by Tewksbury (1985). Sample was collected from thin pelitic horizon near Half Moon Lake. Note: Thin section is cut perpendicular to microfold axes and dips moderately west such that S2 crenulations appear to dip less steeply than actual orientations.
**Figure 13.** Sample ZEP-2 from the western Needle Mountains. This thin section contains two sets of S2 crenulation surfaces at different orientations. Both S2 cleavages weakly crenulate S1 and show variable relative overprinting relations, suggesting that they formed synchronously, possibly as a conjugate crenulation cleavage set, as described in the central Needle Mountains by Tewksbury (1986).
developed as conjugate crenulation cleavages (Figure 13). Tewksbury (1981; 1986) reports similar overprinting relations in the southern part of the Uncompahgre Group in the central Needle Mountains but shows that south dipping S2 cleavages are overprinted by north dipping S2 cleavages in the northern part of the Uncompahgre. In some sections (Figure 14) S2 crenulations are present within andalusite porphyroblasts but not within the S1 matrix fabric, possibly due to decrenulation of S2 in the matrix foliation through reactivation of S1 (Bell, 1986). These observations suggest that andalusite growth may have occurred during development of S2 crenulation cleavages, if both north and south dipping crenulations are related to the same deformation event.

Pelitic units in the hinge zone of the Pine River syncline contain assemblages of quartz + white mica + biotite + andalusite + sillimanite + potassium feldspar + staurolite (Figure 15). Andalusite and potassium feldspar porphyroblasts overgrow small grains of muscovite, biotite and quartz which define S1. Sillimanite and large grains of biotite occur in the matrix, axial planar to folded S1 (Figure 15b). Sillimanite appears to be replacing andalusite, grains of which are skeletal and locally almost completely consumed. Potassium feldspar porphyroblasts overgrow uncrenulated S1 but S1 is moderately crenulated in the matrix (Figure 15a). These textural relationships suggest that andalusite, potassium feldspar and sillimanite appeared successively during folding of S1. Incomplete replacement of andalusite by sillimanite constrains equilibration near the alluminosilicate univariant. Growth of potassium feldspar likely occurred when the sample reached the second sillimanite isograd (muscovite + quartz $\rightarrow$ $\text{Al}_2\text{SiO}_5$ + K-spar) but preservation of muscovite grains indicates this reaction did not proceed to completion. In the CKMASH system (Spear, 1994) this sample contains additional
Figure 14. Sample ZML-7, from pelitic unit in the Uncompahgre Group collected east of Rock Lake, eastern Needle Mountains. Section contains horizons of andalusite overgrowing a spaced S2 crenulation cleavage, as show in inset sketch. S2 crenulations are not present within the matrix S1 fabric, possibly due to decrenulation of S2 in the matrix due to reactivation of S1.
Figure 15. Thin section ZML-9a from the hinge zone of the Pine River syncline. A. Full thin section scan showing microfolds of S0/S1 which are parasitic to the macroscopic Pine River syncline. Boxes show locations of photomicrographs and sketches. B. Porphyroblasts of K-feldspar overgrowing un-crenulated S1 which is moderately crenulated in the matrix. C. Biotite and sillimanite defining the axial planar fabric of microfolds. Note that andalusite only overgrows one fabric. These textural relations suggest that folding of the Pine River syncline occurred synchronously with high-T, low-P metamorphism, likely related to emplacement of the nearby Eolus Granite.
phases suggesting it did not fully equilibrate but the assemblage is generally consistent with isobaric heating at approximately 2 Kbars to temperatures of 600° to 630° (Spear, 1994).

A deformed dike cuts bedding in the northeastern limb of the Pine River syncline. This is the only deformed igneous body yet reported within the entire Needle Mountains cover sequence. The foliation within the dike is defined by aligned biotite and hornblende (Figure 16) and dips steeply to the east-northeast, axial planar to the Pine River syncline. The presence of the hornblende fabric is consistent with high-temperature fabrics in nearby pelitic units. This area is 1.5 km west of the surficial contact of the Eolus Granite and low-pressure, high-temperature assemblages most likely formed during its emplacement.

Results 4: Ductile Shear Zones

Ductile shear zones are present along contacts between the Vallecito Conglomerate and Irving Formation and along the basal contact of the Uncompahgre Group. Shear zones are also present within pelitic units of the Uncompahgre Group. These zones commonly preserve evidence for multiple phases of motion involving both north and south-directed shearing. Porphyroblast-fabric relations and overprinting relations indicate that north-directed shearing preceded south-directed shearing, as discussed below and described by previous workers (i.e. Harris et al., 1987). South-directed shearing is tentatively correlated to D2 based south vergence of F2 macroscopic folds.

Two major shear zones were recognized at the contacts between the Vallecito and
Figure 16. Thin section from a foliated dike near the hinge zone of the Pine River syncline. Foliation in the dike is defined by aligned hornblende and biotite and is deflected around relict quartz phenocrysts. The fabric in the dike is axial planar to the Pine River syncline, suggesting that this high-T fabric developed during folding and high-T, low-P metamorphism recorded in nearby pelitic units.
the Irving formation in the southeastern Needle Mountains. These zones are located within the foliated conglomerate facies along Vallecito Creek and immediately west of Dollar Lake (Plate 1). Both shear zones trend north-northeast and juxtapose the Irving formation structurally above the Vallecito. In Vallecito Creek, the foliated conglomerate facies, which is considered correlative with the foliated conglomerate facies of Table Mountain, contains a strong S1 foliation parallel to graded conglomeratic horizons (S0) and L1 stretching lineation defined by highly elongate metavolcanic clasts. L1 within the foliated conglomerate facies shows one of two orientations (Figure 8h). In the northern part of its exposure, clasts in the Fall Creek conglomerate plunge moderately to the south, subparallel to L1 within the foliated conglomerate facies on Middle Mountain. Pelitic horizons within the stratigraphically highest section of the Vallecito, east of Vallecito Creek also contain elongate clasts parallel to L1 in the foliated conglomerates. In this section of the contact, Gonzales (1988) reported asymmetric clasts indicating west-side-up shearing within the Fall Creek. This shear sense is consistent with juxtaposition of the Irving Formation structurally above the Vallecito Conglomerate.

Along the southern section of the contact, northwest of the Vallecito Creek campground, elongate clasts and a prominent mineral lineation in the foliated conglomerate facies define a subvertical L1 perpendicular to the axes of mesoscopic folds that fold S1. Asymmetric sigma-type clasts, fold geometries and microstructures all indicate east-side-up shearing along this section of the contact (Figure 17a). The shear zone extends at least 20 m into the Irving Formation to the west and into the Vallecito to the east where quartz microstructures within thin shear bands also indicate east-side-up shearing (Figure 17b). These shear fabrics are locally brecciated and cut by subhorizontal
**Figure 17.** Photomicrographs from the southern segment of the Vallecito Creek shear zone showing east-side-up shear. **A.** Quartz asymmetric sigma-type clast within mylonite derived from the Irving formation indicating east-side-up shear. **B.** Asymmetric sigma-type quartz clasts within western Vallecito Conglomerate showing east-side-up shear.
quartz veins. In summary, the southern and section of the Vallecito Creek shear zone shows opposite movement sense to that reported by Gonzales (1988) for the northern segment and is interpreted to have been reactivated. Oblique, west-side-up movement is likely correlative with D1 structures in the Vallecito based on similar movement sense and stretching lineation orientations. Reactivation and E-W shortening could have occurred during either D2 or D3, but the shortening direction is more consistent with that inferred for D3.

Shear fabrics within the Dollar Lake shear zone are primarily restricted to the Irving Formation and contain an oblique south-southwest plunging stretching lineation. The foliated conglomerate facies of the Vallecito Conglomerate shows approximately 2 km of west-side-up offset along this structure if projected from the Table Mountain area. Paleozoic rocks are truncated along this structure but show less than 200 m of offset suggesting reactivated as a brittle fault during the Phanerozoic (Plate 2, section C-C’, D-D’).

The southern basement-cover contact of the Uncompahgre Group shows evidence for both north- and south-directed shearing. In the eastern Needle Mountains, in the vicinity of Moon Lake, the basement-cover shear zone dips moderately to the south and places the Irving Formation over moderately north-dipping quartzites of the Uncompahgre Group (Plate 2, section B-B’). Bedding in the Uncompahgre Group becomes steeply overturned within 300 m of the contact with the Irving Formation. A horizon of strongly foliated pelitic and carbonaceous schists up to 50 m thick is present along sections of the contact and fabrics in these rocks can be traced at least 25 m into the Irving Formation to the south. A prominent L1 stretching lineation defined by aligned
micas and quartz ribbons occurs on foliation surfaces within both units and plunges
variably to the south-southwest, southwest and west-southwest (Figure 6a, 6e). Foliation
at the contact is locally folded into meter scale close folds with “Z” asymmetry and
moderately west to west-southwest plunging fold axes. These folds commonly exhibit
axial planar fabrics parallel to the dominant shear zone foliation and have fold axes
parallel to the stretching lineation.

Thin sections from the Moon Lake shear zone show evidence for both north and
south directed shearing. North-directed shear indicators, associated with steeply south-
southwest plunging stretching lineations, include sigma- and delta-type asymmetric strain
shadows around clots of feldspar-white mica-chlorite aggregates in mylonites derived
from the Irving Formation (Figure 18a). This shear sense is consistent with map relations
in which the Irving Formation is structurally above the Uncompahgre and with
steepening of bedding in the Uncompahgre near the shear zone. In some sections, weakly
asymmetric strain shadows of quartz occur around oxides grains and indicate top-to-the
south shear sense (Figure 18b). Rigid clots of quartz-sericite-oxide aggregates in top-to-the
south domains sometimes contain a spaced crenulation cleavage similar to S1-S2
crenulations and deflect the matrix shear fabric (Figure 18c), indicating south-directed
shearing during or after D2. Stretching direction in top-to-the south domains varies from
south-southwest to west-southwest.

To the east of Emerald Lake, the Uncompahgre-Irving contact is a zone of
strongly foliated and lineated quartzites and gneisses. The Vallecito is absent along the
contact and is likely faulted out as it is approximately 1 km thick 2 km to the southwest.
This relationship is depicted in Plate 2, section D-D’. Foliations within the contact of
Figure 18. Photomicrographs from the south dipping basement-cover shear zone at Moon Lake, eastern Needle Mountains, indicating both north- and south-directed shearing of the Irving Formation over the Uncompahgre Group. 

A. Sample ZML-8 containing asymmetric delta and sigma-type clasts indicating top-to-the northeast shear in mylonite derived from the Irving formation. 

B. Sample ZML-2 showing asymmetric strain shadows around oxide grains in sheared basal pelitic horizon indicating top-to-the southwest (normal) shearing. 

C. Same section as B showing rigid quartz-feldspar clast containing S2 crenulations that deflect matrix shear fabric indicating that south-directed shearing occurred synchronously with or after crenulation of S1
the Uncompahgre and Irving Formation dip moderately to the west-southwest and contain a strong southwest to south-southwest plunging stretching lineation defined by aligned mica and quartz ribbons (Figure 8e). Quartzite at the contact exhibits mm to cm scale gneissic compositional banding. Although this contact is interpreted as a shear zone based on map relations and presence of pervasive foliation within quartzites and Irving Formation, quartzite in thin section is composed of interlocking quartz grains that show evidence for subgrain recrystallization (Passchier and Trouw, 1996), which has likely obscured preexisting shear fabrics.

In the western Needle Mountains, the basement-cover shear zone is parallel to bedding within the Uncompahgre Group. Shear zones are present along the basement-cover contacts and within pelitic units of the Uncompahgre Group near the northern basement-cover contact (Plate 1). Shear zones commonly contain a well developed mylonitic foliation and lineation, cm-scale asymmetric boudins of quartz veins, and anastomosing and folded quartz veins.

The southern basement cover contact shows evidence for both north and south directed shearing of the Uncompahgre Group over the basement. To the west of the Animas River, in the vicinity of Mount Garfield, the shear zone contains asymmetric quartz augen indicating top-to-the north sense of shear along the N-dipping low angle contact. In thin section, S-C and C-C' fabrics, quartz sigma clasts and microfolds of quartz ribbons indicate north-directed shearing. These fabrics are locally crenulaed by S2 and are overgrown by post-tectonic andalusite and chloritoid porphyroblasts and locally by radiating clusters of sillimanite (Figure 19a). To the west of the Animas River, in the vicinity of Snowdon Peak, the same basement-cover shear zone shows evidence for south
Figure 19. Photomicrographs from the southern basement-cover shear zone, western Needle Mountains, showing both top-to-the north and top-to-the south sense of shear. **A.** Sample ZEP-4a from D1 top-to-the north shear zone near Mt. Garfield. Mylonitic fabric is weakly crenulated by S2 and both S1 and S2 are overgrown by andalusite prophyroblasts indicating that north-directed shearing preceded development of S2 crenulations. **B, C and D.** Plane, polarized and sketch images of sample KN02 from the southern basement-cover contact, collected west of Snowdon Peak. This section of the contact shows evidence for top-to-the south shearing of the Uncompahgre Group over the basement. Sample KN02 contains rigid chloritized porphyroblasts within top-to-the south domains that overgrow S2 crenulations, indicating that top-to-the south shearing occurred synchronously with or after D2.
directed shearing of the Uncompahgre Group over the basement. Microstructural shear indicators in this region include quartz sigma clasts and microfolds. Sheared porphyroblasts from this shear zone contain S1-S2 crenulations (Figure 19b) indicating south directed shearing occurred either synchronously with or after development of S2 crenulations.

A shear zone developed within the pelitic units near the northern basement-cover contact also shows evidence for south directed shearing. Oriented samples from this unit collected near the Animas River contain C-C’ shear fabrics and rotated altered oxide-rich porphyroblasts with asymmetric strain shadows (Figure 20a). Porphyroblasts contain the matrix shear foliation and show varying degrees of rotation synthetic with shear sense indicated by C-C’ fabrics. In other samples, andalusite overgrows S1 which is deflected into the matrix shear fabric, parallel to S2 (Figure 20b). Andalusite grains are also offset along S2 indicating that andalusite growth occurred synchronously with south-directed shearing in this area. 1.5 km east of the Animas River, this unit contains mesoscopic S-C shear bands indicating top to the south shearing. In thin section, S fabrics are defined by chlorite and elongate quartz grains and merge asymptotically with C fabrics (Figure 20c).
Figure 20. Shear fabrics from pelitic units of the Uncompahgre Group near the northern basement-cover contact indicating top-to-the south shear. This shear sense is opposite of that previously reported and is incompatible with the cuspatel basement-cover deformation model proposed by Harris et al., (1987). A. Sample KEP-7 from pelite unit P2, 1 km south of northern basement-cover contact in canyon of the Animas River showing synthetically rotated syntectonic oxide-rich prophyroblasts that contain, and are rotated within the matrix fabric. B. Sample KN02-11 collected from same location as A. showing syn-tectonic andalusite grains that overgrow S1 and S2 crenulations and are sheared along S2. C. S-C fabric in quartz-chlorite shear zone from thin pelitic unit 500 m north of Elk Creek pack trail, 1 km east of Animas River indicating top-to-the south shear.
Discussion and interpretations

Previous deformation models for the Uncompahgre Group involve a polyphase deformation sequence consisting of D1 layer parallel shearing, D2 macroscopic folding and a third event of variable intensity and style (Tewksbury, 1981; Harris et al., 1987; Harris, 1990). This structural synthesis reconciles previous models by reinforcing some aspects of each: early N-directed thrusting and multiple shear directions (Harris et al. 1987), S-directed shear zones and related macroscopic folds as the main structural elements of the Uncompahgre Group (Tewsbury, 1985), partial basement-cover detachment (Harris et al, 1987) but basement-cored thrust duplexes (this study) rather than cuspatelobate basement-cover infolding (Harris et al.1987). The data presented in this study are generally consistent with these models but suggest that D1 deformation was more intense than previously believed and requires reassessment of the timing and nature of deformation during D2 and D3. More importantly, this study allows deformation events documented in the Uncompahgre Group to be correlated with deformation of the Vallecito Conglomerate, finally allowing construction of an inclusive model for the tectonic evolution of the Needle Mountains cover sequence. I propose and evaluate two scenarios for the timing of D2 deformation and discuss their regional significance. My data are not strongly supportive of the cuspatelobate infolding model for Uncompahgre deformation in the western Needle Mountains (Harris et al., 1987), the implications of which are discussed below.

D1 Deformation

D1 deformation within the Uncompahgre Group and Vallecito Conglomerate involved north-directed thrusting within the metasedimentary units and along the
basement-cover contacts, as depicted schematically in Figure 21. D1 structures are characterized by layer parallel foliation and south-southwest plunging stretching lineations, indicating a fairly uniform direction of tectonic transport. In the Vallecito Conglomerate, strain was partitioned into the basal foliated conglomerate facies, which is believed to have served as a distributed decollement surface accommodating northward translation of the cover sequence. Strain partitioning is presumably due to the rheologically weak nature of this unit relative to the overlying siliciclastic conglomerates. This interpretation is consistent with the presence of pervasively stretched clasts throughout the unit and parallelism of fold axes with L1. In the Uncompahgre, shearing was localized along the basement-cover contact and within pelitic units and was generally parallel to bedding. Consistent stratigraphic facing within both units indicates that D1 deformation did not involve large scale recumbent folding, with the exception of within the basal foliated conglomerates of Middle Mountain. Previous workers have considered D1 deformation to be thin-skinned (Tewksbury, 1981; Harris et al., 1987). However, activation of north directed D1 shear zones along Vallecito Creek, near Dollar Lake and at the southern basement-cover contact of the Uncompahgre Group resulted in juxtaposition of the Irving formation over the metasedimentary units, indicating thick-skinned, basement-involved thrusting occurred in the southeastern Needle Mountains. Preservation of depositional contacts in the Needle Mountains suggests that D1 thrusting did not result in long distance translation of the cover sequence. Major basement-involved thrusts are interpreted to have offset the basal decollement in the Vallecito, which suggests thick-skinned thrusting initiated after layer parallel shearing, as depicted in Figure 22.
**Figure 21.** Schematic block diagram depicting initial D1 deformation (D1a) of the Needle Mountains cover sequence. D1a is interpreted to have involved layer parallel shearing localized within pelitic units in the Uncompahgre Group and the basal, foliated conglomerate facies of the Vallecito Conglomerate. Layer parallel shearing resulted in the development of S1 parallel to bedding and localized macroscopic folding within the basal foliated conglomerate facies. Tectonic overburden of approximately 5 km is not shown for simplicity.
Figure 22. Block diagram depicting later phases of D1 deformation (D1b) in which basement-involved thrusts offset the D1a basal decollement developed within the foliated conglomerate facies of the Vallecito Conglomerate. This deformation phase also resulted in formation of a system of thrusts and associated lateral thrust ramps which led to development of the Needle Mountains “horseshoe,” or the arcuate map trace of bedding in the Uncompahgre Group in the eastern Needle Mountains.
The Needle Mountains “horseshoe,” or the arcuate trace of bedding within the Uncompahgre Group in the southeastern Needle Mountains, likely formed during D1. This interpretation is based on the consistent orientation of stretching lineations in the shear zone between the Uncompahgre Group and the Irving Formation. The shear zone generally parallels the map trace of bedding in the Uncompahgre Group, trending easterly in the northern segments and bending to southerly trending along southern segments. Stretching lineations in this shear zone consistently plunge to the southwest (Figure 8a, e) indicating dip-slip thrust sense along the northern segment and oblique-dextral-thrust motion along the southern segments. The consistent stretching lineation trends, despite variable shear zone orientation, suggests that the “horseshoe” map pattern formed during D1 and has not been significantly reoriented during subsequent folding events. This conclusion suggests that the shear zone developed as a thrust with an associated lateral thrust ramp, as depicted in Figure 22. Lateral thrust ramps generally develop to accommodate differential translation within different parts of a thrust system. Such a scenario may have occurred in the southeastern Needle Mountains if D1 shearing occurred preferentially within the localized Vallecito Conglomerate. The Dollar Lake and Vallecito Creek shear zones also have oblique stretching lineations and could potentially also have developed as dextral-slip lateral thrust ramps, although these structures may also represent D1 thrusts which were steepened to their present geometries during D3 folding, as discussed below.

Overall, D1 deformation records the progressive evolution of a fold thrust belt that likely developed during the ~1.65 Ga Mazatzal orogeny. North-directed thrusting of the cover sequences is suggested to have occurred throughout the inboard foreland region
of the bivergent Mazatzal orogen (Karlstrom et al. 2004, Magnani et al. 2004). Tectonic transport directions and style of deformation in the Needle Mountains are similar to those reported for Mazatzal related thrusting in the Ortega quartzite of northern New Mexico and the Mazatzal quartzite in Arizona (Puls and Karlstrom, 1985; Williams, 1991). Correlations have been suggested between the Uncompahgre Group and the Ortega and Mazatzal quartzites (Cox et al., 2002). The Ortega quartzite in particular is very close (within 125 km), about the same age (Williams, 1991), and contains similar facies of ultramature quartzite, pelite, and local conglomerate. The Marquenas conglomerate of the Picuris Mountains is very similar to the Vallecito conglomerate. In-situ monazite geochronology from the Ortega quartzite indicates Mazatzal related deformation spanning ~1.67 to 1.65 followed by a protracted thermal event spanning 1.45-1.39 Ga (Kopera et al., 2002). Deformation of the Ortega quartzite was likely somewhat synchronous with D1 in the Needles and provides an approximate minimum age of deposition of the Needle Mountains cover sequence of 1.67 Ga.

**D2 Deformation**

D2 deformation involved folding of the Uncompahgre Group into east to southeasterly trending macroscopic folds with S2 axial planar cleavage and reactivation of D1 shear zones as top-to-the south thrusts, as depicted schematically in Figure 23. This deformation event accounted for the majority of shortening within the Uncompahgre Group. The Vallecito Conglomerate likely experienced only weak macroscopic folding at this time, possibly due to the absence of interbedded pelitic horizons within the 3-km thick quartz-pebble conglomerate facies of the Vallecito, which, if present, would have
D2: Macroscopic folding and south directed thrusting

Reactivation of western basement-cover contact as top-to-the south shear zones.

Macroscopic folding of the Uncompahgre Group

Gentle folding of Vallecito Conglomerate?

~6-12 km

~12-18 km

Figure 23. Block diagram depicting D2 deformation of the Needle Mountains cover sequence. D2 involved the development of macroscopic folds with north dipping axial surfaces within the Uncompahgre Group and reactivation of segments of the basement-cover contact as top-to-the south shear zones. D2 deformation is not well expressed within the Vallecito Conglomerate but may have involved gentle E-W folding.
aided buckling through bedding parallel flexural slip. The timing of this D2 shortening event relative to growth of andalusite is somewhat enigmatic. Andalusite generally overgrows S1 and S2 and appears post-tectonic, but some samples suggest that D2 was synchronous with or continued after andalusite growth. Top-to-the south shear zones were active during and also after porphyroblast growth. These relationships are interpreted to reflect heating and andalusite growth during the latter phases of a protracted D2 deformation event that was synchronous with and continued after andalusite growth.

Recognition of top-to-the south shear zones within the northern part of the Uncompahgre Group in the western Needle Mountains is inconsistent with the cuspaten basement-cover model presented by Harris et al. (1987). Their model involves D3 reactivation of the southern basement-cover contact as a top-to-the south shear zone and top-to-the north shearing along the northern contact during motion of the Uncompahgre Group up and out with respect to the basement. This model requires consistent top-to-the north shearing along the northern contact during both D1 and D3. My data show that shear zones within pelitic units near the northern basement-cover contact were active as top-to-the south shear zones during and after growth of contact metamorphic porphyroblasts. Gibson (1990) reports that top-to-the north shear fabrics from the northern contact are overgrown by andalusite, indicating that north-directed kinematic indicators for the cuspaten in-folding model may record D1 shearing that occurred prior to D2 folding of the basement-cover contact. Data from this study shows no evidence for macroscopic downward-tapering synclinal hinges implicit in cuspaten-basement-cover geometries and instead suggests a more traditional fold-thrust belt geometry involving
shortening through recumbent folding and south-directed thrusting, as depicted in cross section A-A’ (Plate 2).

The timing of andalusite growth is key for understanding D2 deformation of the Needle Mountains cover sequence in a regional context. However, this age is uncertain and growth during both ~1.65 and ~1.4 Ga metamorphic events seem plausible. The first possibility is that andalusite growth occurred during the Mazatzal orogeny at approximately 1.65 Ga. One $\text{Ar}^{40}/\text{Ar}^{39}$ hornblende age from the Tenmile Granite in the western Needle Mountains indicates cooling through 450° at ~1610 Ma (Shaw et al. 2005). The Tenmile Granite was reportedly exhumed to the surface prior to deposition of the cover sequence (Gibson and Simpson, 1988; Tewksbury, 1989), suggesting that the unit was reheated to temperatures greater than 450° between 1700 and 1610 Ma. These conditions are within the stability field for andalusite and suggest that D2 deformation may have occurred during this period. Gibson and Simpson (1988) conclude that deformation of the Tenmile Granite occurred during D2 in the Uncompahgre Group, which is consistent with syn-D2 andalusite growth.

If andalusite formed during the Mazatzal orogeny at ~1.65 Ga, then D2 deformation was likely progressive with D1 thrusting. D2 involved ductile folding of the cover sequence while D1 was initially thin-skinned. The progression from D1 to D2 could represent burial of D1 thrusts by overriding thrust sheets to middle crustal levels followed by folding associated with a change in the direction of tectonic transport, possibly representing the onset of backthrusting in the Mazatzal foreland. The onset of backthrusting in the region could potentially be associated with reactivation of major north dipping shear zones in the region, including the Homesteak shear zone.
It is also possible that andalusite growth occurred at ~1.43 Ga during regional contact metamorphism associated with emplacement of the Eolus Granite. The majority of hornblende and mica cooling ages from the Needle Mountains indicate cooling between 1450 and 1390 Ma (Shaw, 2005), indicating heating during the 1.4 Ga thermal event was a regional event, rather than restricted to the aureoles of 1.4 Ga plutons. This is consistent with presence of andalusite in samples from across the Needle Mountains overgrowing S1 fabrics. The 1610 Ma cooling age from the Tenmile granite could possibly be an apparent age representing Ar diffusion rather than thermal resetting, as interpreted by Shaw et al. (2005).

If the andalusite and D2 structures formed at ~1.4 Ga, then the Needle Mountains were subjected to significant deformation during the regional thermal event. The current understanding of deformation associated with the 1.4 Ga thermal event is that related structures are primarily restricted to the aureoles of 1.4 Ga plutons where thermal softening allowed fabric development within a regional stress field (Nyman et al., 1994; Kirby et al., 1995). The 1.4 Ga thermal event is also believed to have caused reactivation of major, northeast trending Paleoproterozoic shear zones in the Western Colorado (Jessup, in press). If the major shortening structures in the Needle Mountains formed at 1.4 Ga, this would support models for crustal evolution that downplay the significance of the Mazatzal orogeny and associate major deformation with the 1.4 Ga event (Daniel, 2005). It would also further support models attributing the thermal event to broad, inboard crustal deformation related to plate margin tectonism (e.g. Nyman et al., 1994). D2 structures in the Needles accommodated north-northeast-south-southwest shortening, which is perpendicular to the regional shortening direction inferred from the aureoles of
1.4 Ga plutons and could potentially represent temporal or spatial variations in the stress field during the 1.4 event.

**D3 Deformation**

D3 involved macroscopic folding of the Vallecito Conglomerate into south plunging folds. Reactivation of the southern segment of the Vallecito Creek shear zone resulted in east-side-up shearing of the Vallecito Conglomerate over the basement and is tentatively correlated to D3 based on shortening direction consistent with macroscopic folding. D3 folds within the Vallecito Conglomerate are similar in style and orientation to the D3 macroscopic fold in Lime Creek, that refolds a D2 syncline and is correlated to basement structures that fold pegmatite veins (Harris et al., 1987; Gibson and Simpson, 1988). Macroscopic folding during D3 resulted in steepening of the D1 Dollar Lake and Vallecito Creek shear zones to their present geometries and folding of the basement-cover shear zone, as depicted in Plate 2, section D-D’. Refolding of bedding in the easternmost Uncompahgre Group by the Middle Mountain anticline possibly accounts for some of the Needle Mountains “horseshoe,” or the apparent arcuate map trace of bedding in the Uncompahgre Group that trends east-west in the central and south-southeast in the eastern Needle Mountains (Figure 2). The “horseshoe” may also have formed during D1 in the footwall of a lateral thrust ramp, as previously discussed. Unfolding of the Middle Mountain anticline restores bedding in the eastern Uncompahgre Group to northwest trending and shallowly northeast dipping orientations. This orientation is similar to that of bedding in the Uncompahgre Group along much of the southern basement-cover contact. It is also possible that the Middle Mountain anticline is part of a D1 hanging-wall
anticline that formed during D1 thrusting, as is potentially represented in Plate 2, sections C-C’ and D-D’. However, its axis is nearly parallel to the D1 thrusting direction whereas it would be sub-perpendicular to L1 if it formed as a hanging-wall anticline. It is also plausible that the Middle Mountain anticline is analogous to the D2 macroscopic folds within the Uncompaghre Group, but has been folded around the Needle Mountains horseshoe to its present geometry. If the anticline was initially easterly trending but later folded to its present geometry, L1 lineations would also most likely have been folded, which they are not. A D3 assignment for this structure is preferred based on similarities in style with other, well documented D3 folds (the Lime Creek syncline).

The Pine River syncline is texturally associated with high temperature, low pressure metamorphic assemblages which are interpreted to record contact metamorphism related to the 1.43 Ga Eolus Granite. This suggests that the Pine River syncline, and possibly the sub-parallel Middle Mountain anticline, formed to accommodate emplacement of the Eolus batholiths that buttress the Vallecito to the east and west of its exposure. This deformation was likely enhanced by thermal softening of the Vallecito associated with contact metamorphism. Parallelism of D3 macroscopic fold trends with the margins of the plutons in the southeastern and western Needle Mountains is consistent with formation of these structures during pluton emplacement. Accommodation of ballooning plutons through deformation of the wall rocks is well documented in the Ardara pluton in the Caledonian orogen, where foliations and synmagmatic folds in the country rocks form a concentric pattern around the pluton (Meneilly, 1982). Synmagmatic deformation of country rock around the Ardara pluton is believed to be analogous to D3 structures within the Vallecito, although this deformation
was significantly weaker and the Eolus lacks syn-plutonic foliations. This conclusion explains the orthogonal relationship of macroscopic fold trends in the Vallecito Conglomerate and Uncompahgre Group.

South trending D3 structures within the Needle Mountains cover sequence suggest localized east-west shortening during plutonism. The orientation of these structures is inconsistent with north-south shortening reported during emplacement of the ~1435 Ga Electra Lake gabbro in the southwestern Needle Mountains (Gonzales et al., 1996), suggesting that the direction of principal stress was variable around the pluton. However, orientations of D3 folds are consistent with the regional west-northwest-east-southeast contractional stress field as inferred from structures in the margins of other 1.4 Ga plutons in the southwestern U.S (Nyman et al. 1994).
Summary and Conclusions

The Vallecito Conglomerate represents a localized, basal facies of the Uncompahgre Group and was deposited on an uplifted, Yavapai aged basement complex, either during extension and crustal stabilization following the Yavapai Orogeny or in a tectonic basin related to Mazatzal collisional tectonism. The Uncompahgre Group and the Vallecito have a similar polyphase deformation history involving early thin-skinned north-directed layer-parallel shearing that was transitional into thick-skinned basement-involved thrusting in the southeastern Needle Mountains. This fold-thrust belt likely developed in the foreland of the Mazatzal orogen at approximately 1650 Ma. D2 structures account for the majority of shortening within the Uncompahgre Group and are texturally associated with syn-tectonic andalusite. Macroscopic D2 folding was generally synchronous with top-to-the south thrusting within the Uncompahgre Group and along reactivated segments of the basement-cover contacts. While andalusite growth and D2 deformation could have occurred at either ca. 1.65 or 1.4 Ga, major shortening at ~1.65 Ga is more consistent with regional tectonic models. South trending D3 folds formed synchronously with the development of low pressure (2 kbar) contact metamorphic assemblages in conjunction with emplacement of the 1.43 Ga Eolus Granite. The Needle Mountains “horseshoe” in the southeastern part of the range most likely during D1 in a system of thrusts and associated lateral thrust ramps. Recognition that macroscopic folds in the Vallecito Conglomerate are a different generation than those in the Uncompahgre Group explains the orthogonal relationship of fold trends between these two units.
Suggestions for additional work

This study presents a new deformation model for the Needle Mountains metasedimentary cover sequence built on both new and previous work, but requires further evaluation and confirmation through new field studies, petrography and geochronology. Determining the timing of andalusite growth is critical for evaluating models of crustal assembly and evolution. Pending in-situ monazite geochronology to be conducted by Mike Williams on the “ultrachron” microprobe at the University of Massachusetts may determine whether andalusite is ~1.4 or 1.65 Ga. Further petrographic work, focusing on metamorphic assemblages incuded within andalusite and in the aureoles of 1.4 Ga plutons may also be useful for constraining the timing of D2. This study suggests that the Vallecito Creek shear zone underwent oblique, top-to-the northwest shearing prior to reactivation as a top-to-the east shear zone but, this timing is based on similarities in the inferred D1 thrusting direction and top-to-the northwest movement sense along the shear zone. Further work on the Vallecito-Creek shear zone documenting the extent of the east-directed shearing within the zone and its relation to top-to-the north segments of the shear zone would help evaluate the model proposed here. D2 structures are not apparent within the Vallecito but may be present as broad, east trending folds east of Emerald Lake, based on the variable plunge of the Hell Creek anticline. More work, focusing on identification of a dome and basin interference geometry may help resolve this issue. Also, further work on F1 folds in the eastern limb of the D3 Middle Mountain anticline may help better document refolding of F1 during D2 and D3. The textural relationships in the hinge zone of the Pine River syncline suggest that D3 deformation is related to plutonism. Pending U-Pb zircon geochronology
on the nearby foliated dike, to be conducted on the quadropole mass spectrometer at the University of Texas, Austin, may constrain its deformation to post 1.43 Ga, thereby supporting this model. Documentation of refolded D2 folds (yet unrealized) in the hinge zone of the syncline would also support this model. This study suggests that the Needle Mountain horseshoe structure, seen in bedding trends of the Uncompahgre Group is a D1 structure. Work on tectonic fabrics around the structure, especially the orientation of S2 fabrics, could greatly improve our understanding of formation of the horseshoe.
Appendix 1: Description of fold and fabric elements by sub-area

Table Mountain sub-area

The foliated conglomerate facies of the Vallecito Conglomerate is exposed in a 5 km$^2$ region on northern Middle Mountain, between Table Mountain and the ridge west of Dollar Lake. Here, conglomerates contain a strong foliation (S1) and lineation (L1) defined by stretched clasts and mineral lineations that plunge moderately to the south-southwest. Foliation is generally sub-parallel to bedding but is locally at a high angle, indicating the presence of F1 folds of bedding. Bedding in the conglomerates approximately parallels the sinuous, eastern basement-cover contact and cross bedding indicated that beds young away from the basement near the headwaters of Dead Horse Creek and within the drainage 300m south of peak 11,972’. These contacts are interpreted as (locally sheared) unconformities (Burns et al., 1980; Ethridge et al., 1984; Tewksbury, 1989). Along the section of the contact south of peak 11,972’ foliation is steep to subvertical and is consistently at a moderate to high angle to bedding defining the hinge of a macroscopic F1 fold. The contact is interpreted as folded into F1 macroscopic syncline-anticline pairs with S1 axial planar cleavage and moderately southwest- plunging fold axes. An andalusite- bearing unit can be traced around much of the southeastern basement-cover contact and may define the limbs of another macroscopic syncline, although S1 and S0 are sub-parallel throughout much of this area. S0 and S1 trend into the Irving Formation along the northern contact which is likely faulted, as interpreted by previous workers (Burns et al., 1980; Ethridge et al., 1984; Gonzales, 1988). The western contact is poorly exposed and the direction of stratigraphic younging is somewhat unclear but this contact could juxtapose westward- younging conglomerates structurally below the Irving Formation, possibly along a major, unmapped shear zone (Plate 2).

Mesoscopic folds within the Table Mountain domain are rare but two generations were recognized based on the association of S0 and S1. First generation folds (F1) fold bedding and have S1 axial planar cleavage. Second generation F2 folds refold both bedding and S1. The fold axes of all mesoscopic folds at Table Mountain are parallel to the L1 stretching lineation, suggesting that they formed progressively. In thin section, S1 is defined by an alignment of elongate quartz grains, sericite and oxides and is sub-parallel to S0. S0 and S1 are overgrown by retrograde chlorite and cholitized pseudomorphs possibly after andalusite. In summary, this subarea provided documentation for the geometry and style of F1 folding and F1/F3 overprinting.

Vallecito Creek sub-area

An approximately 1000 m-thick section of quartz-pebble conglomerate of the Vallecito Conglomerate is exposed within the canyon of Vallecito Creek, 4-10 km north of Vallecito Reservoir (Plate 1). Preservation of primary sedimentary structures within this section of the Vallecito is excellent and bedding in the unit strikes north to northeast and dips steeply to the west. Cross bedding and graded beds indicate that the entire package of quartz-pebble conglomerate youngs to the west where it is faulted against a thin horizon of Fall Creek conglomerate, which youngs to the east (Gonzales, 1988).

The intensity of S1 foliation in the Vallecito Conglomerate increases up section, towards the contact with the Fall Creek. Near the contact S1 is defined by elongate clasts
and compositional layering with absence of primary sedimentary features. To the east, quartz-pebble conglomerates are dominantly unstrained and S1 is only locally defined by highly elongate pelitic clasts and as the axial surfaces to rare, small scale crenulations of S0.

The Fall Creek conglomerate, which is considered correlative with the foliated conglomerate facies of Table Mountain, contains a strong S1 foliation parallel to graded conglomeratic horizons (S0) and L1 stretching lineation defined by highly elongate metavolcanic clasts. L1 within the Fall Creek shows one of two orientations. In the northern part of its exposure, clasts in the Fall Creek conglomerate plunge moderately to the south. Pelitic horizons within the stratigraphically highest section of the Vallecito, east of Vallecito Creek also contain elongate clasts parallel to L1 in the Fall Creek. Bedding within the Vallecito is truncated against the contact with the fall creek. In this section of the contact, Gonzales (1988) reported asymmetric clasts indicating west-side-up shearing within the Fall Creek. This shear sense is consistent with juxtaposition of the Irving Formation structurally above the Vallecito Conglomerate.

Along the southern section of the contact, northwest of the Vallecito Creek campground, elongate clasts and a prominent mineral lineation in the Fall Creek conglomerate define a subvertical L1 perpendicular to the axes of mesoscopic folds that fold S1. Asymmetric sigma type clasts, fold geometries and microstructures all indicate east-side-up shearing along this section of the contact. The shear zone extends at least 20 m into the Irving Formation to the west and into the Vallecito to the east where quartz microstructures within thin shear bands also indicate east-side-up shearing (Figure 17b). These shear fabrics are locally brecciated and cut by subhorizontal quartz veins.

Bedding immediately north of Vallecito Creek Campground and on the ridge east of Vallecito Creek dips moderately to the south, defining a south plunging, macroscopic homocline. This structure may be a parasitic structure on the limb of the Middle Mountain anticline. In summary, the shear zone along the Vallecito-Irving contact shows evidence for both west and east-side up shearing. S1 is likely associated with movement along this zone as it increases in intensity towards the shear zone.

Pine River sub-area

The largest and thickest portion of the Vallecito Conglomerate is exposed in the valleys of Pine River and Lake Creek. Total thickness of the Vallecito in this area likely exceeds 3 km although some of this thickness may be the result of tectonic duplication. The Vallecito Conglomerate in this region consists primarily of homogenous quartz-pebble conglomerate with rare, thin, discontinuous horizons of pelitic material and boulder conglomerates. The uppermost Vallecito shows an overall fining-upward trend and is gradational into the Uncompahgre Group. Preservation of sedimentary features is excellent and bedding generally dips shallowly to moderately to the east and southeast. In the southern part of its exposure, near the Pine River trailhead, bedding dips 20-30° to the southwest and defines the hinge of a broad, south-southwest plunging anticline. This structure trends into the Hell Canyon anticline to the north and the anticline west of Emerald Lake. Together, these structures define the hinge of the Middle Mountain anticline that has a western limb in Vallecito Creek and eastern Limb in the Pine River-Lake Creek valleys (Plate 1).
Fold-thrust duplex systems are present in the uppermost part of the Vallecito, west of the Pine River trailhead. Folds are broad to open with inclined axial surfaces and have fold axes that plunge shallowly to the southwest and wavelengths of 2-10 m. S1 axial planar cleavage is weak, strikes northwest and dips shallowly to the southeast. S1-S0 intersection lineations are sub-parallel to axes of mesoscopic folds. Quartz slickensides on bedding surfaces and on shallowly southeast to south dipping thrust planes are generally perpendicular to fold axes and indicate folding through flexural slip. Bed truncations and stratigraphic duplication as well as fold asymmetry and quartz slickensides indicate northwest directed thrusting within this portion of the Vallecito. It is unclear how these structures correlate with structural features in other areas. The thrust system is locally a first generation feature but its kinematics may be more consistent with D3 deformation.

A previously unmapped macroscopic syncline is present within the uppermost Vallecito/lower Uncompahgre Group located on the hillside east of Pine River, approximately 2 km northwest of Granite Peak. This fold, referred to as the Pine River syncline, plunges approximately 20° to the south-southeast and has an interlimb angle of approximately 70° (Plate 2, E-E’). Bedding to the east of the Pine River syncline dips moderately to steeply to the south and southeast and is roughly concordant to the margin of the Eolus Granite.

Pelitic units within the core of the Pine River syncline show evidence for two stages of folding and fabric development. S1 exists as a strong foliation within pelites and is everywhere parallel to S0 except in the hinges of F1 interfolial folds. S1 within more quartzose units exists as a weak alignment of micas parallel to S0. F1 mesoscopic folds are isoclinal to tight and have S1 axial planar cleavage. Some are associated with small scale bedding parallel thrusts. Most F1 fold axes plunge shallowly to the south-southeast but some F1 fold axes on the western limb of the syncline plunge to the southwest and show “Z” asymmetry when viewed from the south suggesting that they are not parasitic with the syncline and represent an earlier generation.

F2 (local designation) folds refold both S0 and S1 into broad to tight folds with south-southeast plunging fold axes. F2 folds are generally broad when developed in thicker quartzite beds and include tight buckle folds in thin quartzite horizons within thicker pelitic layers. Asymmetry of F2 folds is consistent with their position on the limbs of the Pine River syncline. The orientation of the fold axes of both mesoscopic and macroscopic folds is similar suggesting that the structures are genetically related. One refolded F1 fold was observed in the float, but refolded F1 folds were not found in outcrop.

Emerald Lake sub-area

The Vallecito Conglomerate, Uncompahgre Group, Eolus Granite and Irving Formation are exposed in the vicinity of Emerald Lake in the central region of the Emerald Lake Quadrangle (Plate 1). The Hell Creek anticline is a NNE trending macroscopic anticline within the Vallecito that passes west of Emerald Lake and through Hell Canyon. The structure is generally open to broad but interlimb angle tightens to < 60° near Hell Canyon. The plunge of the fold axis varies from moderately south dipping to subhorizontal. The Hell Creek anticline marks the hinge of the larger, Middle Mountain anticline with limbs in Vallecito Creek and along Pine River.
The contact between the Vallecito and the underlying Irving formation is exposed on the west side of Emerald Lake. S1 foliation in the Vallecito is parallel to S0, and the basement-cover contact. S1 and L1, defined by a bedding parallel mica alignment and moderately south-southwest plunging stretched metavolcanic clasts, increases in intensity towards the contact with Irving Formation. Similar fabric elements are present in the Irving formation approximately 400 m below the contact where foliation is strongly lineated and folded into broad to open folds with moderately south-southwest plunging axes, parallel to the L1 stretching lineation in the Vallecito.

Fabrics in the Vallecito above the basal unconformity are weak to non-existent within quartz-pebble conglomerates but are well developed within horizons of interbedded siltstone and conglomeratic beds. In the area 1-3 km south of Dollar Lake, these horizons contain mesoscopic F1 folds with S1 axial planar cleavage. In these horizons L1 is defined by stretched clasts and is within S1 which is generally parallel to slightly oblique to S0, except in the hinge regions of F1 folds. F1 folds have amplitudes ranging from 3 cm to >2 m, shallowly east to southeast plunging axes and are overturned to north (Figure 8g). Local deflection of S1 into S0 indicates north-directed slip along bedding planes.

The western margin of the Vallecito Conglomerate is juxtaposed against the Irving Formation along a north striking shear zone that passes immediately west of Dollar Lake, referred to as the Dollar Lake shear zone. The Dollar Lake shear zone dips moderately to the west and places the Irving Formation structurally above the Vallecito Conglomerate. A strong foliation within the Irving Formation near the contact is parallel to the shear zone and contains a south-southwest shallowly to moderately plunging stretching lineation. The basal contact of the Vallecito Conglomerate is offset approximately 2 km along this structure if projected from the Table Mountain area but Paleozoic rocks are displaced less than 200 m suggesting that this structure was reactivated as a brittle fault during the Phanerozoic (Plate 2).

The Uncompahgre Group is exposed on the ridge to the northeast of Emerald Lake. It is in tectonic contact with the Irving Formation along its western contact and is intruded by the Eolus Granite to the south and east. Bedding in the Uncompahgre Group is steep to subvertical, strikes north to north-northwest and youngs to the east. Pelitic units within the Uncompahgre Group contain a strong, subvertical S1 foliation that is axial planar to F1 intrafolial folds. F1 folds have subvertical axes and show “S” type geometries when viewed down the fold axis. F2 folds in pelitic units are gentle, cm scale crenulations with shallowly southwest dipping axial surfaces and shallowly south-southeast plunging fold axes (Figure 8d).

Near its southern contact with the Eolus Granite, bedding in the Uncompahgre group dips steeply to shallowly to the south and southeast, sub-parallel to the flow foliations in the granite. On the ridge 1.5 km to the east of Emerald Lake, the Eolus Granite contains abundant quartzite blocks up to 4 m in length.

To the east of Emerald Lake, the Uncompahgre-Irving contact is a zone of strongly foliated and lineated quartzites and gneisses. The Vallecito is absent along the contact. Foliations at the contact within the Uncompahgre and Irving Formation dip moderately to the west-southwest and contain a strong southwest to south-southwest plunging stretching lineation defined by aligned mica and quartz ribbons. Quartzite at the contact exhibits mm to cm scale gneissic compositional banding. Although this contact is
interpreted as a shear zone based on map relations and presence of pervasive foliation within quartzites and Irving Formation, quartzite in thin section is composed of recrystalized, interlocking quartz grains. Recrystalization has likely obscured preexisting shear fabrics. In summary, the Emerald Lake region shows evidence for top-to-the north basement-involved thrusting. These shear zones were possibly weakly refolded by Middle Mountain anticline during D3.

**Moon Lake sub-area**

The Uncompahgre Group is exposed throughout the northern part of the study area and was studied in detail in the vicinity of Moon Lake, Rock Lake and Mt. Oso (Plate 1). The easterly trending basement-cover contact passes beneath Moon Lake and marks the southern contact of the Uncompahgre Group in the Moon Lake sub-area. Bedding in the Uncompahgre Group dips moderately to the northwest near Mt. Oso and steeply north-northeast near Rock Lake. Bedding becomes steeply overturned near the basement-cover contact at Moon Lake. Bedding generally youngs to the north and northwest and is mapped within the southern limb of a macroscopic syncline in the central Needle Mountains (Tewksbury, 1981).

Pelitic units within the Uncompahgre Group contain multiple folds and fabric elements. In outcrop, S1 is defined by a strong alignment of micas and is subparallel to S0 except in the hinges of F1 folds. L1 is a steeply plunging stretching lineation defined by aligned biotite, white mica and quartz ribbons. F1 folds are generally rare, but when observed are close to isoclinal and have steeply plunging fold axes parallel to L1. In thin section, S1 is a strong alignment of muscovite and elongate quartz grains sometimes containing chlorite and biotite.

D2 structures consist of gentle F2 crenulations of S1 with weak S2 axial planar cleavage and S1-S2 intersection lineations parallel to F2 crenulation axes. In outcrop, S2 strikes northwest and dips steeply to moderately northeast or southwest. Axes of F2 crenulations plunge shallowly to the southeast. In thin section, spaced to strongly developed S2 crenulation cleavage is overgrown by andalusite porphyroblasts. S2 within andalusite is at a high angle to S1 and generally dips to the north. These fabrics are gently folded by a second, weakly developed moderately south dipping crenulation cleavage that is at a high angle to S2 within andalusite. While these fabrics could represent multiple deformation events, they are similar to D2 conjugate crenulation cleavages described in the central Needle Mountains (Tewksbury, 1981). In some sections, S2 crenulations are present within andalusite porphyroblasts but not within the S1 matrix fabric, possibly due to decreration (Bell, 1986) of the S2 in the matrix foliation. The overall trend of S2 is consistent with its formation as the axial planar fabric to macroscopic D2 folds within the Uncompahgre Group.

A shear zone is present along the basement-cover contact in the vicinity of Moon Lake. Bedding in the Uncompahgre Group becomes steeply overturned within 300 m of the contact with the Irving Formation. A horizon of strongly foliated pelitic and carbonaceous schists up to 50 m in thickness is present along sections of the contact and fabrics in these rocks can be traced at least 25 m into the Irving Formation to the south. A prominent L1 stretching lineation defined by aligned micas and quartz ribbons occurs on foliation surfaces within both units and plunges variably to the south-southwest, southwest and west-southwest. Andalusite prophyroblasts are only weakly aligned.
parallel to L1 within aluminous schists. Foliation at the contact is locally folded into
meter scale close folds with “Z” asymmetry and moderately west to west-southwest
plunging fold axes. These folds commonly exhibit axial planar fabrics parallel to the
dominant shear zone foliation and have fold axes parallel to the stretching lineation.

Thin sections from the Moon Lake shear zone show evidence for both north and
south directed shearing. North directed shear indicators, associated with steeply south-
southwest plunging stretching lineations, include sigma and delta type asymmetric strain
shadows around clots of feldspar-white mica-chlorite aggregates in mylonites derived
from the Irving Formation. Stretching direction in top-to-the south domains varies from
south-southwest to west-southwest. In some sections, weakly asymmetric strain shadows
of quartz occur around oxides grains and indicate top-to-the south shear sense. Rigid clots
of quartz-sericite-oxide aggregates in top-to-the south domains sometimes contain a
spaced crenulation cleavage similar to S1-S2 crenulations and deflect the matrix shear
fabric.

A zone of breccia occurs along sections of the basement-cover contact near Moon
Lake and contains blocks of quartzite and metavolcanic rock up to 5 m in length. Matrix
in the breccia consists of quartz veins and fine grain, iron stained material that locally
exhibits a matrix foliation. The long axes of clast are locally aligned in the matrix fabric
and in some localities, large quartzite clasts are highly stretched while nearby
metavolcanic clasts have fragmental tails. These observations suggest that brecciation
may have occurred at conditions near the brittle-ductile transition. Some quartz veins in
the matrix contain stringers of pegmatitic material which is possibly related to the Eolus
Granite. If this shear zone was active at ~1.4 Ga, top-to-the south normal motion along
the shear zone may record N-S extension coeval with E-W D3 folding.

Western Needle Mountains

Oriented samples were collected from shear zones within the Uncompahgre
Group in the western Needle Mountains for the purpose of constraining the timing of
shearing relative to peak metamorphism. Shear zones are present along the basement-
cover contacts and within pelitic units of the Uncompahgre Group near the northern
basement-cover contact (Plate 1). Shear zones commonly contain a well developed
mylonitic foliation and lineation, cm-scale asymmetric boudinage of quartz veins, and
anastomosing and folded quartz veins.

The southern basement cover contact shows evidence for both north and south
directed shearing of the Uncompahgre Group over the basement. To the west of the
Animas River, in the vicinity of Mount Garfield, the shear zone contains asymmetric
quartz augen indicating top-to-the north sense of shear along the N-dipping low angle
contact. In thin sections cut perpendicular to foliation and parallel to the northeast
plunging stretching lineation, S-C and C-C’ fabrics, quartz sigma clasts and microfolds of
quartz ribbons indicate north-directed shearing. These fabrics are overgrown by post-
tectonic andalusite and chloritoid porphyroblasts and locally by radiating clusters of
diagram.
A shear zone developed within the pelitic units near the northern basement-cover contact also shows evidence for south directed shearing. Oriented samples from this unit collected near the Animas River contain C-C’ shear fabrics and rotated altered andalusite porphyroblasts with asymmetric strain shadows. Porphyroblasts contain the matrix shear foliation and show varying degrees of rotation synthetic with shear sense indicated by C-C’ fabrics. 1.5 km east of the Animas River, a thin pelite unit contains mesoscopic S-C shear bands indicating top to the south shearing. S fabrics are defined by chlorite and elongate quartz grains in thin section and merge asymptotically with C fabrics. Thin sections from near the northern basement-cover shear suggest that this shear zone was active synchronously with the growth of andalusite.
Appendix 2: Data CD

Contents
Notes (MS Word Document)
Thesis with color figures (.pdf)
Digital copies of the geologic maps and cross sections (.jpg)
Spread sheets of structural data (MS Excel Worksheets)
StereoNett: structural geology plotting program for Windows
M.S. thesis defense presentation (.ppt)
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