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INTRODUCTION

The Snake Range, located in east central Nevada (Figure 1) is one of the archetypical examples of a metamorphic core complex, where large-scale crustal extension associated with slip on a presently low-angle “detachment” fault (the Northern Snake Range Décollement or NSRD) has juxtaposed mid-crustal, highly strained and metamorphosed rocks in the footwall against imbricately normal faulted-supracrustal rocks in the hanging wall. The Snake Range has played a central role in our understanding of extensional tectonics (e.g. Wernicke, 1981; Miller et al., 1983; Bartley and Wernicke, 1984; Gans et al., 1985 and many others), and yet many fundamental questions about the tectonic and structural development of this feature remain largely unanswered. In particular, the relationship between plutonism, metamorphism, and penetrative strain in the footwall of this complex and the exhumation and slip on the bounding detachment fault remain controversial. The goal of this project was to provide new constraints on the structural and tectonic development of the core complex by combining structural field mapping, strain analyses, and microstructural studies together with U-Pb geochronology and $^{40}$Ar/$^{39}$Ar thermochronology. Our study focused on the lower plate of the core complex and examined spatial variations in the temperatures, magnitude, timing, and kinematics of penetrative strain, the emplacement ages of lower plate intrusions, and the exhumation (cooling) history of metasedimentary and plutonic rocks of the football.

BACKGROUND

The northern Snake Range is an 80 km-long by 25 km-wide range in the northern Basin and Range province. The most prominent structural feature of the range is the northern Snake Range Décollement (NSRD),
a low-angle fault that juxtaposes an upper plate of complexly normal-faulted Paleozoic and Tertiary strata against a footwall of highly strained metasedimentary and igneous rocks (Figure 2). Miogeoclinal strata in the footwall of the NSRD vary in age from late Precambrian to Ordovician and were deeply buried and metamorphosed to amphibolite facies during the late Cretaceous (Miller et al., 1988, Cooper et al., 2010). The footwall is relatively unfaulted but records a complex history of ductile deformation, metamorphism, and intrusion (Lee et al., 1987; Miller et al, 1988). The hanging wall or upper plate of the NSRD includes Middle Cambrian to Permian miogeoclinal rocks and Tertiary sedimentary and volcanic rocks. In striking contrast to the lower plate, these rocks are little metamorphosed but highly faulted and tilted by multiple generations of normal faults (Gans and Miller, 1983). The NSRD defines a north-trending asymmetric dome with ~ 5000 feet (1.5 km) of structural relief. 

The position of the Snake Range in the hinterland of the Cretaceous Sevier orogenic belt (Fig. 1) led Misch (1960) and later workers to relate the low-angle “décollement faulting” in the range to Mesozoic thin-skinned thrust faulting farther east. The first detailed geologic studies in the range by Miller et al. (1983) and Gans and Miller (1983) suggested that the main structural features were instead extensional in origin and Cenozoic in age. Based on stratigraphic and structural relationships, they proposed that the NSRD originated as a sub-horizontal ductile-brittle transition zone between a brittlely extending upper plate and a ductilely stretching lower plate – an interpretation that was challenged by Bartley and Wernicke (1984), who interpreted the structure as a major low-angle normal fault with 10s of km of slip. 

Subsequent studies have expanded the geologic mapping and utilized structural analyses, seismic reflection profiling, metamorphic petrology,
geochronology and thermochronology in further efforts to shed light on the origin of the NSRD, as well as on the age(s) and tectonic significance of lower plate metamorphic fabrics and its geometric and kinematic relationship to the NSRD (e.g. Rowles, 1982; Gans and Miller, 1983; Grier, 1983; Miller et al., 1983; Gans et al., 1985; Lee and others, 1987; Miller et al., 1989; Gans et al., 1989; Lee and Sutter, 1991; Lee, 1995; Gans et al., 1999a and b; Miller et al. 1999a, b, and c; Lee et al., 1999a, b, and c; Cooper et al., 2010). These studies have demonstrated a number of key relationships.

Lower plate metasedimentary rocks consist of poly–metamorphosed late Precambrian to Lower Cambrian quartzites and pelites and Middle Cambrian to Ordovician marble. U-Pb dating has identified Jurassic and Cretaceous granitic plutons and Tertiary dike swarms that locally intrude lower plate units. Lower to upper greenschist-facies retrograde metamorphism and deformation of Paleocene (?) to Miocene age strongly affected much of the lower plate, causing retrogression of older peak-metamorphic assemblages. This retrograde event was accompanied by an intense penetrative strain, resulting in a subhorizontal, bedding-parallel mylonitic foliation and a WNW–trending lineation. The geometry and kinematics of this footwall strain and what relationship (if any) it has to the evolution of the NSRD were the primary focus of our multidisciplinary study.

LOWER PLATE STRAIN

A number of student projects focused on better understanding the geometry, kinematics, magnitude, and temperature conditions of lower plate strain. Four projects investigated strain conditions in footwall quartzite units across the range. Jory Lerback and Jordan Elmiger both examined strain in quartzite units in Hendry’s Creek using petrographic and electron backscatter diffraction (EBSD) studies. Jory examined vertical strain gradients within quartzite units beneath the NSRD. Her work found that strain decreases in the footwall beneath the NSRD from X/Z values >>10 near the top of the footwall to values <4 in the deepest structural levels. Conditions of deformation also appear to increase downwards in the footwall. Jordan studied east-west gradients within the Prospect Mountain quartzite. His work documents a clear top-east sense of shear across the footwall, a gradual rotation of stretching lineations from N50W to S80E from west to east, and an increase in strain magnitude towards the east (confirming work by Lee, 1987?).

Michael Kenney examined quartzite units in the northern footwall (Smith Creek area) and found that deformation mechanisms were dominated by sub-grain rotation (SGR) and grain boundary migration (GBM), suggesting deformation temperatures >400°C and likely 450-550°C. Quartz lattice preferred orientation (LPO) fabrics suggest a dominance of prism <a> and rhomb <a> slip, supporting upper greenschist to lower amphibolite grade conditions during deformation. Similar results were found by Evan Monroe, who focused on deformation in plutonic rocks in the southern part of the range (Silver Creek area).

Casey Portela investigated marble mylonites across the range using a combination of petrographic and EBSD analyses as well as applying the calcite-dolomite thermometer. In contrast to the quartzite units, Casey’s work revealed much greater complexity in the kinematics of the marble, as both top-east and top-west shear were evidence (see also Cooper et al., 2010). This is likely due to highly heterogeneous strain produced by flow around large dolomitic boudins. Calcite-dolomite thermometry results may indicate somewhat lower temperatures of deformation in the marbles (~350-450°C) compared to the quartzite mylonites.

TIMING OF MYLONITIC DEFORMATION

Our work on the temperatures of deformation in the mylonitic shear zone, when combined with new and existing thermochronology, provide important constrains on the timing of mylonitic deformation and whether it is related to Miocene slip on the NSRD.

Joe Wilch analyzed muscovite and K-feldspar Ar/39Ar thermochronologic data originally presented by Gans et al. (2011 and unpublished work). Multiple diffusion domain (MDD) modeling of K-feldspar results suggest a period of rapid footwall cooling beginning at ca. 20 Ma and continuing until at least 15 Ma at cooled the footwall from ~300 °C to <100 °C. These results match well with prior fission track results (Miller et al., 1999) and document rapid top-east (normal) slip on
the NSRD. The $^{40}$Ar/$^{39}$Ar results document a ~150-
200 °C temperature difference between the crest and
eastern flank of the range at ca. 20 Ma, suggesting
that the NSRD initiated at a significantly steeper dip.
Joe’s analysis of muscovite $^{40}$Ar/$^{39}$Ar results indicate
complexity in the age spectrum of most samples,
likely as a result of mixtures of different compositions
of muscovite in the samples. However, the generally
older ages (>20 Ma) given by muscovite and the high
temperature steps of K-feldspar samples suggest the
entire range had cooled below 400°C well before 20
Ma (largely by 30-50 Ma). Given the petrofabric work
described in the previous section, this result suggests
that most, if not all, of the footwall strain occurred
prior to the Miocene and is therefore unrelated to
Miocene slip on the NSRD. It is possible that the
geometric similarity of the NSRD to the underlying
footwall shear zone is a result of the NSRD reactivating
the older mylonitic shear zone rather than the features
being coeval.

AGE AND PETROLOGY OF LOWER PLATE
PLUTONS

Several student projects focused on refining our
understanding of the character, petrology, and age of
plutonic units in the lower plate.

Michael Kenney conducted U-Pb zircon
geochronology by LA-ICPMS in the central/northern
part of the range in Smith Creek. His work on the
Horse Canyon Orthogniess, previously dated at
~100±8 Ma (Gans et al., 1999; Miller et al., 1988),
produced a much more precise age of 100.9–101.6
± 0.5 Ma. He also dated several leucogranite bodies
in the area, with concordant U-Pb ages that are
dominantly 84–85 Ma, with one yielding a concordant
age of 76.1 ± 1.5 Ma. These results are also consistent
with previous geochronology (Miller et al., 1988;
Gans et al., 1999) but greatly improve the precision.
The younger age suggests a more protracted phase of
leucogranite generation than previously recognized.

Evan Monroe conducted U-Pb zircon geochronology
by LA-ICPMS on plutonic units in the southern part
of the Northern Snake Range. Previous work on
these units (Miller, et al., 1988) suggests that both
the Silver Creek and Old Mans Canyon plutons are
approximately 160 Ma and subsequent TIMS dating
(J.E. Wright, unpub. data, referenced in Miller et al.,
1999) concluded both plutons were emplaced 155±5
Ma. Evan’s work precisely dates the Old Man Canyon
pluton at 160 ± 1 Ma and indicates that the wide
range of compositional variations in this mapped unit
are all the same age. Evan also found that the Silver
Creek pluton is modestly but distinctly younger and
was emplaced at 154-152 Ma. Evan’s work on dikes
in the Silver Creek provide important constraints
on the timing of fabric formation. A ~35 Ma dike
cuts the main sub–horizontal foliation in the Silver
Creek granite, but the dike has a well developed fabric
internally – perhaps indicating that mylonitization
was still ongoing at this time, although the fabric in
the dike is quite discordant to the host rock fabric,
suggesting the dike fabric may be highly localized and
younger than the main fabric here. A 23 Ma rhyolite
dike cuts sharply across the mylonitic fabric in Silver
Creek and is entirely undeformed, which provides a
firm minimum age for the fabrics in this area. This
interpretation is consistent with our results combining
the petrofabrics and thermochronology that much of
the footwall fabrics may pre-date Miocene slip and
exhumation on the NSRD.

CONCLUSIONS

A variety of evidence supports the conclusion that the
lower plate fabrics in the Snake Range core complex at
least partly (and perhaps mostly) pre-date Miocene slip
and exhumation on the brittle NSRD (ca. 20 Ma). The
geometric similarities between the ductile fabrics and
brittle fault may be a result of brittle reactivation of the
older ductile shear zone. Most models of core complex
formation view the ductile shear zone as the mid-
crustal manifestation of the brittle detachment fault.
However, our results call into question that model. The
exact timing of this older ductile footwall deformation
remains unclear, as does its tectonic significance, although given its similarity to the geometry and kinematics of Miocene slip on the NSRD, these ductile fabrics may document a pre-Miocene extensional event. At the inception of rapid Miocene slip on the NSRD, the eastern flank of the range was 150-200°C hotter than the crest of the range, suggesting the presently low-angle NSRD initiated at a steeper dip rather than initiating at a mechanically unfavorable shallow dip.

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