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LATE CRETACEOUS TECTONIC BURIAL AND CENOZOIC TECTONIC EXHUMATION OF THE EAST HUMBOLDT-WOOD HILLS-PEQUOP CRUSTAL SECTION, ELKO COUNTY, NEVADA

JEFFREY M. RAHL, Washington and Lee University
ALLEN J. MCGREW, The University of Dayton

INTRODUCTION

The East Humboldt Range (EHR) – Wood Hills (WH) – Pequop Mountains (PM) crustal section of Elko County, Nevada provides an exceptional window into crustal tectonics during both contractional tectonic burial and extensional tectonic exhumation (Figs. 1 and 2). A transect through these ranges exposes a remarkably complete albeit diachronously dissected cross-section extending from paleodepths > 35 km to the near-surface, comprised mainly of a column of Lower Cambrian to Triassic "miogeoclinal" strata with a total thickness of at least 12 km (Camilleri and Chamberlain, 1997). Thrust faults active during the Late Cretaceous to Early Eocene Sevier orogenic event resulted in deep burial of these units, with peak metamorphism in the Late Cretaceous (approximately 75-90 Ma) (McGrew et al., 2000; Hallett and Spear, 2014, 2015). Metamorphic grade increases progressively toward the WNW, from unmetamorphosed rocks as young as Triassic in the upper levels of the PM to conditions as great as ≥750°C, 1000 MPa in the northern EHR (McGrew et al., 2000; Hallett and Spear, 2014). Regional extension in the Cenozoic has thinned the crust, with still-active normal faults creating the iconic Basin and Range topography. In the northern Great Basin, this extension has also exposed several metamorphic core complexes, including the Snake Range, the Raft River-Albion-Grouse Creek Ranges, and the Ruby Mountains (RM) - EHR (Sullivan and Snoke, 2007). Unique among Cordilleran core complexes, the ~1 km thick mylonitic zone and underlying core of the RM-EHR have been dissected by a younger, antithetic high-angle normal fault system that provides exceptionally deep exposures through the metamorphic core. Together, the EHR-WH-PM crustal section presents an extraordinary opportunity to examine tectonic processes at a variety of crustal levels during both regional contraction and extension.

Decades of study have provided a wealth of knowledge about the structural and metamorphic history of RM-EHR core complex, and provide a strong foundation to support investigations into new tectonic questions. The EHR-WH-PM crustal section is located in the western hinterland of the east-vergent Sevier fold-thrust belt. This late Mesozoic retro-arc system is commonly compared to the modern Subandean thrust-belt in the Bolivian Andes (e.g., DeCelles, 2004). A growing body of isotopic and geologic evidence suggests that Nevada may have been a high-elevation plateau during the Mesozoic, much like the orogenic plateau of the Altiplano that exists in South America today (Snell et al., 2014; Long et al., 2015). The position of the core complex in the Sevier hinterland suggests that the rocks exposed in the WH and EHR may provide a window into the deep interior of an orogenic plateau; these rocks may therefore provide insights into the crustal processes that operate within orogenic plateaus such as the modern Altiplano.

Following the cessation of Sevier tectonism, the crust of NE Nevada transitioned to widespread extension. In our study area, mylonitization in the WNW-directed EHR shear zone deforms and therefore at least partly post-dates a suite of 29 Ma biotite monzogranitic orthogneisses, but the timing of onset of this deformation remains debated (Henry et al., 2011). Colgan and others (2010) document cooling ages

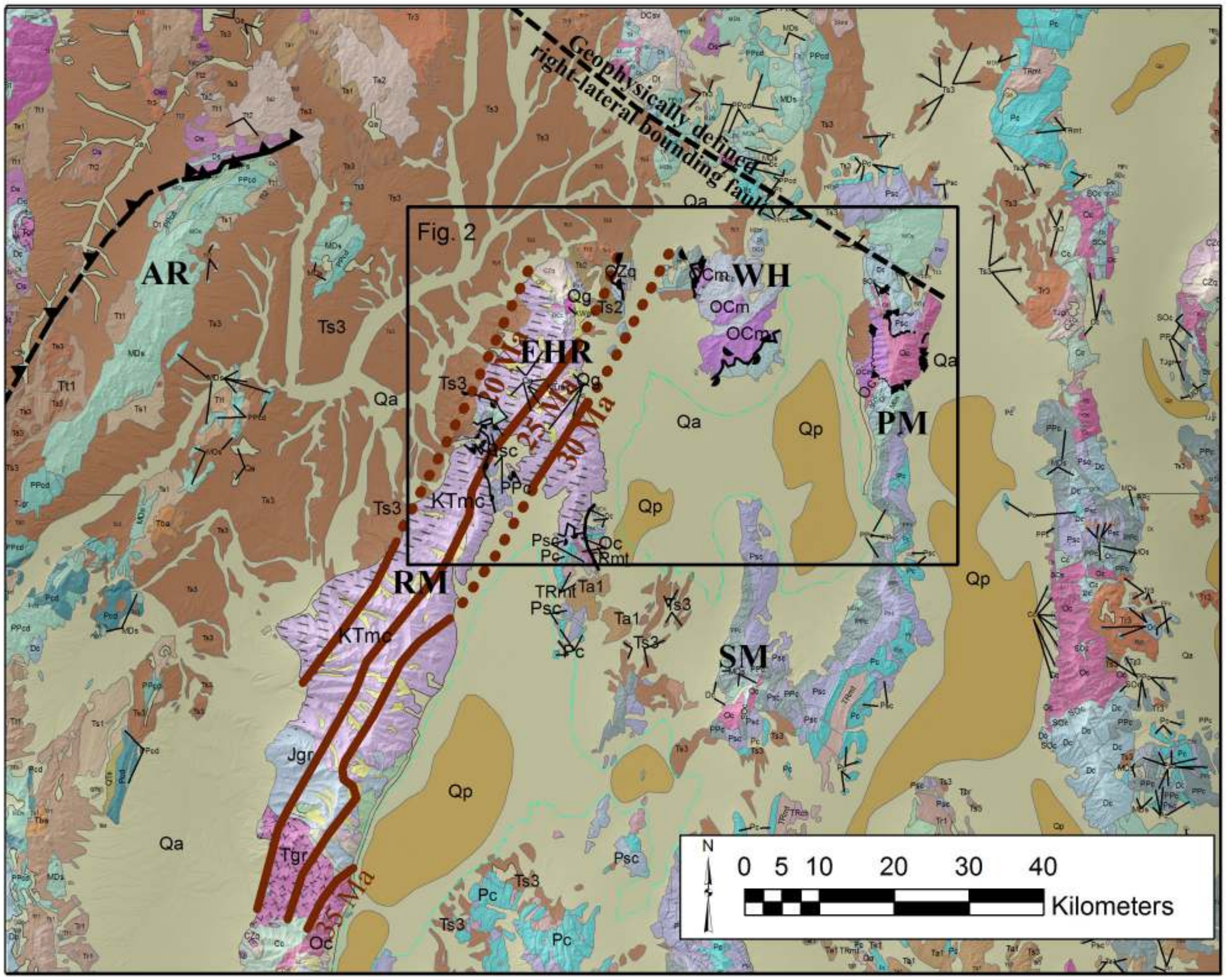

Figure 1. Regional Geologic Map illustrating the tectonic setting of the Ruby Mountains-East Humboldt Range – Wood Hills metamorphic core complex. Abbreviations: AR – Adobe Range, EHR – East Humboldt Range, RM – Ruby Mountains, WH – Wood Hills, PM – Pequop Mountains, and SM – Spruce Mountains. Box outlines approximate area of Figure 2. Rock unit abbreviations follow the state geologic map of Nevada (Stewart and Carlson, 1974), with these exceptions: XWgn indicates the Neoarchean to Paleoproterozoic gneiss complex of Angel Lake (shown as small patch of red in northern EHR); KTmc indicates the Cretaceous to Tertiary metamorphic complex of the RM-EHR metamorphic core complex, undifferentiated, and OCm, indicates the Cambrian to Ordovician marble sequence in the Wood Hills. Low-angle faults decorated with triangular teeth (Pequop Mountains and Adobe Range) indicate the trace of Mesozoic thrust faults; faults with round teeth indicate Tertiary detachment faults. Hachures indicate the extent of the WNW-directed RM-EHR mylonitic shear zone, and thick cherry brown lines labeled 35 Ma to 20 Ma extending NNE across the RM-EHR are K-Ar and 40Ar/39Ar mica cooling age "chrontours" interpreted as recording the WNW-progression of extensional unroofing. The inferred breakaway zone of the detachment system is marked by low-angle normal faults juxtaposing Permian to Triassic strata against low-grade Cambrian to Ordovician metasedimentary rocks in the northern Pequop Mountains and western Spruce Mountain. The inferred hanging wall cutoff of the detachment system is inferred to underlie the basin separating the EHR from the AR. Aeromagnetic and gravity data for the area indicate that the north end of the Tertiary metamorphic complex in the subsurface is bounded by a right-lateral fault along the line labeled. Total displacement of approximately 65 km is inferred for the northern half of the core complex of interest here; net displacements for the southern RM may be no more than 35 km and may reflect activation only after ~23 Ma (Colgan et al., 2010).

from the southern Ruby Mountains indicating that large-magnitude extension there did not begin until the early to mid-Miocene, but the onset of extension farther north remains enigmatic. McGrew and Snee (1994) suggested an Eocene age for the onset of extension in the EHR, and Rahl and others (2002) documented extension beginning as early as 44-40 Ma farther north, as part of a southward sweeping wave of coeval extension and volcanism that could have migrated through the RM-EHR area in the late Eocene to early Oligocene. In addition to the Eocene $^{40}Ar/^{39}Ar$ hornblende cooling ages reported by McGrew and

Snee (1994), limited $^{40}Ar/^{39}Ar$ mica thermochronology from the WH also suggest that exhumation began as early as the Eocene (Thorman and Snee, 1988; Gifford, 2008). In addition, geologic mapping and cross-cutting relationships with dated igneous rocks in the Pequop Mountains and Spruce Mountain (Figs. 1 and 2) suggest the onset of upper crustal normal faulting before 43 Ma and 38 Ma, respectively (Camilleri and Chamberlain, 1997; Pape et al., 2015). Documenting the detailed timing of regional extension is essential for testing models for the collapse of orogenic plateaus (e.g., Colgan and Henry, 2009).

KEY PROBLEMS AND PROJECT GOALS

Our project involved a team of seven undergraduate students and two faculty. Our research focused on several interrelated but independent project goals: 1) to document the nature of deformation and metamorphism during the creation and evolution of an orogenic plateau, at varying structural levels; 2) to investigate changes in the style and kinematics of deformation as a function of tectonic context and crustal level; 3) to explore the deformation processes active both within and beneath the mylonitic carapace in a metamorphic core complex; and 4) to better

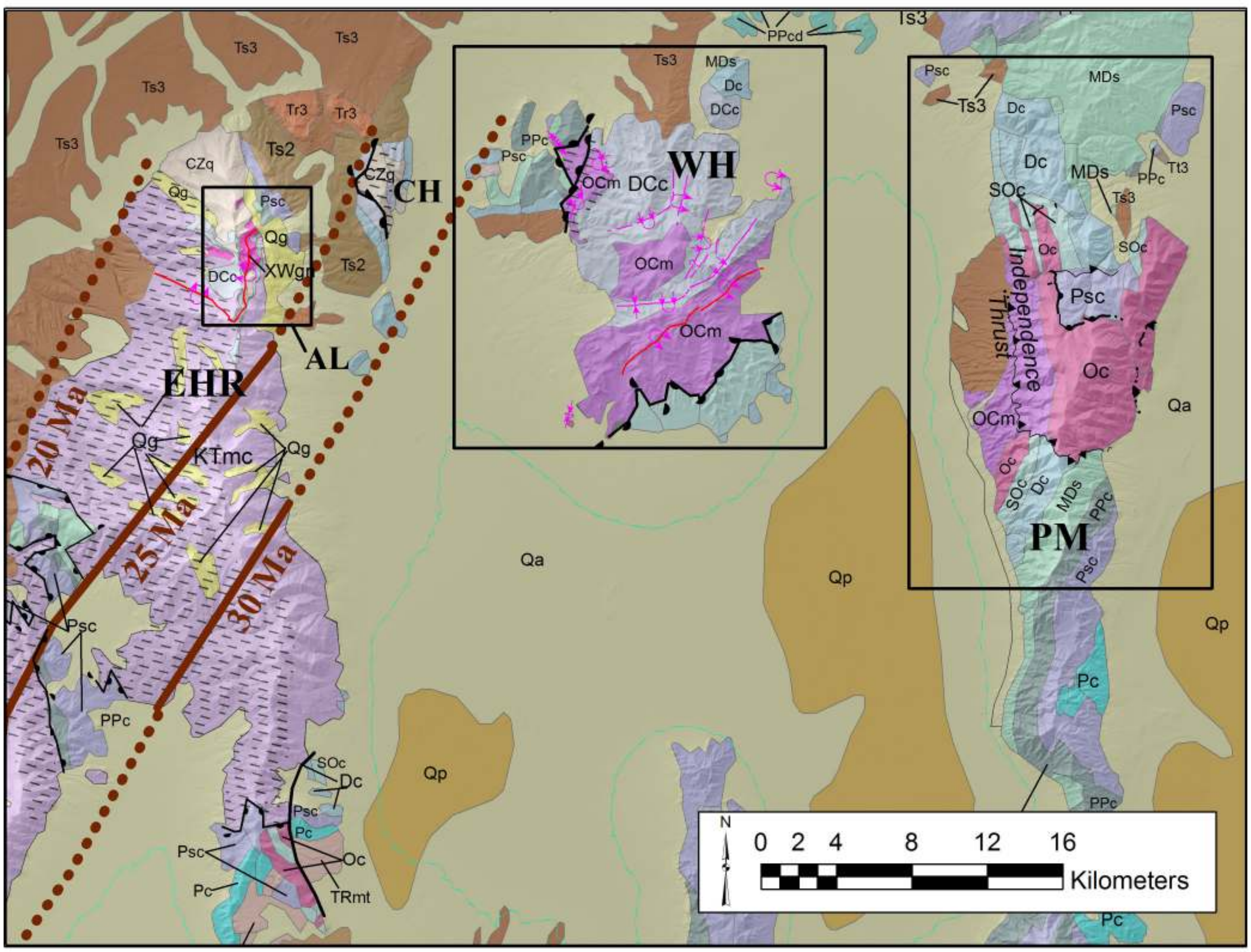

Figure 2. Generalized geologic map of the East Humboldt-Wood Hills – Pequop Mountains crustal transect showing locations of detailed study areas extending from upper crustal exposures in the Pequop Mountains across mid-crustal exposures in the Wood Hills to the deep mid-crustal levels in the northern East Humboldt Range. In addition to previously defined abbreviations, AL indicates the Angel Lake area and CH indicates Clover Hill. In addition, the position of the Independence thrust is labeled in the Pequop Mountains. Otherwise the symbology is as described for Figure 1. Note that younger, east-dipping Basin and Range normal faults drop Clover Hill relative to the EHR and the Wood Hills down relative to Clover Hill, thus exposing progressively deeper parts of the mylonitic shear zone and detachment fault system from east to west.

delineate the timing of metamorphism relative to tectonic burial and the subsequent onset of regional extension. Our research approaches included field mapping and observation, optical microscopy, crystallographic preferred orientation (CPO) analysis in quartz using electron backscatter diffraction (EBSD), calcite-dolomite exchange thermometry, zircon (U-Th)/He dating, and zircon U-Pb petrochronology using laser ablation high resolution inductively coupled plasma mass spectrometry (LA-ICP-MS).

RESEARCH PROJECTS

Processes active during Mesozoic contraction and plateau development

Joshua Latham (University of Dayton) documented deformational processes in the Pequop Mountains (Fig. 2), representing the shallowest part of the crustal section. Kinematic indicators in marble mylonite and a deformed quartz vein indicate a broadly east-directed sense of shear on the Independence Thrust. Away from the thrust fault, deformation mechanisms inferred by EBSD analysis of quartzite and calcite mostly indicate strain under low to moderate metamorphic conditions. Strain is strongly partitioned into marble tectonites rather than coexisting, only weakly deformed quartzites. Many incipiently deformed quartzites show a distinctive, low-intensity CPO characterized by alignment of the positive rhombs perpendicular to the X, Y and Z strain axes, respectively. However, at the deepest structural levels near the western foot of the range, quartzites show significantly higher strain and much higher temperature deformation mechanisms as evidenced by development of microstructures indicating recrystallization by rapid grain boundary migration, more intense CPOs, and large opening angle c-axis patterns. All of the above observations are compatible with the steep metamorphic field gradients identified by Howland (below).

Colby Howland (Union College) obtained the first quantitative estimates of metamorphic temperatures in the Pequop Mountains using calcite-dolomite exchange thermometry. His work documents an exceptionally steep metamorphic field gradient (in excess of 40-50°C/km) that suggests the possibility of a pluton at shallow depth beneath the Pequop Mountains. The timing of metamorphic equilibration is inferred to be synchronous with an U-Pb age on metamorphic sphene of 84.1 Ma reported by Camilleri and Chamberlin (1997).

Sarah Jordan (Carleton College) conducted an extensive investigation into the microstructural development of quartzites in the Wood Hills, using both optical microscopy and quartz EBSD analysis. She documented changes in the style of quartz recrystallization mechanism, consistent with progressively deeper structural levels exposed to the NW. This trend coincides with a change in strain symmetry, with an increase in the role of SE-directed shearing toward the NW. Even farther NW, the Mesozoic fabrics are overprinted by strong, NW-directed mylonitization associated with regional extension. This shear zone is inferred to represent the up-dip projection of the RM-EHR mylonitic zone.

Zoe Dilles (Scripps College) investigated the timing, style, and tectonic significance of deep-crustal deformation in the core of the Winchell Lake fold-nappe as exposed in central Angel Lake cirque in the northern EHR. In the field, she carefully mapped and documented the complex cross-cutting relationships exposed in an outcrop in the core of the Neoarchean gneiss complex of Angel Lake (McGrew and Snoke, 2015). Located in the core of the Winchell Lake fold, this locality displayed three major fold episodes as well as a diverse array or cross-cutting relationships documenting the relative ages of migmatitization, multiple phases of intrusion, and overprinting extensional shear bands. A carefully selected and field contextualized suite of amphibolites, orthogneisses, and paragneisses was analyzed in the University of California -Santa Barbara LA-ICP-MS petrochronology laboratory to obtain an array of new U-Pb zircon ages. Her work confirms the Neoarchean to Early Paleoproterozoic age of the gneiss complex and also identifies a previously poorly documented Late Paleoproterozoic metamorphic/magmatic event. Significantly, the detrital zircon suite from the paragneiss includes a population of extremely ancient early Archean grains. In addition, her work documents Late Cretaceous migmatization inferred to be coeval with tectonic burial of the northern EHR. Significantly, Late Cretaceous migmatization and peak metamorphism in the EHR broadly coincides with upper crustal shortening in the Pequop Mountains and tectonic burial of the Wood Hills (Wills, 2014).

The nature of timing of mylonitic deformation and regional extension

Gabriel Chevalier (Mt. Holyoke College) applied EBSD CPO analysis of quartzite and granitic orthogneiss to characterize transitions in kinematics and deformation mechanisms in quartz in the deep infrastructure beneath the EHR extensional shear zone. Her work documents a transition from asymmetrical Y-maximum c-axis preferred orientations to less asymmetrical large to very large opening angle crossed girdle c-axis textures commonly considered to indicate deformation under upper amphibolite to granulite facies conditions. As with the work of Plummer, development of these textures in late Oligocene granitoid orthogneiss as well as coexisting quartzites indicates that they record late Cenozoic, deep-crustal extensional flow. In addition, Chevalier investigated the relationship of quartz CPOs around the limbs of a deep-seated map-scale, isoclinal fold that has been recognized at the deepest levels of the cirque just west of Angel Lake, but it remains unclear at present whether the CPOs developed pre-, syn-, or post-folding.

Lindsey Plummer (Amherst College) applied EBSD analysis of crystallographic preferred orientations in quartzite and Oligocene granitic orthogneiss to characterize the kinematics and deformation mechanisms of the EHR mylonitic shear zone along a transect from the northwestern Wood Hills to Clover Hill to high structural levels in Angel Lake cirque (Fig. 2). Because younger antithetic normal faults cut the main shear zone and drop it down toward the East, this effectively constitutes a down-dip transect. Her work documents WNW-directed subsimple shear during mylonitic deformation across a range of steadily declining temperature conditions. Y-maximum type c-axis preferred orientations indicate that prism <a> slip dominated during amphibolite facies mylonitization whereas lower temperature CPOs are characterized by straight single girdle c-axis preferred orientations indicative of basal <a> slip.

Franklin Wolfe (Washington and Lee University) worked with Jim Metcalf (UC-Boulder) to acquire a suite of zircon (U-Th)/He data extending from the Pequop Mountains across the Wood Hills to Clover Hill. The Pequop Mountains data show early Cenozoic cooling, demonstrating that significant exhumation did not occur until after the cessation of Mesozoic contraction. A NW-SE transect of five samples through the Wood Hills documents a NW-cooling trend, consistent with exhumation during normal-sense mylonitization. Therefore, the 41 Ma age of the SE-most sample indicates that extension and related cooling began as early as the Eocene. Notably, dated samples from the NW are from samples affected by Tertiary mylonitization that occurred at temperatures in excess of 400°C; this confirms that mylonitzation was well-underway by 41 Ma.

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