Depositional and deformational history: A study of thrusting in the Sevier Hinterlands and Basin and Range extension and the resulting deformation in the Raft River metamorphic core Complex, of Idaho/Utah.

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Abstract

The Raft River range is a metamorphic core complex has a vast and complex depositional and deformational history dating back approximately 2.5 billion years. The oldest rocks in the complex are the basement rocks which include older schist, mafic schist/amphibolite, Trondhjemite/Metapegmatite, and adamellite, deposited around the time when various volcanic arcs were beginning to coalesce into Laurentia. (Hoffman 1988). During and following the formation and subsequent breakup of the supercontinent Rodinia, Utah was underneath an epeiric sea/shallow marine environment, in which the majority of the other strata seen in the Raft Rivers were deposited, these include the Precambrian Elba and Schist of upper narrows, Ordovician Pogonip Group, Eureka Quartzite, and Fish Haven, the poorly exposed and small in abundance Mississippian Diamond peak/Chainman shale, and the Pennsylvanian Oquirrh Formation, and the tectonic mélange, a pulverized mass of older rocks.

Of particular interest are the smaller scale deformational features within the various units. Within the Elba are several smaller scale features, such as “triplets”, a series of foliations, stretching lineations, and high angle fractures. The foliations and stretching lineations measured show a general northeast-southwest sense of shear, with the high angle fractures being oriented roughly perpendicular. (Figure: 3.1, 3.2, 3.3) and dips decreasing in general on the upper limb of the fold hinge. In addition to these, the schist member of the Elba contains prominent S-C fabric (Shear bands and quartz augen respectively), with augen measuring from as small as 1 cm upwards to 6 or 7 centimeters. These SC fabrics show a top to the East, or northeasterly sense of shear consistent with the triplet measurements, and in general, the dips of begin to be primarily to the East. Similarly, in the Schist of the upper narrows, folding and S-C

fabric are fairly abundant and show a top to the east/Northeasterly sense of shear. In general, the S-C fabrics, triplets, and smaller scale features show consistency with the “rolling hinge” hypothesis. The Pogonip, Eureka, and Fish Haven have all undergone various amounts of mylonization and/or brecciation, with the Pogonip having two distinctive units divided by these features, and the Fish Haven being notably less brecciated than either, in general, this mish-mashing of brittle/ductile features throughout the map area is indicative of a brittle/ductile transition.

The Raft Rivers have also undergone several larger scale deformation events which were responsible for forming these features. The “Lowland” shows many signs of compressional deformation of the Sevier Orogeny, such as the aforementioned smaller scale features in the Pogonip, Eureka, and Fish Haven, as well as a couple of faults. A thrust fault and normal fault which are byproducts of the Sevier Orogeny cut through Bald Knoll, through Middle Hill, and through Little Hill before disappearing into the alluvium, with the thrust fault splitting into 3 splays. The Thrust fault is distinguishable by Eureka/Pogonip or Eureka/Fish Haven contacts, as well as a few Pogonip/Pogonip contacts. The Thrust fault is easily distinguishable by a contact between the Pogonip/Eureka and extremely distinctive Oquirrh.

The Highlands is the product of Basin and Range Extension, and several signs of this can be seen. In particular, the exhumation of the Elba Quartzite and Schist of the upper narrows occurred because of Basin and Range activity, with the resulting stretching lineations on various beds also being a byproduct of these same extensional forces. The massive low angle normal fault at the top, created by the “sliding” of the Black Pine Range as the Raft Rivers was uplifted from underneath it. (Dinter 2017)

Introduction

The Raft River Range is an east-west trending mountain range located near the Utah/Idaho border roughly 150 miles from Salt Lake City Utah. The Raft Rivers are a part of a metamorphic core complex, and contain some of the oldest rocks able to be seen in Utah, from 2.5 billion-year-old basement rocks to Ordovician and Permian strata due to exhumation from Basin and Range extension. A total of approximately 10 days were spent in the Southern area of the Raft Rivers, in which depositional contacts were mapped on a combination of the USGS Rosevere point and Park Valley 7.5 minute Quadrangles. These maps used a scale of 1:12,000, with a 20-40 ft. contour interval in an area approximately ~4mi^2 from Bald Knoll in the East to Quaking Aspen Canyon in the West, and from the "Lowlands" to the "Highlands"(Figure 1) Using this map and the plotted contacts and foliation measurements, a cross section of the A-B-C transect from the area of Bald Knoll to the Fold axis was constructed to interpret some of the structural and deformation information of this area.

In addition to the various mapping elements, the characters of each of the units of interest within the mapping area, as well as some of those not exposed within the mapping area itself, but prominently exposed nearby were described, and general depositional environments were determined based upon known protoliths of the metamorphic rocks, as well as the few, relict sedimentary structures that remained in several of the units. A tectonostratigraphic section was also constructed to further this end (Figure 5) Lastly, triplets, a series of Foliation planes, lineations, and their associated High angle fractures were measured with a Brunton, and plotted on stereonets. (Figure 3.4) From this information, the major and minor fold axis were calculated using the "averages" of the measurements. This collection of information and measurements was used to test the “Rolling Hinge” hypothesis proposed by Bartley and Manning in 1994. (Figure 3.1, 3.2, 3.3) (Figure 4, 12)

These methods contributed to the overall goal of the study, which was to see how these various deformational events have affected the area of study, on the southeast side of the range near Bald Knoll, and determining the depositional, structural, and deformational relationships between the various strata and structures present therein.

Geologic Setting

Approximately 2.5 billion years ago, at the beginning of the Proterozoic era many cratons began to coalesce into large landmasses, one of which was the proto-continent Laurentia. It was during the assemblage of Laurentia that many of the Archean- aged basement rocks, such as those in the Raft Rivers were formed. (Hoffman 1988) Approximately 1.5 billion years later, during the Neoproterozoic, Laurentia would in turn would collide and combine with other landmasses to form the supercontinent Rodinia, moving what is now Modern day Utah from a passive continental shoreline into an area within the continent. (Hintze and Kowalis 2009) This period also marked large scale plutonic intrusions which would eventually lead to the breakup of Rodinia some 200-400 million years (~800-750 Ma) later (Windley, et al. 2014).

During the Ordovician, seafloor spreading which followed the breakup of Rodinia peaked during the Ordovician. Tall oceanic ridges produced by sea floor spreading raised seafloor levels to Rise substantially and flood the many continents, including Laurentia which was almost completely submerged by epicontinental seas. Sea levels fluctuated greatly during the Ordovician, with repeated cycles of transgression and regression which created shallow marine environments conducive for deposition of dolostone and limestone, the protoliths that would eventually be deformed into the Pogonip, Eureka, and Fish haven Formations. (Holland 2017) (Figure 6)

From the Late Devonian to the Mississippian period, plate tectonic activity pushed Island arcs eastward and into the on the western edge of the North American plate resulting in a mountain building event known as the Antler Orogeny. (Hintze and Kowalis 2009) The Antler orogeny occurred primarily in the area of present day Nevada, putting Utah in the foredeep basin of two orogenic episodes which would occur separately over several million years. In addition, it was during this time that the Oquirrh basin began to develop in northwestern Utah. These conditions would lead to deposition of deltaic deposits such as the chainman/Diamond peaks formation. (UGS npd.)

Continuing cycles of transgression and regression of the sea continued throughout the Pennsylvanian period. During this time, and throughout the Permian, Utah sat to the west of the Ancestral Rocky Mountains, and was largely covered by shallow seas. As such, Sediments from the Oquirrh and paradox basins accumulated in vast copious amounts. (UGS npd.) (Figure 7.1)

This status quo during the Pennsylvanian remained largely the same into the Permian. During this time, Pangaea began to assemble from the Earth's continents, this led to further rising of the Ancestral Rocky Mountains, causing a general lowering of sea levels and eventually transgression/regression cycles. During this time, Utah remained along a passive continental margin on the western coast of Pangaea, covered by shallow seas. (Ross & Ross 2014) These conditions throughout the late Pennsylvanian and early Permian were conducive to the deposition and formation of various sandstones, dolostones, shales, and limestones (Figure 7.2)

During the Early Cretaceous (~145-100 Ma) the oceanic Farallon plate began to subduct underneath the Continental North American plate. This caused conductive heating and compression, and eventually led to the onset of the Sevier orogenic episode (Occurring from roughly 140-50 Ma). The Sevier orogeny uplifted and formed many of the mountain ranges in Western Utah and Eastern Nevada, as well as a series of thrust faults and folds which were created in response to these compressional forces. (Livacarri 1991) By the time of the Late Cretaceous, the Raft River Range was sitting in the hinterlands of thrusts of the Sevier orogeny. (Figure 10) The Sevier highlands began moving eastward, causing compression as land rose between the border of Utah and Nevada. (Wells, Dallmeyor et al. 1990) (Hintze and Kowallis 2009) The Compressional forces occurring during the Sevier orogeny led to the formation of the many thrusts and normal faults running throughout Utah and the Midwest to western coast of the United States. By the time of the Miocene (~23-5 Ma) the Farallon plate had completely subducted underneath the North American plate. This led to a reduction in compressional forces as the North American plate contacted the Pacific plate. (Dott & Prothero, 2010) Around 17 Ma this compressional relief cause tectonic expansion to begin, which ushered in the beginning of the Basin and Range province, which covers much (~500 miles) of the Western United States from the Westernmost edge of the Colorado Plateau, where the Wasatch Mountains and Wasatch Fault define its easternmost border, to the fault scarp in the Sierra Nevada Mountain Range, which defines its easternmost edge. Basin and Range extension is likely the result of lithospheric thinning and extension with extension characterized by listric normal faulting (Faults which level with depth). Total lateral displacement of the Basin and Range varies from about 60-300 Km since the early Miocene, with the southern portion having a larger degree of extension than the North (about 60 km in Utah). (Figure 11)

Basin and Range extension continues to play an important role in the deformation of the Western United states. Extending at a rate of approximately 0.2-0.6 centimeters per year, and continuing to deform the rocks within the greater Basin and Range province, creating a variety of High Angle normal faults within Utah and to the West. (Salyards and Shoemaker, 1987) (Dinter 2017) The Raft River Mountains and surrounding areas lie within the Basin and Range province, and much of the normal faulting and deformation in the "highlands" is a result of these continuing extensional processes. (Figure 9)

Rock Descriptions

Basement Rocks

The basement rocks of the Raft Rivers are ~2.54 billion-year-old crystalline rocks which make up the majority of the basement in the Raft River range. The basement consists of old schist, Mafics, Trondhjemite/Metapegmatite, and metamorphosed adamellite.

-Older schist

The old schist within the raft River range totals approximately 90-300 meters in total thickness (Hintze & Kowalis 2009) and forms part of the old crystalline basement within the raft river range. This schist is a fine grained, mica-feldspar Quartz schist. This schist contains fairly unsorted pebbles in a pebbly mudstone member and the pebbles contained within it have been stretched approximately 25-30 times their original length in a ductile metamorphic zone. (Dinter 2017)

-Mafics

The mafics within the basement of the Raft Rivers sit atop the older schist. The mafics of the basement consists of dark, blackish hornblende /biotite schist, as well as amphibolite. The amphibolite is greenish in color, and contains about 20% plagioclase, 3% quartz, 2% white mica, and approximately 75% amphiboles, with Hornblende consisting of approximately 55% and Actinolite roughly 20%. The Schist is black in color, and extremely rich with white Mica. White veins run all throughout and various signs of ductile deformation are apparent.

-Trondhjemite/Metapegmatite

The metapegmatite is an intrusive rock a distinctively white rock containing little to no mafic material, with large amounts of quartz comprising approximately, white mica, and feldspar. It has weak foliation and has intruded the surrounding units, giving it a younger age.

-Metamorphosed Adamellite.

The metamorphosed adamellite is a tan to grey quartz monzonite containing biotite, white mica, quartz (~5%), and feldspar. The matrix of the adamellite is composed almost wholly of white mica, while the quartz and feldspar phenocrysts, measuring ~4-6 centimeters are largely elongated throughout, causing them to take on something of a “wormlike” shape. Biotite is abundant in the adamellite and comprises most of the rock.

Lower Plate Metamorphic Core

The metamorphic core is an area of “deep” crust exhumed in association with extension, in the case of the Raft Rivers, primarily Basin and Range extension. The metamorphic core consists of the Schist of the Upper Narrows, and the Elba quartzite, which has both a quartzite and Schist member.

-Elba Quartzite

The Elba quartzite is the most prominent and abundant Formation within the Metamorphic core in the area of study. The Elba quartzite consists of two fairly distinct members, a quartzite member and Schist member. The Elba schist underlies the main quartzite member, and is a dark brown to greenish grey fine-grained quartz, mica, feldspar schist with various quartz banding within. The quartz bands within the Elba schist measures approximately 3 cm in diameter. Quartz makes up the majority of the schist, but it also contains large amounts of white mica and feldspar as well as biotite and other mafics in various abundance. Also within the schist are Quartz augen and S-C fabric (Shear bands and Quartz augen respectively), which show a top to the East, or northeasterly sense of shear.

The Quartzite member of the Elba overlies the Schist member and is a light tan to white color on fresh surfaces, tan to reddish orange on weathered surfaces. The two-main lithology within the quartzite member are naturally quartz and plagioclase feldspar, however, there are many prominently green layers within the Elba Quartzite, containing large amounts of the mineral Fuchsite, a chromium rich variant of muscovite. Contained within the quartzite are various signs of deformation, including stretch lineations, wavy foliation surfaces, and high angle fractures, which run roughly perpendicular to the primarily northeast/southwest oriented foliations and lineations. In less deformed areas, cross bedding can be seen, an indicator of its quartz sandstone heritage. Outside the mapping area, the basal beds of the Elba can be seen. These Elba basal beds contain a conglomerate layer with prominently stretched pebbles, which lie perpendicular to vertical fractures and range from 2 cm to 3 centimeters in total length. All throughout the Elba is a pervasive sense of east to west shear.

-Schist of the Upper Narrows

The Schist of the upper narrows is a dark brown to grey fine-grained schist. The schist is brecciated as a whole, with fine grained gneissic banding near the base comprised of biotite, quartz, and feldspar ranging from about 1-4 centimeters in diameter. Quartz augen are prominent within, and have been stretched near the top. Folding and S-C fabric are fairly abundant within the Schist of the Upper Narrows, and show a top to the east/Northeasterly sense of shear. The schist is highly foliated, and easily fractured along foliation planes. Small Z folds and micro-fractures are also visible and fairly abundant within outcrops.

<u>Tectonic Mélange</u>

The tectonic mélange consists of numerous sediments and rocks crushed up and left as float alongside the hanging wall of the Raft River Detachment Fault. Within the mélange is an assemblage of float from various schist, quartzite, gneiss, as well as some fragments from the surrounding formations. The primary float visible within the tectonic mélange are the Schist of Mahogany Peaks, the schist of Steven's springs, and an unknown Quartzite, assumed to be the Quartzite of Clark's basin.

-Schist of Stevens Springs

The schist of Steven's springs is present only within the mélange in the mapping area hence there are no outcrops or wholly intact rocks visible. In the surroundings areas such as grouse creek however, it has several outcrops which can be used to determine the general mineralogical and physical characteristics. The schist of Steven's springs is fine-very fined grained, has greenish-grey coloration, and is extremely shiny, almost to the extent of looking like a mirror. The minerals that dominate the schist fragments within the mélange are white mica, the likely majority of which are muscovite and quartz. **In** the outcrops in the surrounding areas small garnet porphyroblasts are visible, as well as small staurolite inclusions and phyllite lenses. Additionally, mafics such as hornblende and biotite are visible in the intact Steven's Springs, but are not particularly visible or abundant within the float contained within the mélange.

-Quartzite of Clark's basin.

The unknown quartzite contained within the mélange is assumed to be the quartzite of Clark's basin, based on the presence of outcrops in surrounding areas, as well as similarities between the two. The Quartzite of Clark's basin is a shiny, tannish grey to white schistic quartzite. The primary lithology is a quartzite, containing predominantly quartz and plagioclase, as well white mica which gives its somewhat distinctive sheen. Additionally, the Quartzite of Clark's basin contains a schist layer, with largely similar mineral content to that of the quartzite, but more mica rich, as well as more highly foliated. Outcrops from outside the mapping area show a top to the west shear zone.

-Schist of Mahogany peaks

The Schist of Mahogany peaks is the youngest rock unit of those which dominate the tectonic mélange. This schist of Mahogany peaks is fine grained, and reddish brown to grey in color. Biotite largely dominates the mineral content of the rock, as well as abundant larger garnet and staurolite crystals. Muscovite is also in the rock in smaller amounts, and gives it a slight sheen.

Upper Plate Hanging Wall Rocks.

The rocks of the upper plate are a series of units which lie on the hanging wall of the Raft river detachment and make up the bulk of the “lowland” area. Within the Upper plate are the Pogonip Group, Eureka quartzite, Fish Haven Dolomite, Chainman/diamond peak formation, and Oquirrh formation.

-Pogonip Group

The Pogonip consists of two somewhat distinctive marble units, the lower portion of which is one created from metamorphosed dolostone, and the other lying atop from metamorphosed limestone. The most prominent outcrop in the area of study is an approximately 10-12-meter outcrop located on Bald Knoll. The lower mylonitized Marble layer is fine grained white to brown in color and characterized by strongly expressed foliations defined with alternating coarse/fine beds of dolomite, mica, and quartz. The upper marble layer of the Pogonip is light grey to bluish grey in color and highly brecciated and fractured at the top. The topmost unit is fine grained with ~1mm mica crystals. The Pogonip has a wide range of expressed colors ranging from brown to grey, to bluish grey. The bluish grey expression of the Pogonip is difficult to distinguish from the greyish blue of the younger Fish Haven marble, and the most reliable way to tell them apart is by the brecciated characteristics of the Pogonip that the fish haven lacks.

-Eureka Quartzite

The Eureka quartzite is in general poorly exposed in the area, with small outcrops, the largest of which measures ~2-3 meters, appearing and disappearing at a whim alongside the boundaries of the thrust and normal faults that run from bald knoll to little hill. The Eureka quartzite is a fine grained, highly fractured quartzite with numerous expressions. These various expressions range from whiteish brown quartzite homogeneous quartzite to a completely brown quartzite banded with layers of white. In general, the Eureka expresses itself as translucent white blocks outcrops. The Eureka is non-cliff forming, and consists primarily of quartz. The Eureka in the mapping area is highly brecciated and tends to form small blocks that then disappear. Outside the mapping area, in the undeformed Eureka, white mica and biotite can be found within in varying abundance, but they are largely absent/not visible within the deformed Eureka.

-Fish Haven Dolomite

The Fish Haven dolomite is a greyish blue to grey weakly foliated marble that is poor in abundance in the mapping area and only crops up minimally around fault boundaries on Bald Knoll and Middle hill, with the largest bald knoll exposure being ~11 meters in thickness. The fish haven is gritty and highly fractured, with various 2-3 mm laminations filled with calcite. The Fish Haven is easily confused with Pogonip due to their similar color ranges and expressions, however, the Fish Haven is notably less brecciated than the Pogonip and has more coarse grains, which are the easiest ways to tell the two extremely similar marbles apart.

-Chainman/Diamond peak formation

The Diamond peak formation has only one tiny 1-2 meter exposure on an easily missed edge of bald knoll. It is a dark colored brown to black phyllite/shale, which has been micro brecciated and highly fractured as a result of deformation. It consists primarily of quartz and clay minerals. Due to the limited exposure and general lack of abundance, little else can be described as it pertains to the area.

-Oquirrh Formation.

The Oquirrh Formation is a marble which ranges from Dark grey, to reddish brown, to blueish grey with a rich hue. The Oquirrh is fine grained, fairly homogeneous, and exclusive to the down-thrown side of the normal fault. The most notable feature that distinguishes the Oquirrh are the copious amounts of calcite-filled tension gashes, ranging from, on average, approximately 1-5 centimeters but can be even larger in more rare instances. Further from the fault plane, the calcite-filled tension gashes decrease in both size and abundance, until they all but disappear. Additionally, in a single outcrop near the area of the fault plane, crinoids ranging 1-4 cm can be seen within the Oquirrh in extremely low abundance (~2% or less).

Modern Alluvium

Active erosion and fluvial processes are occurring in the southernmost area of interest. The Alluvium consists of virtually all the units of the area to varying degrees in an assortment rounded of sand, pebbles, and mud as well as some larger float material.

Depositional Environments

Due to the highly deformed and metamorphosed nature of the rocks in the Raft River range, who, in the words of the great David Wheatley “left their old sedimentary lives behind and grew up” the exact depositional environments are somewhat difficult to pinpoint due to the loss of most, if not all of their original sedimentary features. However, using knowledge relict sedimentary features, as well as knowledge of what protoliths a particular metamorphic rock comes from, one can extrapolate a depositional environment. Less metamorphosed/deformed exposures of the units of interest also provide clues as to what environments these particular rock units were deposited.

Basement Rocks.

The older Schist was likely deposited in a high energy environment, possibly some sort of alluvial fan indicated by its likely protolith being a well sorted matrix supported conglomerate. The likely protolith of the mafic amphibolite and schist is likely a basalt, likely deposited from some unknown eruption or volcanic flow. The Trondhjemite/Metapegmatite is an intrusive rock and has intruded the older schist as well as mafic schist, indicating a younger age as well as a volcanic origin due to being plutonic in nature. The adamellite similarly is an intrusive rock, and the elongate nature of the phenocrysts in surrounding mica matrix indicate a slow cooling and a volcanic origin.

Metamorphic Core.

-Elba

The likely protolith of the Elba was that of an arkose sandstone, indicated by the substantial amount of feldspar and quartz within the quartzite member. The various beds within the Elba appear to be indicative of various phases of marine deposition. The stretched pebble conglomerate that comprises the basal beds of the Elba may have been deposited in a high energy marine environment due to their generally well sorted nature. The more homogenous quartzite areas of the Elba contain evidence of trough cross beds in their less deformed areas, indicating an upper shoreface or possible deltaic depositional environment. The schistic member of the Elba was likely metamorphosed from a mudstone, indicating a rising sea level and lowering of overall energy.

-Schist of upper narrows.

Due to the fine-grained nature of the schist, the source rock was likely that of a silica rich mudstone or fine-grained shale. This indicated that the depositional environment of the schist of the upper narrows was likely similar to that of the schistic member of the Elba, a low energy environment, likely an offshore marine environment caused by marine transgression. A lacustrine or lagoonal depositional environment are also possible, but the seeming lack of Calcite deposits seems to mostly rule them out.

Tectonic Mélange

The actual mélange resulted from faulting deforming and crushing the various rocks within, making the actual depositional environment of the mélange itself that of the hanging wall of the Raft river detachment, however, each of the rocks contained within the assemblage each came from an independent source. The schist of Steven's springs as well as the Schist of Mahogany peaks were likely sourced from fine grained sandstone or shales, and their interbedded nature indicates a fluctuation in energy levels, reflecting a possible alternating shallow marine/non-marine depositional environment. The Quartzite likely represents a shoreface deposition in between the deposition of the two schists. Indicated by its protolith being that of a quartz sandstone, indicating higher energy levels.

The Hanging wall.

-Pogonip

Just as there are two somewhat distinctive lithologies within the Pogonip Group, so too are there two likely sources. One marble unit was sourced from a limestone while the other was metamorphosed from a dolostone. In any case, both limestone and dolostone share a common environment. A shallow marine depositional environment with somewhat limited circulation. The formation of the dolostone member would require magnesium rich waters, while the limestone would require abundant calcium carbonate from lime muds or organisms, making a shallow sea the likely depositional environment.

-Eureka quartzite

The Eureka has little to no bedding features and is general poorly exposed, however, being a quartzite, the likely protolith was that of a quartz sandstone. This narrows down the possible depositional environments somewhat, as the coarser grains rule out offshore deposition, while the lack of pebble sized clasts rules out higher energy environments such as an alluvial fan. Ultimately the Eureka quartzite was likely in either a fluvial, deltaic, or beach system. Due to the depositional environments of the surrounding and similarly aged units, a beach or similarly shallow marine area with wave action seems the most likely. In any case, the Eureka was deposited by an epeiric Sea (Dinter 2017)

-Fish Haven Dolomite

Due to the Fish Haven being a dolomite rich marble, the protolith of the Fish Haven was a dolostone. As dolostone typically form in warm, magnesium rich waters with limited circulation, this is an indication that the Fish Haven was deposited within a fairly shallow marginal marine setting, likely a lagoon or tidal flat.

-Chainman/Diamond Peak formation.

The Chainman/Diamond peak formation represent facies within a single depositional sequence. As they are likely derived from a shale protolith, this indicates a shallow marine or fluvial/deltaic depositional environment on or near the continental shelf during the antler orogeny. (Dinter 2017)

-Oquirrh Formation

The Oquirrh formation was derived from sandy limestone and dolostone protoliths, and therefore likely has a depositional environment largely similar to that of the Pogonip. Additionally, the presence of crinoids, though few in number indicate that the likely depositional environment of the Oquirrh was that of a shallow marine environment, possibly a warm shallow marine shelf.

Structural descriptions and interpretations

The Raft River area is something of a heaven for those interested in structural geology, as structural events, ranging from brittle to ductile, and large to small scale are abundant in the area. Perhaps one of the most notable smaller scale features is the stretched pebbles in the older basement schist, in which the conglomerate clasts have been stretched about 30x their original length horizontally as a result of brittle deformation (Dinter 2017). In addition to this, the other basement rocks show similar signs of deformation, with prominent S-C fabric in the Mafic igneous schist, as well as foliated planes oriented approximately East to West, signs of ductile shearing and stretching during the metamorphic processes.

Perhaps the most prominent structural clues lie in the Elba. The Elba is a massive unit of quartzite and schist which makes up the majority of the area colloquially termed the “highlands”, making up the majority of the slopes on the southern side of the range. Within the Elba are several smaller scale features, such as “triplets” (Figure 3.4), a series of foliations, stretching lineations, and high angle fractures. The foliations and stretching lineations show a general northeast-southwest sense of shear, with the high angle fractures being oriented roughly perpendicular. (Figure 3.1, 3.2, 3.3) and dips decreasing in general on the upper limb of the fold hinge. In addition to these, the schist member of the Elba contains prominent S-C fabric (Shear bands and quartz augen respectively), with augen measuring from as small as 1 cm upwards to 6 or 7 centimeters. These SC fabrics show a top to the East, or northeasterly sense of shear consistent with the triplet measurements, and in general, the dips of begin to be primarily to the East. These Results, as well as the nature of the faults mentioned later, are consistent with the rolling hinge hypothesis proposed by Bartley and Manning in 1994 (Figure 4, 12). Based upon deep erosion and a drastic change in dip near the fold hinge (moving from approximately 15 to 6 degrees) it was determined that folding had indeed occurred, and the schist known unofficially as “Rattlesnake rock” in the lowlands was actually the schist of the upper narrows, rather than the Elba schist, making the entire slope overturned. The edge of the Elba, where the tectonic mélange and Elba meet marks the area of the Raft River décollement, a basal detachment fault/gliding plane between two distinctive masses of rock, marking the “border” between the highlands and lowlands and their differing deformational settings.

The schist of the Upper narrows shows augens and S-C fabric like that of the Elba schist, also showing a top to the east/northeasterly sense of shearing. Also seen within the Schist of the Upper narrows are z folds, and some quartz augen. The schist of the upper narrows is in general fairly brecciated. In addition, the contact between the schist of the upper narrows and the Elba quartzite roughly makes up the “fold axis”. Several cliff faces in the highlands show prominent “M folds” of an overturned anticlinal nature where much of this folding has occurred, these M folds serve as “fold hinges”. In the area of little rocky canyon, several orphaned hinges can be seen, indicated by the sudden and abrupt termination of several Elba Cliff faces, as well as being able to be determined with a Brunton by drastic changes in dip as mentioned previously(Figure 2)

The Tectonic mélange itself has been created as a result of brittle deformation, with the mélange consisting wholly of crushed fragments from various formations both seen in the surrounding areas, as well as several units that don't outcrop at all in the mapping area. These rocks were fragmented and broken while large scale shearing of the décollement occurred. In addition to this two prominent, essentially mirror image incision blocks are incised square in the middle of the mélange unit, starting near the base and continuing up little hill, which consist of Elba quartzite and the now-known Schist of the Upper Narrows. (Rattlesnake). The mélange and associated décollement marks the "border" between the highland area and lowland area, where the Precambrian metamorphic core is exposed against Ordovician and younger rocks, and the extensional forces associated with Basin and Range prominent in the Highlands gives way to Sevier compressional forces which make up the bulk of the Lowlands. (Dinter 2017).

In the lowlands, in the area of bald knoll are two prominent Sevier related faults, a thrust fault, marked by a sequence of Eureka and Fish Haven thrust above the older Pogonip Group, and a normal fault, signified by an extremely distinctive border between the Pogonip Group and Oquirrh Formation. The thrust continues down bald knoll to middle hill, where the Eureka and Fish Haven pinch out, and the fault plane becomes increasingly difficult to follow due to a Pogonip contact. Eventually, in the saddle between Little Hill and Bald Knoll, the Fish Haven and Eureka appear ephemerally once again, only to pinch out soon after. The thrust continues down the western side of middle hill, originally thought to only be a single fault. However, it has recently been proposed that this singular fault splits into 2-3 extremely closely spaced splays by grad students and TA's David Wheatley and Grant Rhea-Downing based upon small extremely easy to miss outcrops in which the fault plane can actually be seen and measured. Only one of these supposed outcrops could be found personally, and was measured to have an approximate orientation of 346, 46, however, the dip using a 3 point problem was found to be substantially lower, at about 14 degrees. In any case, this fault/these fault splays eventually disappear under the alluvium, only to appear once again as 3 distinctive and more widely spaced, roughly parallel splays along little hill, with the plane of the thrust marked by small sequences of reappearing and disappearing Eureka outcrops.

The normal fault is much more obvious than the thrust(s) due to the extremely distinctive contact between the Eureka Quartzite/Oquirrh Formation, and Pogonip Group/Oquirrh Formation. Interestingly the dip of the normal fault was calculated to be about ~21 degrees, which is substantially lower than what one would expect in a typical normal fault. It is known that this normal fault is a result of Sevier Compressional forces rather than Basin and Range extension (Dinter 2017). One possible explanation is that the abnormally low angle of this normal fault is due to gravitational failure. As thrust faulting pushed higher and higher, it eventually reached a point where it couldn't sustain itself and the less competent rocks on the bottom began to break and lose cohesion, causing the entire area to slide and fault, creating a normal fault at such a low angle. The Fault is generally easy to follow, with the Oquirrh being a distinct and ever-present contact all throughout. Interestingly, in the area of middle hill, the normal fault begins to do some strange curves. This is due to the fault plane being corrugated, rather than actually planar. This paired with erosion gives the appearance of fault plane doing some extremely bizarre things, when in reality, the erosion is simply causing the exposures to appear multiple times, and giving it its odd geometry. The fault eventually "normalizes" around the area of little hill, after which it completely disappears beneath the quaternary alluvial deposits.

Within the actual formations of the highlands, there are numerous smaller scale deformational structures which paint a fairly vivid picture of the area. The Pogonip in particular consists of 2 distinctive units representative of 2 deformational regimes. A myelinated marble unit, consistent with ductile deformation, and a brecciated marble unit, which is typical of brittle deformation. In addition to this it is generally highly foliated, and contains several sigmoid structures and quartz augen which show a generally top to the east (northeast) sense of shear.

The Fish Haven and Eureka are not prominently exposed, and reappear and pinch out, seemingly at a whim alongside the fault planes. The cause of this seemingly random appearance/disappearance Is due to tectonics and “faulting out (Dinter 2017). The Eureka Quartzite has been heavily metamorphosed, and little to no sedimentary structures remain, however, it outcrops in such little abundance in the area, and its outcrops are in general so poor, that very few deformational structures can be distinguished, however, small quartz augen faint S-C fabric can be seen within some of the more intact Eureka, also indicating a top to the East sense of shear.

Discussion and Geologic history

The history of the Raft River metamorphic core complex began with the deposition of the crystalline basement rocks, formed some 2.5 billion years ago on the passive margin of a volcanic arc system during the building of Laurentia (Dinter 2017) Included In this basement are the older schist, mafic igneous, Trondhjemite/Metapegmatite, and metamorphosed adamellite. Laurentia began to form as these volcanic island arcs accumulated into larger and more stable land masses, eventually causing these rocks to undergo high grade metamorphism. (Hintze and Kowalis 2009) As uplift continued as the Laurentia craton was building, erosional forces and non-depositional periods would reign, causing a massive 1.0-1.5 billion gap in the depositional history (Dinter 2017). Eventually, the Laurentian craton would begin to collide and combine with other “continental masses”, finally culminating in the formation of the supercontinent Rodinia, approximately 1.0-1.2 billion years ago. (Dott&Prothero 2010). Eventually, approximately 750 million years ago, the Rodinian supercontinent would begin to break apart, setting Northwestern Utah and the eventual area of the Raft River mountains on a hinge line as what would become modern Antarctica and Australia “drifted away” (Dott&Prothero 2010)

From the end of the Proterozoic to the end of the Paleozoic, Western North America, and the eventual Raft Rivers would be dominated by a shallow epeiric sea on a shallow marine carbonate shelf, resulting in the deposition of large amounts of dolostones, limestones, shales, and sandstones. The formations formed during this time period include the Elba Quartzite and its schist member in the Precambrian, the schist of the upper narrows also in the Precambrian, as well as the Pogonip group, Eureka quartzite, and Fish Haven in the Ordovician period, and the Oquirrh formation in the Pennsylvanian-Permian transition. (Dott&Prothero 2010) (Hintze and Kowalis 2009)

During the Cretaceous, around approximately 140 million years ago, the Sevier Orogeny began as the oceanic Farallon plate began to subduct underneath the Continental North American plate. This subduction caused conductive heating and resulted in the eventual compression of the North American continent. The Sevier orogeny uplifted and formed many of the mountain ranges in Western Utah and Eastern Nevada, as well as a series of thrust faults and folds which were created in response to these compressional forces. (Livacarri 1991) By this, the Raft River Range was sitting in the "hinterlands" of thrusts of the Sevier orogeny, where the thrusts had broken the surface. (Figure 10) The Sevier highlands began moving eastward, causing compression as land rose between the border of Utah and Nevada. (Wells, Dallmeyor et al. 1990) (Hintze and Kowallis 2009). The Sevier orogeny was responsible for a large amount of the deformation seen in the "lowlands" area of the Raft River mountain range, including the thrust fault (and its splays) as well as the normal fault, assumed to have been created as a result of gravitational failure due to continual sevier uplift resulting in less competent rocks eventually breaking, causing a slide. A large amount of ductile deformation occurred during Sevier activity, resulting in mylonitization of all units involved. Occurred. Uplift from the normal fault also caused brittle deformation, such as can be seen in the large amounts of vein filled fractures and slickenlines seen in the Oquirrh Formation.

The Farallon plate eventually completely subducted underneath the North American plate approximately 23 million years ago by the time of the Miocene. This led to a reduction in compressional forces as the North American plate made contact with the Pacific plate. (Dott & Prothero, 2010). Around 17 Ma this compressional relief caused expansion to begin, which ushered in the beginning Basin and Range extension and the formation of the Basin and Range province which encompasses a large portion of the Western coast of North America. This extension was responsible for the majority of deformation seen in the "Highlands" area, including the exhumation of the Raft River metamorphic core and extended the region by upwards of 100 % (Dinter 2017) (Figure 11)

The Elba Quartzite was deformed as a result of basin and range extension and this exhumation. Foliation of the elba, as well as several stretching lineations and their associated high angle fractures occurred as a result of Basin and Range extension, with the foliation and stretching lineations oriented approximately parallel to shear, and the high angled fractured being formed roughly perpendicular. In addition to smaller scale deformation in the Elba, larger scale features also occurred as a result of basin and range extension. The small angle normal fault at the top of the range occurred as the Raft Rivers rose beneath the Black Pine Mountain Range, eventually moving the black pines several kilometers to the East. In addition to this, large scale overturning of the “highlands” area occurred in the evolving shear zone.

In the present, Basin and Range extension is continuing to affect this area at a rate of approximately 0.2-0.6 centimeters per year (Dinter 2017) and active creeks, rivers, and alluvial fans in the Raft Rivers continue to erode and deposit new sediments, creating new rocks from the old in an ever-present cycle of destruction and creation. This erosion leads to mass wasting and collapse of some structures, burying some, and exposing new areas.

In addition to mapping describing, and interpreting the depositional history of the area, a large part was testing the “Rolling Hinge” hypothesis proposed by Bartley and Manning in 1994. To test this hypothesis, a series of “triplets” a series of associated foliation planes, stretching lineations, and their corresponding high angle factures were measured within the Elba Quartzite in the Highlands area. The results of these were plotted on a stereonet, and they were evaluated in order to test this hypothesis. Overall, small scale deformational structures within the units themselves, such as SC fabrics show a top to the East, or northeasterly sense of shear. The triplet measurements in general show a similar trend, with the High Angle Fractures being generally perpendicular, and in general, the dips begin to be primarily to the East. These Results, as well as the nature of the faults mentioned later, are consistent with the rolling hinge hypothesis. (Figure 4, 12)

Conclusions

The Raft River Mountains has a complex depositional and deformational history. The Depositional story began 2.5 Billion years ago, where Earth was a very different place, and continents as we know them today were just entering their infancy. From the formation of Laurentia, to the eventual breakup to Rodinia, Utah lie on a passive continental margin in which the dolostones, sandstones, limestones, and others which form the strata in the Raft Rivers were deposited. The climax of the main depositional story came to a head in the Pennsylvanian, in which the Oquirrh was deposited, however, it continues to trickle along in the present with ever continuing and active processes, which may, in the distant future, make its own story.

While the depositional story is beautiful in its own way, the structural and deformational story is of particular interest in this area. As all the exposed units are in general, heavily metamorphosed, and deformed, they give many clues to the deformational forces at play. There are two riveting deformational tales to be told in this area, the highlands, largely made what it is as a result of Basin and Range extensional processes, and lowlands, where Sevier Compression forces were the primary driver.

During Sevier thrusting, the Raft Rivers sat in the Hinterlands (Figure 10), in the ductile deformation regime. It was during this period that a great deal of the ductile deformation, such as mylonization occurred in the rocks exposed in the lowlands, and the thrust fault/associated splays, as well as the normal fault were formed. After the Farallon plate fully subducted, plate dynamics changed and Basin and Range extension began. It was these extensional forces which exhumed from beneath the Black Pine Range, bringing the various units and features seen prominently within the highlands to the surface, where they could at last be seen.

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References

Hintze, Lehi F., and Bart J. Kowallis. Geologic History of Utah. Provo, UT: Dept. of Geology, Brigham Young U, 2009. Print.

Hoffman, Paul F. (1988). "United Plates of America, The Birth of a Craton: Early Proterozoic Assembly and Growth of Laurentia" (PDF). Annual Review of Earth and Planetary Sciences.

Holland, Steven M. "Ordovician Period." Encyclopædia Britannica. Encyclopædia Britannica, Inc., 03 May 2017. Web. 10 June 2017.

Livacarri, R.F., 1991, Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide Orogeny, Western United States, Geology [Boulder], Vol. 19, Issue 11, pp. 1104-1107.

"Utah's Geologic History." Utah Geological Survey. N.p., n.d. Web. 10 June 2017.

Ross, Charles A., and June R.P. Ross. "Permian Period." Encyclopædia Britannica. Encyclopædia Britannica, Inc., 2014. Web. 10 June 2017.

Wells-Michael-L; Dallmeyer-R-David; Allmendinger-Richard-W, 1990, Late Cretaceous extension inthe hinterland of the Sevier thrust belt, northwestern Utah and southern Idaho; with Suppl. Data 90-20.Geology (Boulder). 18; 10, Pages 929-933. 1990. Geological Society of America (GSA).

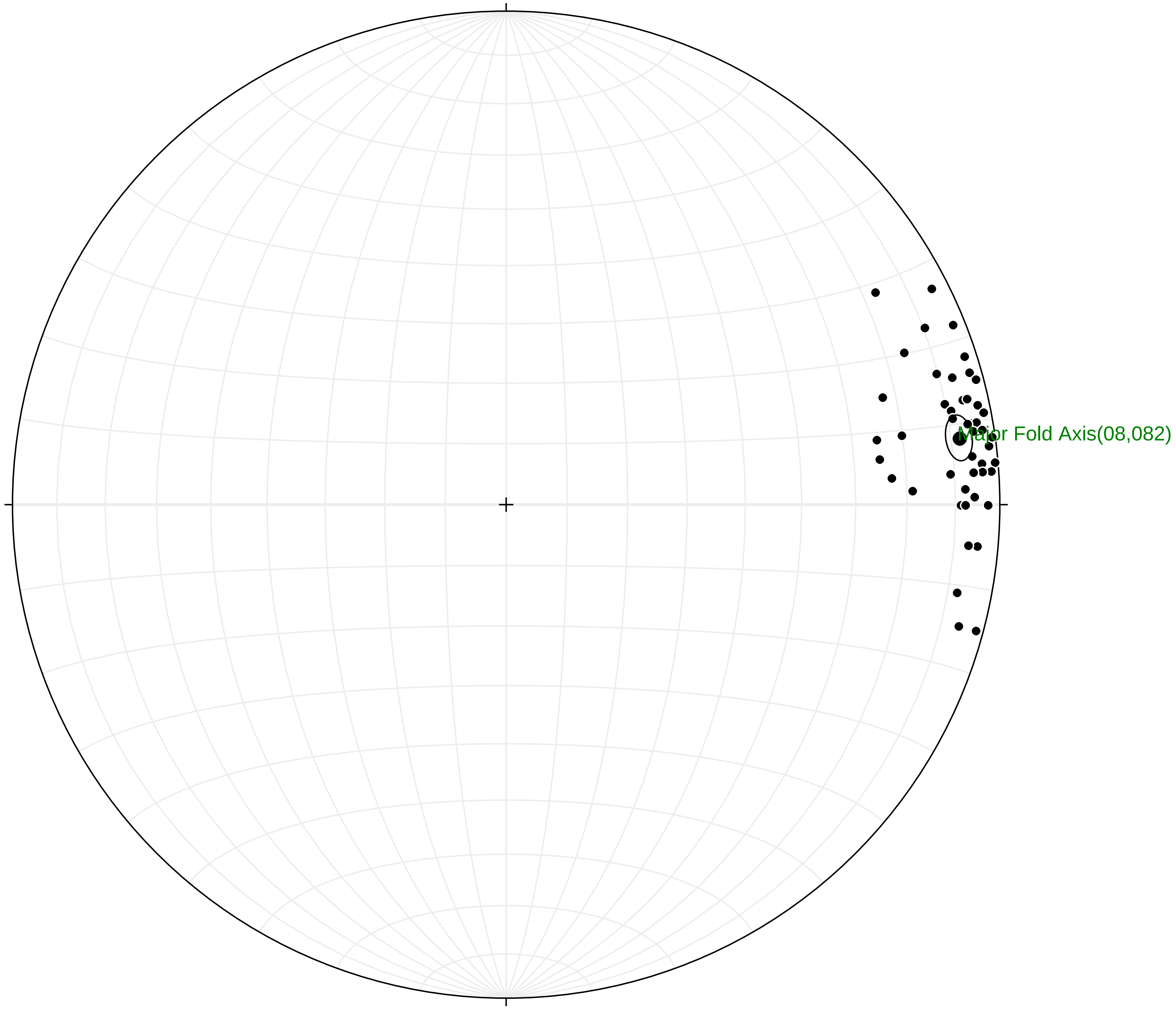
Salyards and Shoemaker. "Landslide and Debris Flow Deposits in Miocene Horse Spring Formation, Nevada: A Measure of Basin and Range Extension". GSA Centennial Field Guide, 1987.

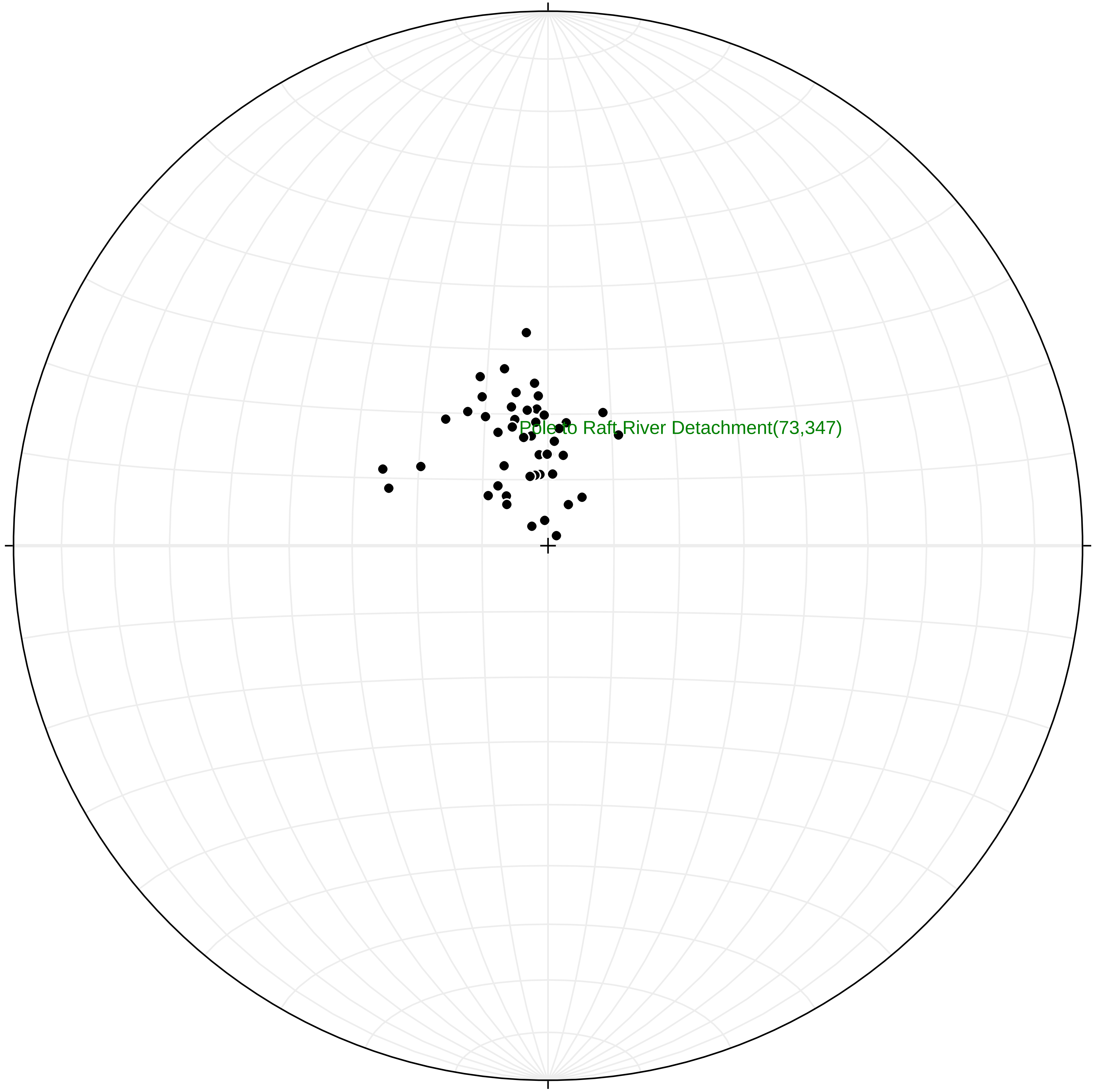
Prothero, Donald R., and Robert H. Dott. Evolution of the Earth. New York: McGraw-Hill, 2010. Print.

Manning, A., and Bartley, J. M., 1994, Postmylonitic deformation in the Raft River metamorphic core complex, northwestern Utah: Evidence of a rolling hinge. Tectonics, vol. 13, no. 2, p. 596-612.

Dr David Dinter, field methods and Field camp lectures and handouts, 2017.

David Wheatley and Grant Rhea-downing. Verbal 2017


Major Fold Axis(08,082)


Pole to Raft River Detachment(73,347)