Geologic Map of the east half of the Black Canyon City 7 ½′ Quadrangle and the west half of the Squaw Creek Mesa 7 ½′ Quadrangle, Maricopa and Yavapai Counties, Arizona

by

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Arizona Geological Survey Digital Geologic Map DGM-64

version 1.0

June 2008

Scale 1:24,000 (1 sheet, with text)

Arizona Geological Survey
416 W. Congress St., #100, Tucson, Arizona 85701

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program, award no. 06HQAG0051. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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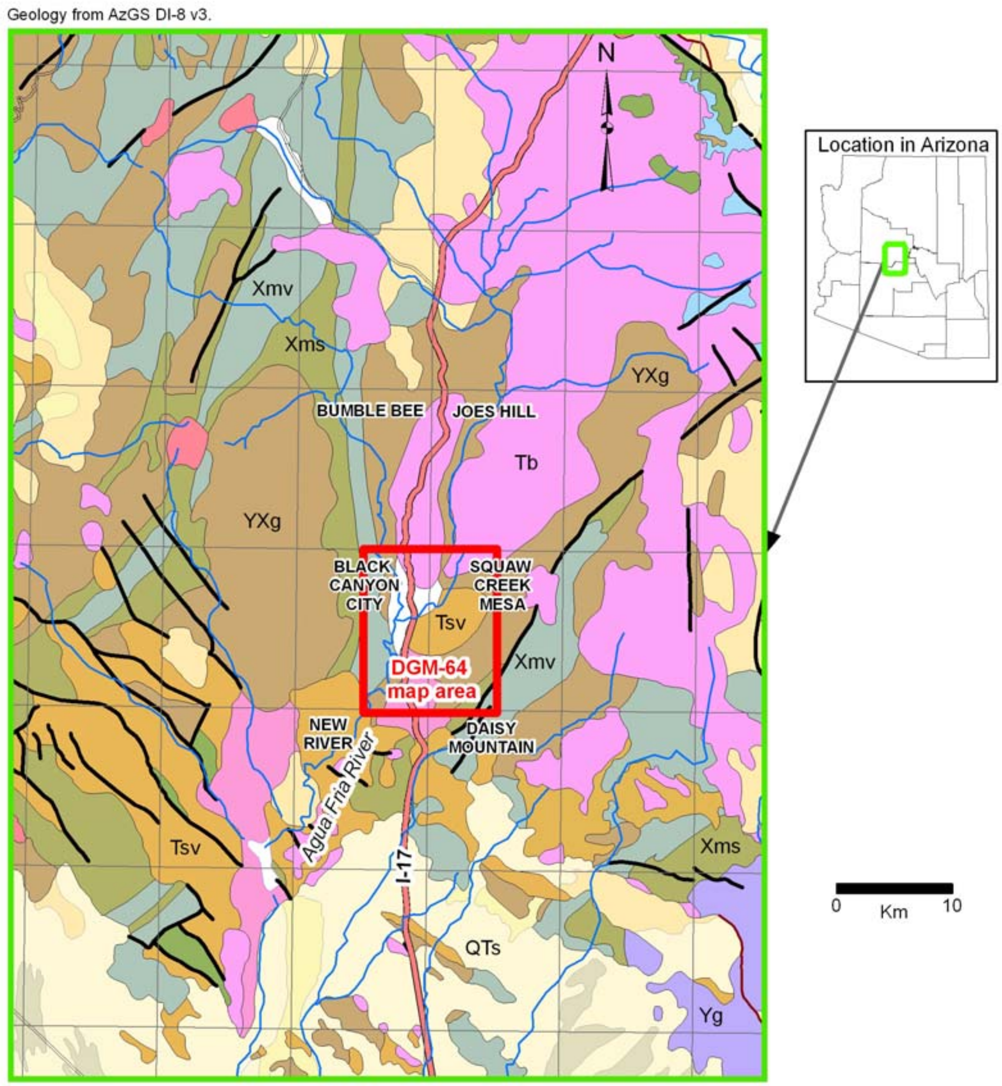
INTRODUCTION

The eastern Black Canyon City 7 ½' Quadrangle and the western Squaw Creek Mesa 7 ½' Quadrangle includes the Interstate 17 corridor where it passes through Black Canyon City and Rock Springs and continues north up the steep grade on the southwest slope of Black Mesa (Figure 1). Production of this geologic map continues the Arizona Geological Survey mapping program at the periphery of the Phoenix metropolitan area. Mapping was done under the joint State-Federal STATEMAP program, as specified in the National Geologic Mapping Act of 1992, and was jointly funded by the Arizona Geological Survey and the U.S. Geological Survey under STATEMAP Program Contract award number 06HQAG0051. Mapping was compiled digitally using ESRI ArcGIS software.

ACKNOWLEDGEMENTS

Mapping was done during the winter/spring of 2006/2007 during the final stages of Robert Leighty’s compilation of many years of work in which he summarizes and expands on aspects of his Ph.D. research (Leighty, 1997) in the Transition Zone of central Arizona that impact the Black Canyon City area. Robert kindly shared the results of his manuscript and map (Leighty, 2007) with us, and this allowed us to focus on aspects of the geology that were not addressed in detail in his studies; specifically details of Proterozoic and Cenozoic structure, and stratigraphy of the sedimentary portion of the Chalk Canyon Formation. Steve Maynard and Bruce Bryant also shared information regarding work they had done in Moore Gulch and southerly adjacent portions of the study area. The exhaustive research done by these workers and their bibliographies, including several important unpublished and unavailable documents, was of inestimable value to us.



QTs - Quaternary and upper Tertiary sedimentary units
Tb - Miocene and Pliocene basalt
Tsv - Oligo-Miocene sedimentary and volcanic rocks
TKg - Early Tertiary and late Cretaceous (Laramide) granitic rocks
Yg - Mesoproterozoic granitic rocks
YXg - Proterozoic granitic rocks, undivided
Xms - Paleoproterozoic metasedimentary rocks
Xmv - Paleoproterozoic metavolcanic rocks

Figure 1. Geologic map of the Black Canyon City area, central Arizona, showing 7.5' quadrangles and DGM map area.

Figure 1. Location of map area, showing regional geology (from Richard et al., 2000).

SURFICIAL MAP UNIT DESCRIPTIONS

d **Man made deposits (<~50 yrs)** – Disturbed areas consisting mostly of road and bridge embankments.

River Deposits

Qy_cr **Late Holocene active river channel deposits (<~100 yrs) -** This unit includes active, open channel deposits of the Agua Fria River, Black Canyon Creek and Squaw Creek drainages. The deposits are composed of unconsolidated, poorly sorted and well-rounded fine to coarse sand, pebbles (4-64 mm), cobbles (64-256 mm) and boulders (>256 mm). Qy_cr is generally incised between 1 and 4 m below adjacent Holocene terraces, and up to 60 m below abandoned Pleistocene terraces (Qi_1r). Channel areas are prone to deep inundation and high-velocity flow during moderate to large flood events that may result in scouring and bar deposition. Bar-and-swale topography is present on active point bars. Channel banks and cut banks are subject to undercutting and lateral erosion during flood events. The main channel generally diverges into braided channels where meanders are absent. Surfaces of this unit have little vegetation cover consisting of grasses and small shrubs, and no soil development is present. Imbrication of pebbles and cobbles is obvious and consistent with the direction of current flow.

Qy_3r **Late Holocene river terrace and point-bar deposits (<~100 yrs)** - Qy_3r exhibits flat surfaces of low-lying terraces and bar-and-swale topography in point bars. Elevations of this unit typically range between 0.5 and 1.5 m above the main channel (Qy_cr). The unit is composed of unconsolidated and moderately sorted fine to medium sand, pebbles, and cobbles. Qy_3r is prone to high-velocity flow and scouring during moderate to large flood events. This unit has little to moderate vegetation cover that consists of grasses and shrubs. Imbrication of pebbles and cobbles is obvious and consistent with the direction of current flow.

Qy_2r **Late Holocene river terrace deposits (<~1.5 ka)** - This unit consists of terraces that flank the main channel (Qy_cr). Elevations of Qy_2r typically range between 1 and 2 m above the main channel. Terrace surfaces dip very gently toward the main channel and are incised near tributary drainages. Qy_2r deposits consist of unconsolidated to weakly consolidated and well-rounded medium sand, pebbles, and cobbles. This unit is susceptible to shallow inundation and lateral erosion during large flooding events. Surfaces of Qy_2r are covered by moderately dense vegetation that consists of shrubs and some small trees. Imbrication of pebbles and cobbles is moderately exposed and consistent with the direction of current flow.

Qy_1r **Middle Holocene river terrace deposits (~1.5 to ~5.5 ka)** - Qy_1r consists of historical terraces that flank Qy_2r in some areas, but more commonly flank the main channel (Qy_cr). Elevations of this unit typically range between 1.5 and 3 m above the main channel. Terrace surfaces dip gently toward the main channel, and are composed of moderately consolidated, rounded to sub-rounded pebbles and cobbles. Soils in this unit are moderately developed and consist of silt, fine to coarse sand, and some carbonate filaments. This unit is prone to lateral bank erosion and may be subject to inundation during very large flooding events. Imbrication of pebbles and cobbles is poorly preserved on surfaces of Qy_1r, but moderately preserved in cross sectional exposures and are consistent with the direction of current flow.

Qi_3r **Late Pleistocene river terrace deposits (~10 to ~200 ka)** - Qi_3r consists of flat and beveled terraces that flank Qy_1r near the confluence of the Agua Fria River and Black Canyon Creek. Other Qi_3r deposits make up higher portions of point bar deposits within meanders of the main channel (Qy_cr). Elevations of Qi_3r range between 3 and 10 m above the main channel. Terrace deposits are typically 2 to 4 m thick and are composed of silt, fine to coarse sand, and carbonate filaments. This unit also consists of moderately consolidated and sub-rounded pebbles and cobbles. Qi_3r terrace surfaces are generally not subject to flood inundation. Imbrication of pebbles and cobbles is apparent on surfaces and in cross sectional exposures of the unit and is consistent with the direction of current flow.

Qi_2r **Middle Pleistocene river terrace deposits, younger member (~200 to ~600 ka) -** This unit consists of flat and beveled terrace remnants that commonly mantle underlying bedrock. Thicknesses of Qi_2r deposits range between 1 and 3 m. Elevations of this unit range between 15 and 30 m above the main channel (Qy_cr). It is composed of moderately consolidated, rounded to sub-rounded pebbles, and cobbles that contain moderate carbonate coating. Soils are moderately to well developed and consist of silt, sand and carbonate filaments. Reddening of clay and finer sand is present near surface soil horizons. No imbrication is apparent on surfaces of Qi_2r, but poorly preserved imbrication is exhibited in cross-sectional exposures of this unit.

Qi_1r **Middle Pleistocene river terrace deposits (~600 ka to ~1 Ma)** - Qi_1r consists of isolated terrace remnants with beveled edges. This unit commonly mantles underlying bedrock, and has thicknesses that range between 1 and 2 m. Elevations of this unit range between 50 and 60 m above the main channel (Qy_cr). It is composed of moderately to well-consolidated, rounded to sub-rounded pebbles and cobbles that contain moderate carbonate coating. Strong reddening of soils is present in this unit. Soils typically consist of silt, sand, and carbonate filaments. No imbrication is apparent on surfaces or in cross-sectional exposures of Qi_1r.

Piedmont Deposits

Qy_c **Late Holocene active stream channel deposits (<~100 yrs) -** This unit includes active, open channels of larger piedmont tributaries to the Agua Fria River (Little Squaw Creek and Moore Gulch). Qy_c is composed of unconsolidated, poorly to moderately sorted and well-rounded coarse sand, pebbles, cobbles, and boulders. It is generally incised between 0.5 and 3 m below adjacent late Holocene terraces. Channels are prone to deep inundation and high-velocity flow during moderate to large flood events that may result in scouring, lateral bank erosion, and bar deposition. Morphologies of Qy_c generally consist of a single deep channel or braided low flow channels with adjacent gravel bars. Surfaces of this unit have no to moderate vegetation cover consisting of grasses and shrubs. No soil development is present in **Qy_c**. Imbrication of pebbles and cobbles is well exposed and consistent with the direction of current flow.

Qy_3 **Late Holocene alluvium (<~1.5 ka) - Qy_3** includes channel and low terrace deposits associated with small piedmont tributary washes. Deposits of **Qy_3** consist of well- to sub-rounded, unconsolidated to weakly consolidated coarse sand, pebbles, cobbles, and boulders. Channels in this unit are typically incised between 0.5 and 2 m below adjacent Holocene terraces, and are prone to flooding during large flood events. Low to moderate vegetation cover on **Qy_3** terraces consists of shrubs and small trees. No soil development is present in channels of this unit, with little to moderate soil development present in terraces. Imbrication of pebbles and cobbles is moderately exposed and consistent with the direction of flow in channels of **Qy_3**. No imbrication is apparent on surfaces of terraces.

Qy_2 **Middle Holocene alluvium (~1.5 to ~5.5 ka)** - This unit includes abandoned channel and terrace deposits that flank small piedmont tributaries. Deposits of **Qy_2** consist of sub-rounded, weakly consolidated pebbles and cobbles. Channels in this unit are typically incised between 0.5 and 1 m below adjacent terraces. Imbrication of pebbles and cobbles is moderately exposed and consistent with the direction of flow in channels of **Qy_2**. Moderate to dense vegetation cover on **Qy_2** terraces consists of shrubs and small trees.

Qy_1 **Early Holocene alluvium (~5.5 to ~10 ka)** - **Qy_1** consists of older channel and terrace deposits that typically flank **Qy_2** deposits. Deposits of this unit consist of sub-angular, moderately consolidated pebbles and cobbles. **Qy_1** channels are incised between 0.5-1.5 m below adjacent Holocene terraces. Imbrication of pebbles and cobbles is moderately exposed in channels, but not apparent on the surfaces of terraces of this unit. Moderate to dense vegetation cover is present on the surfaces of **Qy_1** terraces, and includes large shrubs and relatively large trees.

Qi_2 **Middle to Late Pleistocene alluvium, younger member (~10 to ~600 ka)** - **Qi_2** consists of relatively flat surfaces that are typically perched on bluffs of the Chalk Canyon Formation (**Tc, Tcl, Tcs**). Elevations of this unit range between 6 and 15 m above larger tributary drainages of the Agua Fria River (Little Squaw Creek and Moore Gulch). Other deposits of **Qi_2** flank smaller tributaries of the Agua Fria River. This unit is composed of poorly to moderately consolidated, rounded to well-rounded pebbles and cobbles. Soils are moderately to well developed and typically consist of clay, sand and silt, with thick carbonate coatings on gravel clasts. Imbrication of pebbles and cobbles is not present on the surfaces of **Qi_2**, but is moderately preserved in cross-sectional exposures of the unit.

Qi_1 **Early Pleistocene alluvium (~600 ka to ~1.5 Ma)** - This unit consists of isolated, planar surfaces that are remnants of old alluvial fans. Elevations of **Qi_1** range between 30 and 60 m above major tributary drainages of the Agua Fria River (Little Squaw Creek and Moore Gulch). Other deposits of **Qi_1** flank smaller tributaries of the Agua Fria River.

This unit is composed of poorly to moderately consolidated, rounded to well-rounded pebbles and cobbles. Soils are well developed and typically consist of reddened, argillic horizons over weakly indurated calcic horizons.

Qtc **Quaternary talus and colluvium, undivided** - **Qtc** consists of unconsolidated, poorly sorted, and angular colluvial debris that is derived from adjacent bedrock. It is commonly distributed along the base of bedrock slopes and commonly grades into alluvium farther downslope.

Landslide Deposits

$Qyls_d$ **Holocene landslide deposits (less than ~10 ka)** - This unit consists of well-preserved young landslide-derived debris. It is commonly distributed on slopes of mesas that are composed of basalt-capped Chalk Canyon Formation (**Tc, Tcl, Tcs**). Rotational slides contain arcuate main and lesser head scarps, intact toreva blocks, and toes. Other **$Qyls_d$** landslides consist of poorly sorted and angular debris.

$Qyls_s$ **Holocene landslide scars (less than ~10 ka)** - This unit is shown on digital shape files accompanying this map. **$Qyls_s$** includes basal shear surface scars of landslides that have been exposed by the removal of displaced deposits. These scars are distributed on slopes of mesas that are composed of basalt-capped Chalk Canyon Formation (**Tc, Tcl, Tcs**). Small streams commonly erode headward along landslide margins and form small valleys within the landslide scars.

Qils **Pleistocene landslides (~10 ka to ~ 800 ka)** - This unit consists of relatively older landslides that are distributed along slopes of canyon walls. **Qils** debris typically includes intact toreva blocks that are bounded by arcuate main scarps, and subdued rotated blocks that have been moderately dissected by small drainages further along the axial length of the landslides. The geologic setting that favors **Qils** consists of basalt-capped Chalk Canyon Formation. Some surfaces of this unit contain younger landslides (**Qyls**) where more recent material displacement has occurred.

Qlso **Older Pleistocene landslides (>~800 ka) - Qlso** consists of old and highly degraded landslides that are distributed along slopes of canyon walls. This unit exhibits subdued and rotated toreva blocks that have been deeply dissected by small drainages. Debris of **Qlso** is commonly covered by Quaternary colluvium (**Qtc**).

BEDROCK MAP UNITS

Tcy **Younger conglomerate (Miocene) –** Cobble-boulder conglomerate capping Squaw Creek Mesa and other nearby mesas and interfluves. Outcrops are rarely exposed, and the unit is defined by distinctive sub-rounded to sub-angular clasts consisting of felsic medium- to coarse-grained granitoid, fine- to medium-grained mafic granitoid, felsic metavolcanics, and schist (New River Mts provenance). The unit is restricted, with one exception to areas east of Agua Fria, and is somewhat limited in its extent north of Squaw Creek. Where exposed, the unit consists of massive, to very thick-bedded, clast-supported, sandy matrix conglomerate. One exposure west of Agua Fria in the southwestern part of the map area is tentatively correlated with this unit, because it contains a bimodal assemblage of sub-angular schist and leucogranite clasts (Bradshaw Mts provenance), whereas younger river gravel terrace deposits in this area contain well-rounded polymict clasts, and older Chalk Canyon conglomerate has pumiceous matrix.

Ta **Hornblende trachyandesite lava (Miocene) –** Lava containing 5-25%, 2-3mm euhedral hornblende phenocrysts in a fine-grained, dark gray to lavender crystalline groundmass. The name is based on geochemical analysis by Leighty (2007) who also refers to the rock as a benmoreiite.

Tb **Basalt lava (Miocene) –** Basalt lava containing 2-10%, 0.5-3mm olivine, pyroxene, and generally subordinate plagioclase phenocrysts. The matrix ranges from vitric to highly crystalline. Flows interbedded with fine-grained facies Chalk Canyon Formation (Tcl) are commonly strongly brecciated with extensive stockwork veins of white calcite. Flows toward the top of the sequence are generally thicker, occur in amalgamated sets with little or no scoria and/or volcaniclastic sandstone interbeds, are more phenocryst-rich, and have thicker generally coarser grained crystalline matrix cores. Flows in areas where a sequence can be established are numbered Tb1, Tb2, Tb3, Tb4 (1 being oldest). Flows in areas where the sequence is not obvious are mapped as Tb. Leighty (2007) divides the series into two sequences based on subtle variations in petrography and composition, and their association or lack of association with interbedded fluvial and lacustrine sedimentary rocks; a lower, assigned to the Chalk Canyon Formation, and an upper, assigned to the Hickey Formation. Leigthy (2007) provides detailed descriptions, discussions, and multiple geochemical analyses of these rocks.

Tcl **Chalk Canyon Formation, fine-grained facies (Miocene) –** Variably calcareous shale, mudstone, and laminated siltstone, with subordinate interbeds of fine-grained, argillaceous, thin- to medium-bedded sandstone, and thin- to medium-bedded strongly silicified white carbonate. Carbonate, typically forming resistant ledges, is commonly internally laminated with abundant mudcracks, and convoluted laminae. Algal laminated stromatolitic zones are present in some areas, but not common. Mudstone intervals are generally thick-bedded, poorly exposed and light colored with zones of rhizolith bioturbation common towards the top of beds. Siltstone and fine-grained sandstone beds are locally abundant, but subordinate in this unit. This unit is generally restricted to the central part of the basin east and southeast of Black Canyon City.

Tcs **Chalk Canyon Formation, sandstone-conglomerate facies (Miocene) –** Dominantly medium- to thick-bedded conglomerate, sandstone, and pebbly sandstone. The unit commonly occurs in amalgamated sequences of clast-supported conglomerate and sandstone with trough to wedge-planar cross-stratified beds defined by pebble-cobble trains and diffuse truncation surfaces. Matrix-supported conglomerate and pebbly sandstone intervals are typically thick-bedded with poorly defined boundaries in tabular-planar sets and are prevalent to the east and northeast. Clasts range from angular to rounded and consist mostly of Proterozoic granitoid, metavolcanics, schist and quartzite, but locally abundant Cenozoic basaltic and silicic volcanic clasts are also present. In general, coarser grained more angular sequences occur around the periphery of the basin where rapid along strike changes in clast content reflect changes in the constitution of nearby Proterozoic bedrock. Sandstone and the sandy matrix of conglomerate is dominated by quartz-feldspar lithic grains derived from Proterozoic bedrock, but locally, felsic volcanic and pumiceous material dominates. Felsic pumiceous dominated matrix occurs mostly to the northwest where strata are generally very light-colored, poorly indurated, and contain up to 70% felsic pumice and volcaniclastic sand. In the south, distinctive light gray, variably vitric, moderately phenocryst-rich, hornblende-phyric dacitic lava clasts constitute up to 15% of the clasts. These clasts strongly resemble the Gavilan Peak hornblende-phyric trachydacite dome (Bryant, 1999) dated at 21.55 $\pm$ 0.5Ma (Damon et al., 1996) about 10km south of the southern edge of the map area.

Xdb **Diorite (Mesoproterozoic to Paleoproterozoic)** – Fine- to medium-grained diorite, locally weakly foliated. The diorite contains at least 35% mafics, and locally displays diabase texture. It occurs as a series of steeply dipping, north to northeast striking dikes and narrow plutons that apparently intrude strongly foliated tonalite (Xt) and schist (Xs) in the northwest part of the map area. The unit is differentiated from the larger diorite, quartz diorite (Xd) unit in the southeast corner by its more homogeneous texture, and its weak to nonexistent foliation.

Xgr **Granitoid (Paleoproterozoic)** – An elongate pod of strongly altered and sheared medium-grained granite in the northeast part of the map area.

Xlg **Leucogranite (Paleoproterozoic)** – Fine- to medium-grained leucogranite containing less than 5% biotite. Locally weakly foliated, and intimately mixed with the tonalite batholith (Xt) towards its southern outcrop limit.

Xtp **Porphyritic leucogranite (Paleoproterozoic)** – Small bodies of coarse-grained quartz and potassium feldspar porphyritic, fine-grained matrix leucogranite within the tonalite batholith (Xt) near its southern edge.

Xt **Tonalite (Paleoproterozoic)** –Medium- to coarse-grained tonalite, typically containing 10-20% altered mafic minerals (chloritized biotite and epidotized hornblende). Screens and inclusions of fine-grained diorite or metabasite form <2% of the unit. The tonalite is massive to heterogeneously foliated, grading to quartz-feldspar-sericite-chlorite schist in high-strain zones. Many of the high-strain zones coincide with concentrations of screens. The tonalite is slightly more leucocratic to the southwest (5-15% mafics) and in some areas may grade into granodiorite. To the east and northeast the tonalite becomes more mafic and grades into the tonalite to quartz diorite map unit (Xtd). The tonalite represents the southern part of the Cherry Creek batholith of Anderson (1989b) which has been dated at 1735 ± 15Ma (Anderson et al., 1971) 1740 ± 10Ma and 1750 ± 10Ma (Karlstrom et al., 1987) to the north of the map area. The tonalite corresponds to what has been called the quartz diorite of Bland in the map area, which has been dated at 1720 ± 9Ma (Bowring et al., 1986), and the tonalite of Little Squaw Creek (Anderson, 1989b; DeWitt, 1989).

Xtd **Tonalite-diorite complex (Paleoproterozoic)** – Tonalite and quartz diorite containing 10-40% mafic minerals and locally abundant enclaves or pods of diorite. Medium- to coarse-grained equigranular tonalite (like unit **Xt**) grades to more mafic tonalite and quartz diorite that typically is medium-grained and equigranular but that grades to fine-grained and plagioclase-porphyritic. The mafic-mineral content in this suite ranges from 10-40%, and is generally highest in the northeastern and northern exposures of the unit. The abundance of variably epidotized hornblende relative to chloritized biotite increases with overall mafic content. Medium-grained mesocratic hornblende quartz diorite is abundant in Little Squaw Creek near the eastern edge of the map area. Contacts between this phase and medium-grained leucocratic tonalite are marked by an abrupt decrease in hornblende content and a distinct increase in quartz content, but plagioclase crystals cross contacts and are indistinguishable on both sides. Enclaves or pods of diorite and quartz diorite of unit **Xd** are common, especially near the contact with that unit. These range from inclusions a few cm across to zones more than 100m in maximum dimension in which hornblende diorite or quartz diorite is more abundant than tonalite (some of the larger zones have been mapped separately as **Xd**). Within these zones, medium-grained tonalite forms tongue-like bodies that contain inclusions of fine-grained diorite and quartz diorite. The tongues grade locally to fine-grained plagioclase-porphyritic quartz diorite, and contacts between them and the fine-grained diorite range from sharp to indistinct. The plagioclase-porphyritic quartz diorite is interpreted as a hybrid phase produced by mixing of medium-grained tonalite and fine-grained diorite components.

Medium-grained tonalite which dominates this unit contains lenticular to tabular inclusions, a few cm to several meters across, of fine-grained hornblende quartz diorite and diorite that locally define a prominent magmatic flow foliation. The contacts typically are sharp, and the margins of the inclusions range from rounded to interdigitated with the host tonalite. Some of the inclusions are finer-grained (chilled) near their margins. Some of them contain plagioclase xenocrysts from the tonalite and resemble the hybrid plagioclase-porphyritic quartz diorite. Contacts between the tonalitic and dioritic phases become indistinct where the flow foliation is well developed. Solid-state tectonic foliation (characterized by deformed quartz, disaggregated feldspar, and preferred orientation of chlorite) is locally superimposed on the flow foliation. Tabular zones of strongly foliated tonalite grading to quartz-feldspar-sericite-chlorite schist (interpreted as protomylonitic to ultramylonitic tonalite) occur throughout unit **Xtd**.

Xd **Diorite-metabasite complex (Paleoproterozoic)** – Fine- to medium-grained hornblende diorite and quartz diorite, with minor fine-grained plagioclase-porphyritic quartz diorite and coarse-grained melanocratic hornblende diorite or gabbro. The unit locally contains up to 30% tonalite. Fine-grained to nearly aphanitic diorite displays sharp to gradational contacts with medium-grained diorite. Medium- to fine-grained tonalite forms irregularly shaped tongue-like bodies, which contain round pillow-like inclusions of diorite a few cm to >1m across. Some of the inclusions have chilled margins and some grade to medium-grained cores. Medium- to coarse-grained tonalite dikes with fine-grained leucocratic apophyses locally display intrusive contacts with the diorite. Tabular bodies up to 20m thick of foliated tonalite and quartz-feldspar-sericite-chlorite schist are common and are interpreted as deformed (protomylonitic to ultramylonitic) tonalite dikes. Diorite locally grades to chloritic schist, especially near the deformed tonalite dikes.

Xv **Felsic metavolcanics (Paleoproterozoic)** – Phenocryst-poor to moderately phenocryst-rich quartz-feldspar sericitic schist and porphyritic rhyolite to rhyodacite. Primary volcanic textures such as flow-foliation and eutaxitic foliation are preserved throughout the outcrop area, especially in the southeast. Locally, distinct compositional zonations were mapped within this unit and are shown as intraformational contacts. The felsic metavolcanic map unit is shown on both sides of the Moore Gulch fault, but it should not be assumed that these rocks are correlative.

Xs **Schist (Paleoproterozoic)** – Complexely interleaved lenses of variably quartz-porphyroblastic quartz-sericite schist, chloritic schist, and amphibolite schist, locally including zones of ferruginous chert, rusty calcareous schist and marble. Most of these were not mapped separately, but in some areas the ferruginous chert forms discrete mappable units. Zones of amphibolite schist commonly grade into relatively massive metabasite units, but in most areas, these zones are so strongly interdigitated with the quartz-sericite schist and chlorite schist that they were not mapped separately. Zones that were mapped separately are included within the diorite, quartz diorite (Xd) map unit. Quartz porphyroblastic schist within this unit, present for the most part along the eastern edge of the Black Canyon belt have been interpreted to have a felsic volcanic protolith (Jerome, 1956). Alternatively, these rocks may have been metamorphosed from a variety of hypabyssal felsic porphyritic rocks, strongly deuterically altered plutonic rocks, granule to pebbly volcaniclastic sedimentary rocks, and volcanic rocks.

Xst **Talc Schist (Paleoproterozoic)** – Talc schist lenses within the schist unit (Xs).

SURFICIAL GEOLOGY
by David E. Haddad

Introduction

The distribution of surfaces of different ages and sources in the Black Canyon City quadrangle is associated with the Agua Fria River and Quaternary landslides in the southern and northern halves of the quadrangle, respectively. The southern half of the quadrangle is dominated by the incised Agua Fria River and its tributaries (Little Squaw Creek and Moore Gulch). The Agua Fria River has incised up to 60 m into Paleoproterozoic bedrock (Xs) in the southwestern quarter of the quadrangle. The Little Squaw Creek and Moore Gulch have incised up to 20 m into Chalk Canyon Formation (Tc, Tcl, Tcs) in the southern half of the quadrangle.

The northern half of the quadrangle is dominated by Quaternary landslides (Figure 2, 3) ranging from relatively fresh Holocene landslides ($Qyls_d$) to degraded Pleistocene landslides (Qlso). Several older landslide deposits contain younger landslides, indicating that younger mass-wasting events have occurred on older landslide deposits.

Methodology

The surficial geology of the Black Canyon City quadrangle was primarily mapped using 1:24,000 Bureau of Land Management color aerial photographs that were taken in 1993. Topographic relief between adjacent alluvial surfaces and the depth of entrenchment of channels was determined by viewing the aerial photographs in stereographic projection. Elevation data from ten-meter USGS Digital Elevation Models (DEMs) were used to match recent and historic Agua Fria River, Black Canyon Creek, and Squaw Creek terraces. Unit boundaries were checked in the field, and mapping was supplemented by observations and descriptions of soils and surface morphology. The Quaternary deposits were then digitized using Digital Orthoimagery Quarter Quadrangles (DOQQs) as a base. Mapping was compiled in a GIS format and the final linework was generated from the digital data.

The physical characteristics of Quaternary alluvial surfaces (main channels, main channel terraces, floodplains, and stream terraces) evident on aerial photographs and in the field were used to differentiate their associated deposits by age. Exposures along cut banks and road cuts were used to assess soil characteristics associated with deposits of different ages and from different sources. Terraces that are less than a few thousand years old still retain clear evidence of the original depositional topography such as swales, gravel bars, and gravel imbrication. Young alluvial surfaces have little rock varnish and carbonate coating on the surfaces of their clasts, and exhibit little soil development. Very old terrace surfaces, in contrast, have been isolated from substantial fluvial deposition or reworking for hundreds of thousands of years. These surfaces are characterized by strongly developed soils with argillic horizons and cemented calcium-carbonate horizons, well-developed tributary stream networks that are entrenched 1 to 10 m below adjacent surfaces, and strongly developed varnish on surface rocks.

The ages of landslides and their associated material were divided into three categories: (1) young, Holocene-aged landslides and landslide scars ($Qyls_d$ and $Qyls_s$), (2) Middle to Late Pleistocene landslide deposits (Qils), and (3) Early Pleistocene landslide deposits (Qlso). The ages of landslides were based on their potential for failure; old, degraded landslides were considered stable relative to young, fresh landslides. This relationship coincides with the relative sizes of the landslides where multiple mass-wasting events that have amalgamated into large deposits represent old landslides, and small and isolated landslide deposits represent young landslides.

Geologic Hazards
Landslides

The geomorphology and surficial geology of the quadrangle provide clues to the extent and character of mass wasting in the Black Canyon City area and Agua Fria River canyon. Landslides and landslide scars are abundant in the northern and central thirds of the quadrangle.

The status of these landslides (active vs. inactive) has not been determined. Several unpublished survey results and field studies suggest some displacement of material within one of the landslides. However, we currently do not have conclusive evidence for this.

We note that Interstate 17 forms the boundary of an old landslide deposit (**Qils**) in the northern extent of the quadrangle. This stretch of the Interstate just north of Black Canyon City (near the exit to the towns of Bumble Bee and Crown King) is especially susceptible to mass wasting in the forms of debris flows, rotational landslides, and rock falls.

Figure 2. Example of a complex landslide east of Interstate 17 ($Qyls_d$). Flow direction is from left to right (north to south on map). The upper surfaces of the rotated slide blocks may be traced by a discrete and left-tilted (north-dipping on map) basalt lava flow.

Figure 3. Example of a landslide scar ($Qyls_s$). The displaced material was eroded by small drainages that have later incised into the exposed basal shear surface of the landslide. Landslide scars are depicted as shape files accompanying the digital version of this map.

Flooding

Substantial flood-prone areas exist along the Agua Fria River and its tributaries. The largest well-documented flood on the Agua Fria River occurred in 1919, with a peak discharge of about 85,000 cubic feet/second (Pope et al., 1998). Five subsequent floods have been greater than 40,000 cubic feet/second, most recently in 1993.

BEDROCK GEOLOGY
by Charles A. Ferguson

Introduction

The Black Canyon City area lies near the southern edge of the Transition Zone of central Arizona, which separates the Basin and Range province to the southwest from the Colorado Plateau to the northeast. The area is deeply incised by the south-flowing Agua Fria and its main tributaries, Squaw Creek and Black Canyon. Proterozoic crystalline rocks are directly overlain by essentially flat-lying Cenozoic sedimentary and volcanic rocks throughout the map area. Paleozoic and Mesozoic are absent, presumably due to erosion during Mesozoic-Cenozoic orogeny. Greenschist to amphibolite grade metamorphosed argillaceous sedimentary, volcanic and volcaniclastic rocks intruded by a tonalite- quartz diorite plutonic complex, the ~1740-1720Ma Cherry Batholith, comprise crystalline basement. Cenozoic rocks consist of a complex succession of pre- to syn-volcanic conglomerate, sandstone, mudstone, and lacustrine carbonate overlain and interleaved with basaltic lava of the Chalk Canyon (~21-17Ma) and Hickey formations (~17-14Ma). A post-volcanic conglomerate caps high-standing mesas. Extensive landslide deposits occur at the base of nearly all of the steep-sided mesas where incompetent strata of the Chalk Canyon Formation is exposed beneath thick basaltic lava flows of the Hickey Formation.

Cenozoic rocks are essentially flat-lying but cut by a pair of sinistral, northerly strike-slip fault zones. The main fault zone is overlain to the north by a huge expanse of Quaternary landslide deposits that occupy the mouth of Agua Fria Canyon. The coincident orientation of the canyon and fault zone, and uncertainty about the fault zone's younger age constraints are worthy of further investigation since it is not possible at this time to conclude that the landslides were not seismically generated.

Cenozoic
Stratigraphic units

Cenozoic volcanic and sedimentary rocks within the study area where deposited in a broad, north to northeast-trending basin referred to as the Agua Fria paleobasin (Leighty and Reynolds, 1998; Leighty, 2007). The package consists of the Chalk Canyon Formation; a conglomerate, sandstone, mudstone, carbonate unit (Tcs and Tcl) that interfingers upwards into increasingly abundant basaltic lava flows (Tb), that span the upward transition from Chalk Canyon to Hickey formations (Leighty, 1997; 2007). The basaltic flows are capped abruptly by a post-volcanic conglomerate of limited areal extent (Tcy). Based largely on geochronology in adjacent areas (Leighty, 2007), the Chalk Canyon Formation ranges in age from approximately 21-17Ma, and the Hickey Formation approximately 17-14Ma. The younger conglomerate is loosely constrained to be somewhere between approximately15-3Ma.

Chalk Canyon Formation

The southeastern and western edges of the Agua Fria paleobasin are defined by outward tapering wedges of thick-bedded to massive clast-supported and matrix-supported sub-angular to sub-rounded clast conglomerate and conglomeratic sandstone of the Chalk Canyon Formation

(Tcs). The wedges, which are interpreted as alluvial fans, are capped by olivine basalt and basaltic andesite lava flows on both sides of the basin. To the east, these flows connect with extensive flows that cap high parts of the adjacent New River Mountains (Leighty, 2007). To the southeast, a hornblende trachyandesite lava (Maynard, 1986, and Leighty, 2007) overlies a thin proximal wedge of the conglomeratic deposits (Maynard, 1986).

Clasts west of Agua Fria are dominated by muscovite-rich leucogranite, greenstone, schist, and phyllite derived from the Bradshaw Mountains and the Black Canyon schist belt, whereas those to the east are dominated by tonalite-diorite plutonics of the Cherry batholith and intermediate to felsic volcanics of the New River Mountains.

Towards the central part of the basin, alluvial fan deposits grade into axial fluvial facies of dominantly clast-supported, sub-rounded to rounded boulder-cobble-pebble conglomerate, pebbly sandstone, and sandstone (Tcs). The axial fluvial facies strata intertongue with lacustrine facies mudstone, shale, and carbonate with minor amounts of siltstone and sandstone (Tcl). These rocks occupy an ~30km^2 area just southeast of Black Canyon City that appears to be isolated from a similar succession of siliceous limestone and mudstone 12km to the southwest (Bryant, 1999). The lacustrine facies near Black Canyon City occur in three distinct successions to the west of a major strike-slip fault zone that transects the basin from south to north. To the east of the fault, only one lacustrine sequence is present and the center of its distribution is displaced to the north 3-5km from the center of the lacustrine sequences west of the fault. Sinistral strike-slip faulting is suggested.

Axial facies conglomerate contains abundant felsic to intermediate volcanic clasts. To the northwest, thick-bedded pumiceous sandstone in and around Black Canyon City that were mapped as a separate unit by Leighty (2007), contain abundant pebble trains of angular to sub-angular biotite- and plagioclase-phyric pumiceous lava and/or tuff clasts. In the south, rounded clasts of massive, hornblende-porphyritic dacitic lava make up as much as 25% of the conglomerate along lower Moore Gulch. The nearest possible source area for these clasts is about 7km to the south at Gavilan Peak, a 21.55 $\pm$ 0.5Ma hornblende trachydacite plug (Damon et al., 1996; Bryant, 1999). Another possible source is a hornblende latite plug near Cordes about 40km to the north (McKee and Anderson, 1971). Lava from both plugs strongly resemble the clasts in the Chalk Canyon conglomerate, but since resistant clasts are not present to the north of Moore Gulch it seems more likely that the source area was to the south. If so, this suggests northerly paleoflow for this part of Chalk Canyon Formation. Based on paleocurrents in the middle to upper Chalk Canyon Formation, Leighty (2007) concludes that the Agua Fria paleobasin debouched to the south, but this interpretation seems strongly influenced by a single paleocurrent locality at Black Mesa where paleocurrents are to the southeast. Everywhere else, Leighty's (2007) paleocurrents indicate only that paleoflow was towards the axis of the basin.

Although seemingly contradictory, the conflicting paleoflow indicators (southerly paleocurrents of Leighty (2007), and northerly directed clast provenance information from this study) might indicate a reversal of paleoflow during evolution of the Agua Fria paleobasin. In the nearby Cave Creek area, an older pre-volcanic conglomerate (>21Ma) was deposited by northeasterly paleoflow (Ferguson et al., 1998), and younger conglomerates were deposited in south-directed basins (Gilbert et al., 1998). The Agua Fria paleobasin may also have had a two-fold, northeasterly succeeded by southwesterly, paleoflow history. The presence of lacustrine deposits in the middle of an otherwise alluvial-dominated sequence might be evidence of drainage reorganization that accompanied the reversal.

Basaltic lava

Basaltic lavas of the study area are described petrographically, and geochemically in great detail by Leighty (1997; 2007) whose analytical studies show a consistent upward transition from medium-K alkaline basalt, basanite, and trachybasalt (Chalk Canyon Formation) to medium-K subalkaline olivine basalt and basaltic andesite (Hickey Formation). Basalts of the Chalk Canyon Formation, which are intimately interleaved with Chalk Canyon sedimentary rocks contain 2-15% olivine-plagioclase-clinopyroxene phenocrysts, whereas those of the Hickey Formation contain 5-15% phenocrysts divisible into suites that contain the following mineral assemblages: olivine, olivine-plagioclase, plagioclase-olivine-clinopyroxene, and olivine-clinopyroxene (Leighty, 2007). Petrographically, however, the basalts are indistinguishable in the field, and we found it impractical to pick a contact between the two petrochemically defined units, especially in light of the structural evidence discussed in a following section, and because of stratigraphic uncertainties discussed in detail by Leighty (2007). In general the transition corresponds to the base of thick, amalgamated cliff-forming flow sequences of Squaw Creek Mesa and Black Mesa.

Younger Conglomerate

The younger conglomerate is restricted to a northeast-southwest trending belt that transects the map area. Cropping out mostly to the southeast of Agua Fria in the eastern part of the map area, the conglomerate contains sub-rounded to well-rounded clasts of lithologies found mostly in the New River Mountains but also including some Cenozoic basaltic material. A lone exposure of a clast-supported sub-angular to sub-rounded schist and leucogranite clast conglomerate on the west side of Agua Fria is correlated with the younger conglomerate (Tcy) because it lacks pumiceous sandy matrix, a component abundantly present in conglomeratic units of the Chalk Canyon Formation in this area. Leighty (2007), who maps this lone exposure of conglomerate as part of the Chalk Canyon Formation, shows outcrops of the younger conglomerate (his Tsm) capping Williams Mesa 3km farther to the southwest, .

Structure

Strike-slip faults

Although Cenozoic strata are essentially flat-lying throughout the map area, two significant fault zones are present. The widest and longest is a fault array up to 0.5km wide that extends north-northeast from the southwest corner of the Squaw Creek Mesa quadrangle (the south-central part of this map area) towards the confluence of Squaw Creek with Agua Fria River. From here its trace is concealed, but if it extended along strike to the north it would run upstream parallel to the 2-3km wide, 300m deep Agua Fria Canyon. The canyon forms a steep-sided box filled almost entirely with Quaternary landslide deposits (with some younger alluvial units occupying the axial drainage). The fault zone has little or no obvious dip-slip offset. Cenozoic units do not obviously match across the structure either, particularly in the south where fairly thick lacustrine units (Tcl), and fairly low-lying outliers of the younger conglomerate (Tcy) occur only to the west of the fault. Subhorizontal slickenline lineations are abundant on nearly all the exposed fault surfaces, and the map pattern is suggestive of a sinistral system. Several synthetic southwest-side-down normal faults and at least one belt of northeast-striking folds grow out of the fault zone and die away from it. Stratigraphic information also indicates sinistral offset. Treating the midpoints of a pair of lacustrine facies belts on either side of fault zone as piercing points (a 5km wide belt on the west side and a 3km wide belt on the east side), results in a sinistral offset of about 3-5km. Sinsistral faults of this orientation and magnitude have been described sparingly elsewhere in the Transition Zone. For example, Conway (1976) describes an array of northeast-striking sinsitral faults with 3-4km displacement that cut older faults in Paleoproterozoic rocks of Tonto Basin and the Mazatzal Mountains.

Another north-northeast striking high-angle fault zone that displays horizontal slickenlines is recognized in the southwest corner of the map area. The fault cuts volcanic and sedimentary rocks (Tcs, Tb), but there are no indicators, kinematic or stratigaphic to indicate sense. The fault, which curves slightly in a concave to the east-southeast direction appears to displace Cenozoic rocks approximately 1km in a sinistral sense, but this is equivocal. The same fault runs parallel to a prominent set of aligned cliffs parallel to schistosity in the schist (**Xs**) along the eastern canyon wall of the Agua Fria River where it exists the map area to the south.

Timing of faulting

One fault strand near the north end of the main zone is apparently overlain by younger basalt flows indicating that it has been inactive since the middle Miocene. The main zone projects towards a high-angle fault in the New River map area to the south (Bryant, 1999) which is shown dying out farther south. The fault conceivably continues farther south along a fairly straight stretch of New River concealed by young valley alluvium towards the town of New River. The Moore Gulch fault, concealed below a wide area of Cenozoic cover to the east of New River in this area, emerges again and continues to the southwest (Bryant, 1999). Owing to the lack of precise control as to where the Moore Gulch fault connects through this country, it is entirely possible for it to be displaced up to 3km in a sinistral sense. The fault does not obviously disrupt Quaternary deposits, and since there is no definitive age relationship with the younger conglomerate (Tcy), the age of its most recent activity is poorly constrained. The question of whether or not this fault zone cuts the younger conglomerate is of critical importance, and it should be investigated further. If cut by the fault, its age (depending on how young the younger conglomerate is) might be vaulted into the neotectonic realm. This would have obvious implications regarding the possibility of linking the area’s extensive landslide deposits to seismic activity, particularly since the main area of landslides occurs along the presumed extension of the fault zone to the north.

Paleoproterozoic
Metamorphic rocks

Metamorphic rocks of two main types; schist and silicic volcanic, occur in three belts within the map area. The two largest are schist belts frequently referred to somewhat indiscriminately as shear zones (eg. Karlstrom et al., 1987; Darrach et al., 1991); a north-striking belt along the western edge of the map area is the Black Canyon belt (Anderson (1989b), and a northeast-striking belt parallel to Moore Gulch in the southeast corner is the Moore Gulch belt (Maynard, 1986). The Moore Gulch belt is faulted against the third belt which occupies the extreme southeast corner of the map area and consists of weakly cleaved silicic metavolcanics rocks that represent the western edge of a major silicic volcanic field and intrusive complex that extends 30-90km to the east-northeast (Anderson, 1989a).

Schist belts

Both schist belts contain a diverse suite of greenschist to lower amphibolite facies pelitic metasedimentary rocks, and mafic (and to a lesser degree felsic) hypabyssal-volcanic-volcaniclastic rocks. Listed in order of decreasing abundance these are; quartz-sericite-chlorite schist, massive to foliated greenstone and greenstone schist (quartz-plagioclase porphyroclastic chlorite-sericite-magnetite schist), quartz-sericite-chlorite-carbonate and/or calc-silicate schist, quartz porphyroblastic sericite-chlorite schist, ferruginous chert and/or fine-grained quartzite associated with variably calcareous quartz-sericite-chlorite schist, amphibolite, talc schist, and marble. Stratabound massive sulfides of the Kay Mine in the Black Canyon belt and the Orizaba Mine in the Moore Gulch belt are associated with the ferruginous chert, calc-silicate, and talc schist units.

The geology of the Moore Gulch schist belt is described in detail by Maynard (1986) who reports that 60% of outcrop is a quartz-plagioclase-chlorite-sericite-magnetite phylllite with abundant quartz and plagioclase porphyroclasts up to 1mm. Maynard interpreted these rocks as an arkosic wacke (his MP1 map unit). We note that rocks of this lithology are nearly as abundant in the Black Canyon belt and that in both belts they typically grade into fairly massive greenstone units best interpreted as metabasite. These rocks, in association with ferruginous chert host the Orizaba massive sulfide deposit (Maynard, 1986). Maynard’s (1986) MP2 unit, representing 20% of the Moore Gulch belt, consists of calcareous quartz wacke with abundant carbonate and ferruginous chert lenses and ribbon like bands. In thin-section these rocks contain the mineral assemblage quartz-sericite-chlorite-clinozoisite. 15% of Maynard’s (1986) outcrops consist of quartz-chlorite schist which he interpreted as a pelite or sandy pelite. The unit MS of Maynard (1986) does not include ferruginous cherts but it does include locally abundant chert and carbonate layers less than 3cm and in some areas thin-banded to laminated magnetite-stilpnomelane layers. Other rocks noted by Maynard (1986) include amphibolite (ma) with subophitic texture and hornblende up to 0.75mm interpreted as diabase dikes or basaltic flows, very sparse outcrops of coarse-grained crystalline marble (mm), and a single band of quartz phyllite (MP3) interpreted as a felsic dike.

Ferruginous chert lenses and ribbon-like outcrops (mfc) are scattered throughout the sequence, and consist of banded fine-grained quartzite and specular hematite with lesser calcite in a typical ratio of 50:30:20 and locally up to 20% magnetite associated with stilpnomelane and chlorite (Maynard, 1986). We noted a strong association of ferruginous chert with calcareous and calc-silicate schist and phyllite in both schist belts.

The Black Canyon belt consists of similar rocks, but here there is a general westerly transition from quartz and feldspar porphyroblastic schist to finer grained quartz-sericite-chlorite schist. As in the Moore Gulch belt, somewhat massive greenstone units are present throughout.

The facies associations of the rocks in the schist belts are universally interpreted as a marine turbidite and mafic volcanic and volcaniclastic sequence with locally important banded iron formation and massive sulfide depositional centers (Jerome, 1956; Winn, 1982; O’Hara, 1980; Darrach et al., 1991; Burr, 1991; Maynard, 1986; Bryant, 1999). A problematic unit is the quartz porphyroblastic schist, present in both belts but more abundantly in the Black Canyon belt (corresponding mostly to the Townsend Butte unit along the east edged of the belt (Jerome, 1956; Anderson (1989b)). These were mapped as felsic metavolcanics throughout much of the Black Canyon belt (Jerome, 1956), but they may, alternatively, represent deuterically altered hypabyssal intrusive units or strongly clay-altered quartzofeldspathic volcaniclastic sedimentary rocks. These rocks grade to the east and northeast into extensive zones of quartz-feldspar-sericite-chlorite schist that in turn grade into mylonitic and weakly foliated tonalite. We reinterpret much of the quartzofeldspathic rocks in the Black Canyon belt, that had been mapped as felsic to intermediate volcanic rocks (Jerome, 1956; Leighty, 2007) as strongly foliated, mostly mylonitic granodiorite and tonalite of the Cherry Creek batholith and related apophyses.

As noted by previous workers (Jerome, 1956; Winn, 1982; Maynard, 1986) primary sedimentary structures in the schist belts give sparse and inconsistent facing directions and are commonly nearly coincident or slightly inclined with respect to the prominent cleavage or schistosity. The various lithologies described in detail by Jerome (1956), Winn (1982), and Maynard (1986) are present and correspond approximately to where they have been mapped, but not, in our opinion, consistently enough to be compiled as part of this report. Since contacts are so poorly defined and difficult to map consistently, we conclude that an accurate portrayal of all the various lithologies described in the metamorphic belts of the map area would require a considerable effort, and this effort would be inappropriate for the scope of this project. A small, strike-perpendicular strip of these rocks were mapped in detail in the northern part of the Black Canyon schist belt so that interested readers can compare our unit boundaries with those of Jerome (1956, Winn, (1982), and Leighty (2007). Maynard's (1986) discussion regarding his doubts of how consistent his detailed mapping efforts were[1] are telling, and we believe the same could be said about the consistency of many of the boundaries between the various pelitic schist units throughout the area. In contrast to the predictions of Leighty (2007, p. 8, p. 10), we concentrated our mapping efforts on collecting structural information in terms of progressive development of ductile fabrics.

Silicic volcanic belt

The New River Mountains are cored by silicic volcanics (**Xv**) in fault contact with pelitic schist (**Xs**) in Moore Gulch in the southeast corner of the study area. The silicic volcanics are remarkably fresh, but they are deformed by fabrics similar in orientation, intensity (locally), and without apparently different metamorphic grade to those in the Moore Gulch pelitic schist belt. The age of these volcanics is not known, except that they have been correlated in a general way (Maynard, 1986; Bryant, 1999; Leighty, 2007) with volcanics of the ~1700Ma Red Rock Group (Conway et al., 1987) much farther to the east. The strong ductility contrast has lead to suggestions that the pelitic rocks were deformed prior to emplacement of these volcanics (Bryant, 1999), but we found no definitive evidence for this. Locally, the volcanics are strongly sheared and they include inliers of strongly foliated pelitic schist (Maynard, 1986; DeWitt, 1991; Bryant, 1999). The bounding fault, widely referred to as the Moore Gulch fault (Maynard, 1986; Bryant, 1999) or the Moore Gulch shear zone (eg. Karlstrom and Bowring, 1993) is steep and

[1] Maynard compared his efforts to the consistencies and inconsistencies of three different umpires calling balls and strikes in a baseball game. The first umpire said, "Some are balls and some are strikes, and I call em as I see em." The second umpire said, "Some are balls and some are strikes, and I call em as they are." The third umpire said, "Some are balls and some are strikes, and they ain't nuthin' till I call 'em."

fairly sharp with relatively narrow adjacent zones of increased fabric development, but without definitive kinematic indicators (Maynard, 1986; Bryant, 1999; this report). Although shown cutting the Cenozoic hornblende trachyandesite (Ta) in the southeast corner of this map area (Maynard, 1986), we agree with Bryant (1999) that there is no definitive evidence of Cenozoic displacement on Moore Gulch fault. Leighty (2007) shows the fault overlapped by Cenozoic Hickey Formation basalts farther northeast.

Plutonic rocks

The entire central and northeastern part of the map area is underlain by the southern part of the ~1800km^2 Cherry Creek batholith which is pre-tectonic and pre-metamorphic in this map area (Anderson, 1989b). It is dominated by massive, medium- to coarse-grained equigranular tonalite to the north that grades to the south into a tonalite-diorite, and diorite complex that is in fault and/or shear zone contact with Moore Gulch schist belt rocks to the south. To the southwest, it grades into an irregular, interdigitated leucogranite complex near its intrusive contact into a complex sequence of interleaved metavolcanic rocks similar to the silicic volcanic rocks of the southeastern corner of the map area, and metasedimentary rocks similar to those in both of the schist belts. The plutonic complex as a whole exposes deeper levels to the north, consistent with the regional post-metamorphic tilting of the area indicated by the general southwesterly decrease in metamorphic grade in both schist belt. The diorite, quartz diorite and tonalite in the Little Squaw Creek area (units **Xd** and **Xtd**) exhibit evidence for multiple intrusion and commingling of different magmatic phases. Evidence includes mutually intrusive relationships between tonalite and diorite, a magmatic flow foliation involving tonalitic and dioritic components, and a hybrid quartz diorite phase. So, although the complex clearly intrudes silicic and intermediate volcanic rocks in some areas along its southern boundary, internal relationships in the mafic complex to the east (Xtd, and Xd) indicate that parts of it also intrude the tonalite.

Considering these mutually intrusive relationships within the diorite, and the mutually intrusive relationships between diorite and tonalite described above, it is concluded that emplacement of tonalitic and dioritic magmas overlapped in time. This interpretation is consistent with the locally prominent flow foliation that involves both phases. Where the flow foliation is well developed, contacts between the tonalitic and dioritic phases become indistinct.

Structure

Both schist belts in the study area are frequently referred to as shear zones (ie. Karlstrom and Bowring, 1987; Darrach et al., 1991). In reality, both belts are composed of phyllite and schist foliated to a degree that is typical of other greenschist to amphibolite grade metasedimentary belts throughout the world. Both belts are locally highly strained including relatively narrow, discontinuous shear zones that cut across the regional schistose fabric at an angle of about 15-25 degrees. In each case the asymmetry matches the overall asymmetry of minor folds in each belt; counterclockwise or sinistral in the Black Canyon belt, and clockwise or dextral in the Moore Gulch belt.

Cleavage, schistosity, mylonite, and axial planar fabric elements

Tectonic fabric(s) in the schist and silicic volcanic belts consist(s) of at least one cleavage, commonly two, and rarely three, typically with the oldest being the most prominent and with the younger fabrics expressed as a variety of crenulation cleavages, spaced disjunct, kink-fold axial planar fabrics, and shear bands. Associated lineations, representing complexly overprinting intersection, crenulation, stretching, and mineral lineations mostly plunge moderately to steeply to the southwest. The study area was mapped by 5 different geologists who, as expected, described the various complex fabrics and the interactions of the fabrics in different ways. For this reason fabric elements were categorized first with respect to relative age at each field station, and secondly with respect to the kind of fabric element that was observed. One geologist's schistosity might be equivalent to another's cleavage, and yet another's close disjunct cleavage. Likewise, linear elements are named inconsistently throughout the map (in many cases, mineral lineation of some of the mappers equates with intersection lineations of others), but the common denominator is that all fabrics are classified according to age relative to each other. In instances where multiple fabrics could not be differentiated with respect to relative age, they were classified simply as "unknown". The only planar fabric element that was consistently represented as a distinct type was mylonite. The hierarchy of fabric elements as depicted on the map (Sheet 1) should not be considered regionally or even locally consistent (ie. first generation fabrics in one area are not necessarily equivalent to first generation fabrics anywhere else).

Where bedding and/or compositional layering is present, close, tight to isoclinal, and to lesser degree, open folds are expressed as asymmetric structures that consistently climb towards an anticlinal culmination to the southwest (ie. s-folds in the Moore Gulch belt, z-folds in the Black Canyon belt). Likewise, second generation planar elements consistently cross-cut older fabric elements with more southwesterly strikes in the Black Canyon belt, and more southerly strikes in the Moore Gulch belt.

Mylonitic fabrics in both belts are roughly parallel to other planar fabric elements. In both belts they are concentrated near the contact zone between the tonalite batholith (Xt) and mafic complex (Xd). Mylonitic fabrics, where recognized, are always the oldest element at any individual field station. In both belts they are cut either by younger shear bands, and/or assymetric axial planar cleavage that is consistently more southwesterly striking in the Black Canyon belt, and more southerly striking in the Moore Gulch belt.

The pelitic schist belt in Moore Gulch (Xs) is bounded to the north by a mafic-dominated, variably deformed schist belt (Xd, Xv) interpreted as a volcanic-hypabyssal complex that is in turn complexely interfoliated and interleaved with the tonalite (Xt, Xtd) farther north. All of these rocks are sheared, but the contact between the mafic schist and the pelitic schist is a particularly intense mylonitic shear zone. Throughout most of the map area, this zone is a discrete strand shown as a fault on the map, but to the northeast and southwest it splays into zones up to 100m wide. Stretching lineations are dominantly northeast-plunging in the northeast and southwest-plunging in the southwest.

Discrete shear zones of the type mapped in Moore Gulch were not recognized in the Black Canyon belt (in agreement with Jerome, 1956), although there are abundant references in the literature of a major shear zone and/or crustal boundary within these rocks (Burr, 1991; Darrach et al., 1991; Leighty et al., 1991; Karlstrom and Bowring, 1987.) Intstead, the contact zone between the schist and the tonalite is a widely distributed high-strain zone that itself appears to define the trace of a map-scale z-fold. Mylonitic fabrics within the tonalite are cut by consistently more southwesterly striking shear bands (parallel to the axial plane of the supposed z-fold). Within the schist belt, minor folds, bedding-cleavage, and second generation-first generation ductile fabric relationships are all predominantly counter-clockwise. The structures are mirror-image (a la Anderson, 1989b) to structures in the Moore Gulch belt (s-folds, and clockwise asymmetric fabric relationships). The interpretation of the Black Canyon belt as the attenuated limb of a major antiform (O'Hara, 1980) seems very reasonable with the Moore Gulch belt representing the opposite limb.

Timing

Deformation was accomplished during a narrow time interval between emplacement of the area's two main plutonic complexes. The older is the 1740-1720Ma (Anderson et al., 1971; Bowring et al., 1986) pre-kinematic tonalite batholith (Xt, Xd, Xtd) that intruded the schist and volcanic belts apparently from below, since it now occupies the central axial core of the structure. The syn- to post-tectonic, leucocratic 1699Ma Crazy Basin Monzogranite[2] intrudes the western edge of the Black Canyon belt just to the west of the map area (Leighty, 2007).

Discussion

The tectonic-stratigraphic relationship of the Moore Gulch and Black Canyon schist belts to the southeastern silicic volcanic and magmatic belt has been debated heatedly for many years. Maynard (1986) concluded that the silicic volcanics are younger because their tectonic fabric elements are relatively simple and apparently singular in origin, whereas Moore Gulch Rocks are multiply deformed with complex patterns of overprinted fabrics. In this regard the rocks are markedly different in at least two major ways, and this lead many workers to suggest Moore Gulch fault is a major terrane boundary (refs). Maynard (1986) recognized it as a major structure, but argued instead that it was a southeast-side-down normal fault related to formation of the major volcanic-plutonic field to the east. DeWitt (1991) shows the Moore Gulch dying out to the southwest and observed that there are areas of thick argillaceous siliciclastic rocks (that were also recognized and discussed by Maynard, 1986) within the volcanic field that are complexly deformed in ways similar to the rocks of the Moore Gulch belt. In this view the rocks of the two belts share a common deformational history and may have been juxtaposed throughout their histories. Bryant (1999) mapped the Moore Gulch fault continuously to the southwest where it is finally concealed by Cenozoic cover. Supracrustal rocks south of the Moore Gulch fault are considered by Bryant (1999) to be northwest-facing, and apparently contradicts interpretations that rocks in the Moore Gulch belt are southeast-facing (Maynard, 1986). However, since the two areas are bounded by the fault, and since there is an intermediate zone just north of New River where rocks face northwest and southeast in roughly equal

[2] All reported dates of this pluton, ranging from 1680 to 1700Ma, are in abstracts (Blacet et al., 1971; Bowring et al., 1986), references to oral presentations (Silver, 1970), or unpublished data referred to in journal articles (Karlstrom et al., 1987). In nearly all cases, the citations, if given at all, are either inaccurate, incomplete, or have nothing to do with this pluton.

proportions based on a superficial interpretation of Bryant's (1999) map[3], this does not seem to be a problem.

Our observation and conclusion is that the Black Canyon and Moore Gulch schist belts contain the same kinds of rocks in roughly the same proportions, at similar metamorphic grade(s), and that they are structurally deformed in a systematic way that strongly suggests they are the opposing limbs of a regional southwest-plunging antiform. Multiple fabrics are interpreted as the product of progressive deformation (eg. Anderson, 1989b) with progressively steeper lineations reflecting attenuation of the fold limbs during tightening of the structure (eg. O'Hara, 1980). Some degree of post-metamorphic south or southwesterly tilting, possibly related to progressive fold development and consistent with the southwesterly plunge of the structure, is indicated since regional metamorphic grade (independent of the contact aureole of the Crazy Basin batholith) increases systematically to the north from lower greenschist phyllite-slates just south of the Moore Gulch - Agua Fria River confluence to amphibolite facies coarse-grained biotite-garnet schist within the Black Canyon belt. Similar increases in grain size of greenschist facies rocks in the Moore Gulch belt to the north are also observed.

Mylonitic shear zones are present in both schist belts along the contact between "underlying" plutonic rocks of the Cherry Creek batholith and the schist. The shear zones are overprinted by mirror-image asymmetric ductile fabrics; clockwise in the Moore Gulch belt, and counter-clockwise in the Black Canyon belt suggesting that the shear zones may have been folded as part of a structural multilayer consisting of plutonics overlain by supracrustals. If so, whether or not this was part of the progressive development of structures during a single orogenic episode (ie. a thrust contact folded during continued convergence), or completely unrelated is not and may never be known. The short (~20Ma) interval of time between emplacement of the pre-kinematic tonalite batholith and the syn- to post-kinematic leucogranite, however, suggests that a single episode was responsible (eg. Anderson, 1989b).

Mineral deposits

Two principal mineral deposits in the study area are massive sulphides hosted in pelitic schist (Xs). The Kay mineral district, located in the Shylock schist belt just west of Black Canyon City, yielded 296,000 pounds of copper, 13,000 pounds of lead, and 2,700 ounces of silver during the early part of the 20th century (Keith et al., 1983). The Orizaba Mine, located in Moore Gulch, has a long complex history described wonderfully by Maynard (1986) based on proprietary reports and personal communications with some of the key players in its development. Unofficially, the mine produced over 130,000 tons of 4-6% copper ore (Maynard, 1986) between 1917 and 1946. Unfortunately, nearly all of the reports, assays, and core have been lost or misplaced. The location of the shaft at the bottom of Moore Gulch has made it easy for water to flood the underground workings.

SUMMARY

The structural and geomorphic configuration of Proterozoic rocks in the Black Canyon City area consists of a pair of divergent, steeply-dipping schist belts (Black Canyon to the west, Moore Gulch to the southeast), each forming the inner flank of prominent ranges cored by silicic

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[3] Bryant (personal communication, 2008) cautions that many of the attitudes that were used in his structural analysis do not appear on the map.

igneous rock (Bradshaw Mts to the west, New River Mts to the southeast), and separated by a southwest-trending erosional Miocene basin, the Aqua Fria paleobasin, underlain by a strongly foliated tonalite batholith. The schist belts have been extensively studied and written about, and the protolith has universally been interpreted as subaqueous greenstone with associated turbidites interspersed with thin, but ubiquitous ferruginous chert/quartzite/carbonate intervals, and sparse massive sulphides. A wide variety of complexly interleaved lithostratigraphic elements are present in both belts (although in differing proportions) at greenschist to lower amphibolite metamorphic grade.

The tonalite forms the core of what appears to be a southwest-plunging antiform (originally proposed by O'Hara, 1980), but the hinge zone is almost entirely concealed by Miocene basin-fill. The predominate asymmetry of ductile structures; clockwise in Moore Gulch, and counter-clockwise in the Black Canyon, supports this interpretation, as does the general decrease of metamorphic grade towards the southwest. Sparse exposures of schist with interbeds of ferruginous chert just east of the supposed hinge zone just to the south of the map area display m-folds with steeply southwest-plunging intersection lineations.

The timing of Proterozoic deformation is bracketed by the tonalite which is pre-kinematic and part of the composite 1740-1720Ma (Anderson et al., 1971; Bowring et al., 1986) Cherry Springs batholith, and the syn-to post-kinematic, 2-mica ~1700MaCrazy Basin monzogranite.

Cenozoic sinistral strike-slip faults and fault zones, oriented roughly parallel to Proterozoic ductile fabrics have displacements on the order of several kilometers. The lack of a younger age constraint for this faulting should be considered when evaluating geologic hazards such as landslide deposits in this area. Structural analyses of Proterozoic rocks should be especially careful to consider the possibility of Cenozoic overprint, which has been largely dismissed in this area.

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