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HIGH THERMAL GRADIENT IN THE UPPER PLATE OF A CORE COMPLEX, DETERMINED BY CALCITE-DOLOMITE THERMOMETRY, PEQUOP MOUNTAINS, NV

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INTRODUCTION

The Pequop Mountains (PM) in northeastern Nevada expose the structurally shallowest levels of the Ruby Mountains–East Humbolt Range (RM-EHR) metamorphic core complex. Mineral assemblages show that metamorphism in the PM progressively increase from unmetamorphosed in the east to lower amphibolite facies in the west. However, to date no quantitative thermometry has been reported for the PM. Insight into the thermal evolution and degree of metamorphism can be better defined by establishing a paleogeothermal gradient in the PM in order to enhance the overall understanding of the metamorphic core complex as well as the thermal structure of the Mesozoic crustal thickening in an orogenic plateau. Scanning Electron Microscopy (SEM) and petrographic observations combined with calcite-dolomite thermometry were used to document metamorphic temperatures in the PM and to assess the relationship of an important structure, the Independence Thrust, to the exhumation history of the core complex. The primary goal of this research is to determine the temperature conditions that the metamorphic rocks in the the PM were subjected to and to construct a thermal gradient across a transect of metamorphic rocks in the footwall of the Independence Thrust. The results suggest a steep geothermal gradient of 50 °C/km in the footwall of the Independence Thrust. This steep geothermal gradient could be the result of low pressure metamorphism from a shallow pluton under the base of the exposed stratigraphic section, that coincided with Late Cretaceous peak metamorphism.

BACKGROUND

The PM are located in the hinterland of the Sevier Orogeny, a Mesozoic episode of E-W contraction. A commonly proposed modern analogue is the thrust belt on the eastern side of the Andes. There is a growing consensus that in the Mesozoic the crust in eastern Nevada was thickened into a high-elevation plateau, the Nevadaplano, that resembled the modern Andean Puna-Altiplano (Camilleri and Chamberlain, 1997; DeCellles, 2004 and Sullivan and Snoke, 2007).
To the west of the PM, the Wood Hills and the East Humboldt Range expose progressively higher grade and structurally deeper rocks of the metamorphic core complex (Hudec, 1992; McGrew, 1992; McGrew and Snee, 1994; Camilleri and Chamberlain, 1997). The PM provide an almost continuous section of strata from the Precambrian to the Mesozoic and contain metamorphosed and unmetamorphosed carbonates and siliciclastic ranging from lower amphibolite to greenschist facies. Previous work in the area suggests contraction occurred in two phases and was followed by two phases of extension (Camilleri and Chamberlain, 1997). The onset of contraction in this area is thought to have started around 155 Ma and obtained its peak crustal thickness around 84 Ma (Sullivan and Snoke 2007; Chapman et al., 2015). Camilleri and Chamberlain (1997) reported a U-Pb age of 84 Ma from the Clifside Limestone at the base of the stratigraphic section which, is thought to record the age of peak metamorphism in the PM (Fig. 1). Mineral assemblages in the PM indicate relatively high temperatures that are thought to be the result of tectonic burial by the Windermere Thrust fault (153 to 84 Ma), which doubled the local stratigraphy and has since been eroded away (Camilleri and Chamberlain,

1997). The Independence Thrust accommodated an additional phase of contraction in the PM around 84 Ma based on a single U-Pb titanite age (Camilleri and Chamberlain, 1997). Thrusting in the hinterland of the Sevier Orogeny could be coeval with foreland thrust faulting, which would indicate that the Sevier orogeny did not form a foreland younging sequence. Another hypothesis is that thrust-faulting in the PM could be contemporaneous with the better documented thrust faulting in the Central Nevada thrust belt which has a southward strike direction. Early extension was accomplished by the Pequop Fault and is thought to have partially exhumed the metamorphic rocks and created approximately 10 km of crustal thinning. The Pequop Fault is bracketed between 84 Ma and 41 Ma by cross cutting relationships and volcanic rocks that are deposited on its hangingwall and footwall (Camilleri, 2010). New (U-Th)/He zircon ages from the Prospect Mountain Quartzite at the base of the stratigraphic section in the footwall of the Independence Thrust recorded a cooling age of 43 Ma (Wolfe, this volume and Fig. 1). A sample from the Eureka Quartzite in the hangingwall of the Pequop Fault recorded a (U-Th)/He zircon of 60 Ma (Wolfe, this volume). Previous work in this area has indicated that the hangingwall of the Pequop Fault failed to reach low grade metamorphic temperatures. However, the (U-Th)/He system in the zircon grains were reset in the Eureka Quartzite indicating that the hangingwall of the Pequop Fault must have reached temperatures in excess of 180-220 °C before cooling at 60 Ma. It is possible that these ages record erosional exhumation however, more sampling is required to make a definitive conclusion.

METHODS

Field Collection

A total of 41 samples of metamorphic carbonates, metapelites and quartzites were collected and analyzed from two main transects across the footwall and the hangingwall of the Independence Thrust in the PM (Fig. 1). One transect was created by sampling along the footwall of the fault starting at the Prospect Mountain Quartzite up to the Pogonip BA group in the hanging wall. (Fig. 1). A second transect intersecting the fault to the north was also created from the Clifside Limestone to the noten peak limestone in the hangingwall of the Independence Thrust (Fig. 1). Marbles were extensively sampled in an effort to find coexisting calcite and dolomite for calcite-dolomite thermometry. Samples were also taken from areas with known Barrovian style metamorphism (Camilleri, 2010).

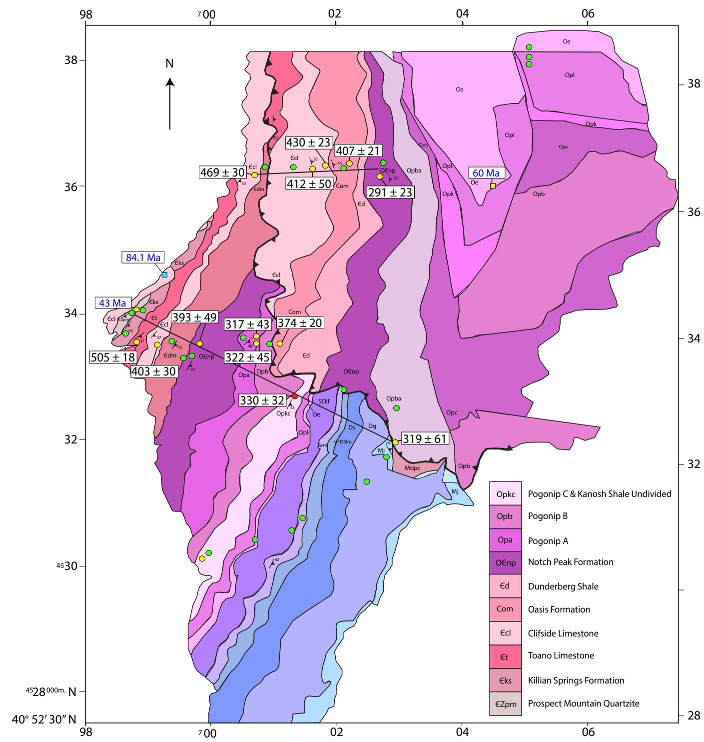

Figure 1. A simplified geologic map of the Pequop Mountains in Northeastern Nevada showing sample locations in green and yellow circles. A simplified stratigraphic column in the bottom left shows the units that this study focuses on. Samples with coexisting calcite and dolomite are indicated by yellow circles and have calcite-dolomite temperature with 2σ as indicated. Black lines are temperature vs. relative distance transects used in Figure 3. The red circle and temperature in the Opkc formation were moved along strike in order to create the relative distance transect shown in Figure 3. Yellow squares are zircon (U-Th)/He ages from Wolfe (this volume) and the blue square shows the titanite U-Pb age from Camilleri and Chamberlain (1997).

Observational and Analytical Methods for Calcite-Dolomite Thermometry

Calcite-dolomite thermometry is commonly used to estimate peak metamorphic temperatures in carbonates and is based on the temperature dependence of the solvus between calcite and dolomite grains in equilibrium (Anovitz and Essene,1987; Müller et al., 2008). This method has been successfully calibrated

Formation	Ct	Cnp		Opa	Opb	Opba	Opc		Com	Ccl		CZpm	Cdm
Fault position	FW	FW	HW	FW	FW	HW	FW		HW	HW	FW	FW	FW
Dolomite	X	X	X	X		X	X		X	X	X		
Calcite	X	X	X	X	X	X	X	X	X	X	X		X
Quartz	X	X	X	X	X	X	X	X	X		X	X	X
Garnet												Alm	
Biotite	X	Phl		Phl		Phl		Phl	Phl		Phl	X	X
Chlorite	X			Clc				X			Clc	X	X
Tremolite	X												
talc				X									
Plagioclase	An, Ab				Ab	Ab			Ab	Ab	Ab		An, Ab
Muscovite		X	X	X	X	X	X	X	X	X	X	X	X
K-Spar		X	X	X	X	X	X		X				
apatite	X	X	X	X		X	X	X	X	X		X	X
Fe-ox		X	X	X			X	X	X	X	X	X	X
Rutile	X	X		X			X		X	X	X		X
Zircon	X					X			X	X		X	
monazite					X				X			X	
Allanite	X												
Tourmaline	X								X			X	
Titanite													X
Other			Pyr			Kln		Kln	Kln	Pyr, Kln	Kln, Pyr		

Table 1. Mineral assemblages of selected samples examined in this study. FW= Footwall and HW= Hangingwall of the Independence Thrust.

and compared to other thermometers such as silicate-carbonate equilibria, garnet-biotite and calcite-graphite thermometry (Holness et al. 1991; Cook and Bowman 1994; Letargo et al., 1995; Ferry, 1996; Rathmel et al., 1999; Müller et al., 2008). Our samples were cut into 30 micron-thick polished thin sections so that observations could be made using the petrographic microscope and SEM. The mineralogy of each sample was examined on the SEM and determined using energy dispersive X-ray spectroscopy (EDS) (Table 1). This allowed for the comparison of mineralogy with pervious work done in the area as well as locating calcite and dolomite in equilibrium within the marbles (Camilleri and Chamberlin, 1997; Camilleri, 2009; Camilleri, 2010).

Analyses were obtained with the Zessis Evo 50 SEM equipped with a Bruker XFlash 6130 SDD at Union College. The beam was operated at 15 kV accelerating voltage and current was set between 4 and 10 nA, rastered over a 10x10 µm area box in order to reduce the risk of damaging the carbonate grains with the electron beam. Acquisition time was set to automatic exhaustive (real time in 100 seconds). The EDS was calibrated using a copper standard, and spectra quantified using phirhoz corrections based on well characterized natural standards include calcite (Ca), dolomite (Mg), ankerite (Fe), and rhodochrosite (Mn). Carbon and oxygen were calculated from stoichiometry. Replicate analyses of identical spots suggest an analytical precession within ± 5 relative mol % Mg resulting in an analytical uncertainty of ~20 ˚C at 350 °C. Temperatures were calculated using the calibration of Anovitz and Essene (1987). The textural relationships between the calcite and dolomite of each spot were then examined to compare the composition of grains in equilibrium and the grains in the matrix. The temperature of the spots in equilibrium, which appeared as distinct populations were averaged. All errors in temperature are reported as ± 2σ.

RESULTS

Footwall of the Independence Thrust

At the base of the stratigraphic section, aluminous layers within the Prospect Mountain Quartzite show an assemblage of qtz+alm+ms+phl+chl with alm replacing chl at higher grades and is estimated to have been metamorphosed at temperatures of 530 °C (Table 1). The Toano Limestone in the PM is a tremolite bearing marble with calcite and dolomite growing in equilibrium (Table 1 and Fig. 2). The measured X_{Mg} values from the Toano Limestone yielded an analytical temperature of 505 ± 18 °C and provides the highest analytical temperature at the base of the stratigraphic section in the footwall of the Independence Thrust (Table 1 and Fig. 1). This analytical temperature is consistent with temperatures needed for the metamorphic reactions observed in the sample which occur at approximately 500 to ~650 °C at pressures of 500 MPa to 800 MPa with 0.1 to 0.02 X_{CO2} (Yardley, 1989 and Bucher and Frey, 2002). The Pogonip Kanosh Shale, yielded a temperature of 330 ± 32 °C and provides one of the lowest analytical temperature estimates at the highest stratigraphic level in the footwall of the Independence Thrust (Fig. 1). The temperature with relative distance profiles show a clear trend of decreasing temperatures up the stratigraphic section (Fig. 3). Similar temperatures were found for samples from the Pogonip Group located in both the hangingwall and the footwall of the thrust (Fig. 1). Samples from the Oasis Mountain Formation and the Pogonip B Formation produced similar temperatures across the fault (Fig. 1 and 3). These temperature relationships indicate that the Independence Thrust was either pre-metamorphic or synchronous with metamorphism.

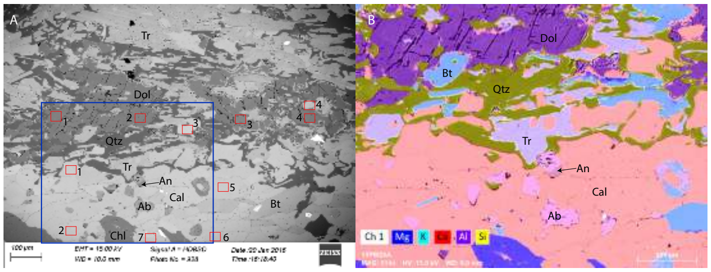

Figure 2. (A) BSE image of the Toano Limestone, with minerals abbreviations after Kretz (1983). Red boxes are analysis spots for calcite-dolomite thermometry. Calcite and dolomite coexist near spots 3 and 4, and a large tremolite prophyroblast is present at the top of the image. The blue box is the elemental map location in (B). (B) Elemental map of the Toano Limestone.

Hangingwall of the Independence Thrust

In the hangingwall of the Independence Thrust, temperatures decrease up section from the Clifside Limestone at 411 ± 50 °C to the Notch Peak Limestone at 291 ± 23 °C (Fig.1 and Fig. 3). The temperature vs. relative distance profile of the northern transect depicts temperature decreasing up the stratigraphic section as well as a similar temperature on both sides of the Independence Thrust (Fig. 3). The lack of offset in peak temperature across the structure further supports the hypothesis that the Independence Thrust is either pre-metamorphic or syn-metamorphic.

DISCUSSION

The paleodepths of the units that were sampled in this study were estimated from the unit thickness of a correlative stratigraphic section of unmetamorposhed rocks found in the Toano Range to the northeast (McCollum and Miller, 1991; Camilleri 2010). In this region of Nevada, the stratigraphic position of the basal Tertiary unconformity indicates broad folding but low erosion rates until after the Eocene (Long 2012 and Long et al., 2015). Thus, the paleodepths of the rocks were similar to their stratigraphic depths. Triassic rocks that are preserved in the southern part of the PM and Pennsylvanian to Permian rocks that outcrop in the northern PM are overlain by Eocene Nanny Creek paleovalley deposits, indicating that there was little pre-Tertiary erosion in this area. Thus, a paleosurface of 0 km was assumed and the surface gradient was assumed to be 15 °C. The temperatures found from calcite-dolomite thermometry in the footwall indicate a high geothermal gradient of

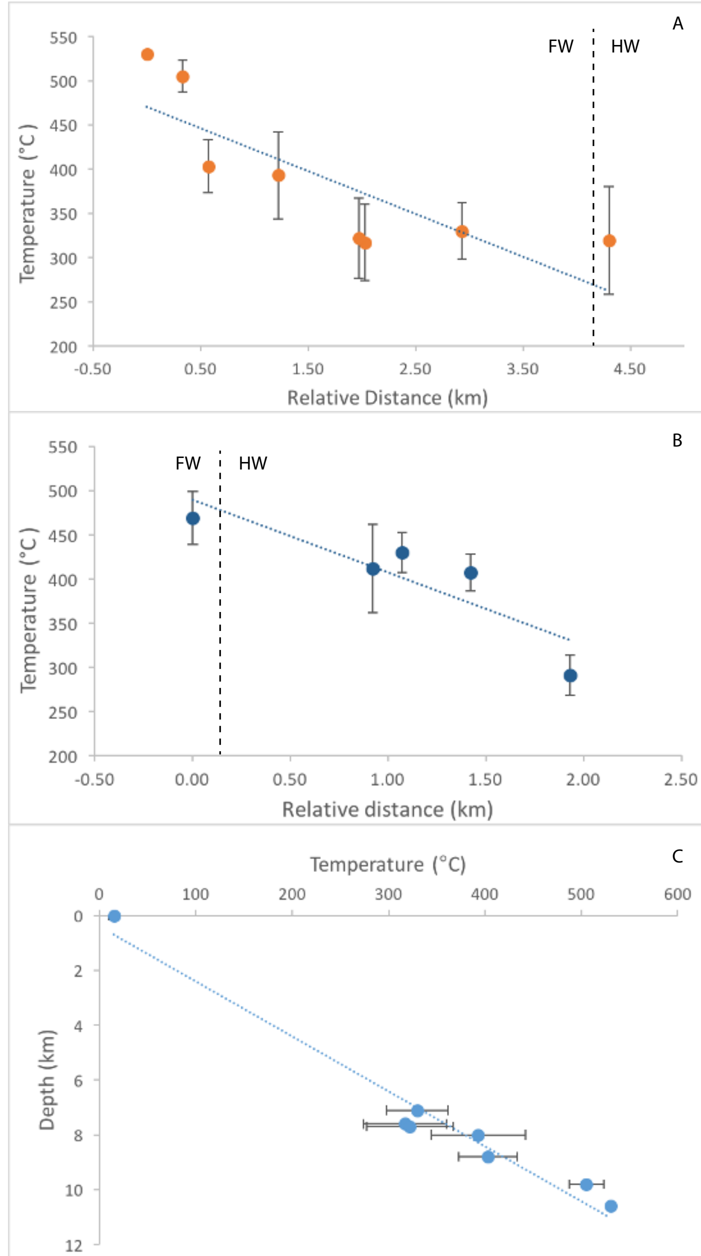

Figure 3. Temperatures vs. relative distance of samples along the northern and southern transect in Fig. 1 in panels A and B. The dotted vertical line in panels A and B represents the relative location of the Independence Thrust (FW=Footwall and HW=Hangingwall). The dotted blue line in (A), (B) and (C) is the line of best fit. (A) Temperatures decrease up section with relative distance away from the Prospect Mountain Quartzite for samples that lie along the southern transect line. (B) Temperatures along the northern transect in the hangingwall of the thrust show temperature decreasing with relative distance up the stratigraphic section. In A and B the temperatures on either side of the thrust are similar. (C) Paleogeothermal gradient of the southern transect in the footwall of the Independence Thrust using an inferred paleosurface due to limited erosion (Long, 2012) and depths corresponding to unmetamorphsed unit thickness found in a correlative stratigraphic section from the Toano Range. Temperature data from the Pequop Mountains indicate a steep metamorphic field gradient of 50 °C assuming no attenuation.

50 °C/km (Fig. 3). However, if these units were attenuated during deformation or had smaller thicknesses than those found in the Toanao Range the paleogeothermal gradient would be far higher.

A typical crustal geothermal gradient is ~25 °C/km, making the geothermal gradient observed in the PM unusually high and implying an additional source of heat. This steep geothermal gradient is compatible with the presence of a shallow pluton beneath the deepest levels of exposure. High metamorphic field gradients, like those documented in this study are common in Buchan facies series, which is characteristic of contact metamorphic environments and records extreme thermal gradients with distance from the pluton. For example, shallow plutons have been found to increase geothermal gradients to above 35 °C/km in the upper 15 km of the crust and regionally can exceed 50 °C/km (Barton and Hanson, 1989). Low pressure metamorphic belts form in regions of continental extension, magmatic belts or rapid uplift associated with continental collision and areas related to subduction (Barton and Hanson, 1989). The PM lack barometric minerals so an unmetamorphosed stratigraphic thickness has been used to estimate depth and pressure conditions. This depth is a reasonable minimum estimation given the continuity of the stratigraphic section in the PM. If significant attenuation due to deformation occurred, then the burial depth in this area could be higher, which would ultimately increase the paleogeothermal gradient. Thus, metamorphism in the central and northern PM could be the result of heating from a pluton underneath the exposed stratigraphic units. Gravity data from this locality indicates a high gravitational anomaly in the northern PM where a mining district has recently been established (Ponce et al., 2011). Aeromagnetic data does not indicate any large scale anomalies from the central or northern Peqoups; however, leucogranites like those which are prominent in this core complex are difficult to record on aeromagnetic surveys due to their low abundance of magnetic minerals (Grauch, 1996 and Ponce et al., 2011).

CONCLUSIONS

Temperature estimates from this study indicate that the Independence Thrust was either pre- or coeval with peak metamorphism and also suggest a high metamorphic field gradient in the PM. Temperatures at the base of the section reached upwards of 505 ± 18 °C and are consistent with metamorphic reactions observed in this study as well as previous work. Metamorphism may be a result of a buried pluton underneath the deepest structural level exposed in the PM and could have created the high paleogeothermal gradient observed in this study. The results in this study suggest that plutonism in the retroarc region of growing orogenic plateaus could be an important process. Future work could include higher resolution gravity and magnetic anomaly data as well as more extensive age dating and temperature values.

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REFERENCES

Anovitz, L. M., & Essene, E. J., 1987, Phase equilibria in the system CaCO3-MgCO3-FeCO3. *Journal of Petrology*, *28*(2), 389-415.

Barton, M. D., & Hanson, R. B., 1989, Magmatism and the development of low-pressure metamorphic belts: Implications from the western United States and thermal modeling. *Geological Society of America Bulletin*, *101*(8), 1051-1065.

Camilleri, P. A., & Chamberlain, K. R., 1997, Mesozoic tectonics and metamorphism in the Pequop Mountains and Wood Hills region, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen.

Geological Society of America Bulletin, *109*(1), 74-94.

Camilleri, P. A., 2009, Growth, behavior, and textural sector zoning of biotite porphyroblasts during regional metamorphism and the implications for interpretation of inclusion trails: Insights from the Pequop Mountains and Wood Hills, Nevada, USA. *Geosphere*, *5*(3), 215-251.

Camilleri, P. A., 2010, *Geologic Map of the Northern Pequop Mountains, Elko County, Nevada*. Nevada Bureau of Mines and Geology.

Chapman, J. B., Ducea, M. N., DeCelles, P. G., & Profeta, L., 2015, Tracking changes in crustal thickness during orogenic evolution with Sr/Y: An example from the North American Cordillera. *Geology*, *43*(10), 919-922.

Cook, S. J., & Bowman, J. R., 1994, Contact metamorphism surrounding the Alta stock; thermal constraints and evidence of advective heat transport from calcite+ dolomite geothermometry. *American Mineralogist*, *79*(5-6), 513-525.

DeCelles, P. G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. *American Journal of Science*, *304*(2), 105-168.

Ferry, J. M., 1996, Three novel isograds in metamorphosed siliceous dolomites from the Ballachulish aureole, Scotland. *American Mineralogist*,*81*(3-4), 485-494.

Grauch, V.J.S., 1996. Magnetically interpreted, granitoid plutonic bodies in Nevada. *An Analysis of Nevada's Metal-Bearing Mineral Resources*, pp.96-2.

Holness, M. B., Bickle, M. J., & Graham, C. M., 1991, On the kinetics of textural equilibration in forsterite marbles. *Contributions to Mineralogy and Petrology*, *108*(3), 356-367.

Hudec, M. R., 1992, Mesozoic structural and metamorphic history of the central Ruby Mountains metamorphic core complex, Nevada. *Geological Society of America Bulletin*, *104*(9), 1086-1100.

Letargo, C. M., Lamb, W. M., & Park, J. S., 1995, Comparison of calcite+ dolomite thermometry and carbonate+ silicate equilibria: Constraints on the conditions of metamorphism of the Llano uplift, central Texas, USA. *American Mineralogist*, *80*(1-2), 131-143.

Long, S. P., 2012, Magnitudes and spatial patterns of erosional exhumation in the Sevier hinterland, eastern Nevada and western Utah, USA: Insights from a Paleogene paleogeologic map. *Geosphere*, *8*(4), 881-901.

Long, S. P., 2015, An upper-crustal fold province in the hinterland of the Sevier orogenic belt, eastern Nevada, USA: A Cordilleran Valley and Ridge in the Basin and Range. *Geosphere*, GES01102-1.

McCollum, L.B., and Miller, D.M., 1991, Cambrian stratigraphy of the Wendover area, Utah and Nevada: U.S. Geological Survey Bulletin 1948, 43 p.

McGrew, A.J., 1992. Tectonic evolution of the northeastern Humbodlt Range metamorphic core complex, Nevada Ph.D. Thesis, University of Wyoming, 191 p.

McGrew, A. J., & Snee, L. W., 1994. 40 Ar/39 Ar thermochronologic constraints on the tectonothermal evolution of the Northern East Humboldt range metamorphic core complex, Nevada. *Tectonophysics*, *238*(1), 425-450.

Müller, T., Baumgartner, L. P., Foster, C. T., & Roselle, G. T., 2008, Forward modeling of the effects of mixed volatile reaction, volume diffusion, and formation of submicroscopic exsolution lamellae on calcite-dolomite thermometry. *American Mineralogist*, *93*(8-9), 1245-1259.

Ponce D.A., Watt, J.T., and Bouligand, C., 2011, Geophyscial Setting of the February 21, 2008 M_w 6.0 Wells Earthquake, Nevada, Implications fro Earthquake Hazards. Nevada Bureau of Mines and Geology.

Rathmell, M. A., Streepey, M. M., Essene, E. J., & Van der Pluijm, B. A.,1999, Comparison of garnet-biotite, calcite-graphite, and calcite-dolomite thermometry in the Grenville Orogen; Ontario, Canada. *Contributions to mineralogy and petrology*, *134*(2-3), 217-231.

Yardley, B. W. Y., 1989, *An introduction to metamorphic petrology* (No. 552.3/. 4 YAR).