

Geologic Map of the McClure Spring Syncline, Central Pancake Range, Nye County, Nevada

by

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INTRODUCTION

Documenting the style, geometry, and timing of contractional deformation is critical to understanding how orogenic systems evolve. In the Jurassic-Paleogene Cordilleran orogenic belt, many questions remain regarding the timing and geometry of crustal shortening, particularly within the hinterland region of the Sevier fold-thrust belt in Nevada, where Cenozoic extension has complexly overprinted Cordilleran contractional deformation (e.g., Gans and Miller, 1983; Taylor et al., 1993; 2000; Colgan and Henry, 2009; Long, 2012, 2015, 2019). In particular, the geometry and timing of deformation in the central Nevada thrust belt (CNTB), a system of east-vergent thrust faults and folds that branches northward off of the Sevier thrust belt in southern Nevada (fig. 1), have yet to be resolved along much of the along-strike length of this province (e.g., Bartley and Gleason, 1990; Vandervoort and Schmitt, 1990; Taylor et al., 1993, 2000; Long, 2012, 2015; Long et al., 2014). Near Eureka, Nevada (fig. 1), deformation in the CNTB has been interpreted to be coeval with deposition and folding of the Early Cretaceous Newark Canyon Formation, a sparsely-preserved fluvio-lacustrine rock unit (Long et al., 2014; Di Fiori et al., 2020). However, south of Eureka, the timing of motion of the CNTB structures can, in most places, only be bracketed between the Pennsylvanian and Oligocene (Taylor et al., 2000).

The central Pancake Range, located ~50 km southeast of Eureka, lies near the eastern limit of the CNTB (fig. 1). 1:250,000-scale reconnaissance geologic mapping in this range by Kleinhamp and Ziony (1985) revealed the presence of a broad-scale (~10 km minimum north-south length, ~3 km minimum east-west width), N-trending, overturned fold: the McClure Spring syncline. An aerially restricted exposure, the Cretaceous Newark Canyon Formation has been mapped within its hinge zone; however,

there is disagreement over whether the Newark Canyon Formation is folded or whether it overlaps the fold (Perry and Dixon, 1993). The existing 1:250,000-scale mapping does not permit evaluation of this important field relationship, which warrants investigation at a more detailed scale. To address this issue, we performed 1:24,000-scale geologic mapping of the full extent of exposed Paleozoic bedrock that defines the McClure Spring syncline (fig. 1). Our map encompasses a north-south extent of ~16 km and an east-west extent of ~5.5 km.

STRATIGRAPHY

Bedrock exposures in the map area consist of Mississippian-Permian clastic and carbonate rocks, Cretaceous fluvio-lacustrine clastic sediments of the Newark Canyon Formation, and overlying late Eocene-Oligocene volcanic rocks. The Mississippian, Pennsylvanian, and Permian rocks have been folded into the NNW-trending McClure Spring syncline. Paleozoic rocks are exposed primarily in the center of the map, with local exposures of Mississippian rocks in the southwestern corner. The Newark Canyon Formation (NCF; map unit Knc) is exposed in only one isolated exposure in the center of the map. Paleozoic and Mesozoic rocks are covered on the east, north, and southwest by Cenozoic volcanic rocks, which lie above folded Paleozoic rocks across an angular unconformity, and disconformably over NCF.

The Mississippian section consists of the Joana Limestone, Chainman Shale, and Diamond Peak Formation. The Joana Limestone (Mj) is exposed in the southwest corner of the map and has been overturned, brecciated, and pervasively silicified by hydrothermal alteration (unit Tj – jasperoid breccia). The Chainman Shale (Mc) is a thick section of mudstone and siltstone that is only exposed in the southwest corner of the map, where it forms subdued

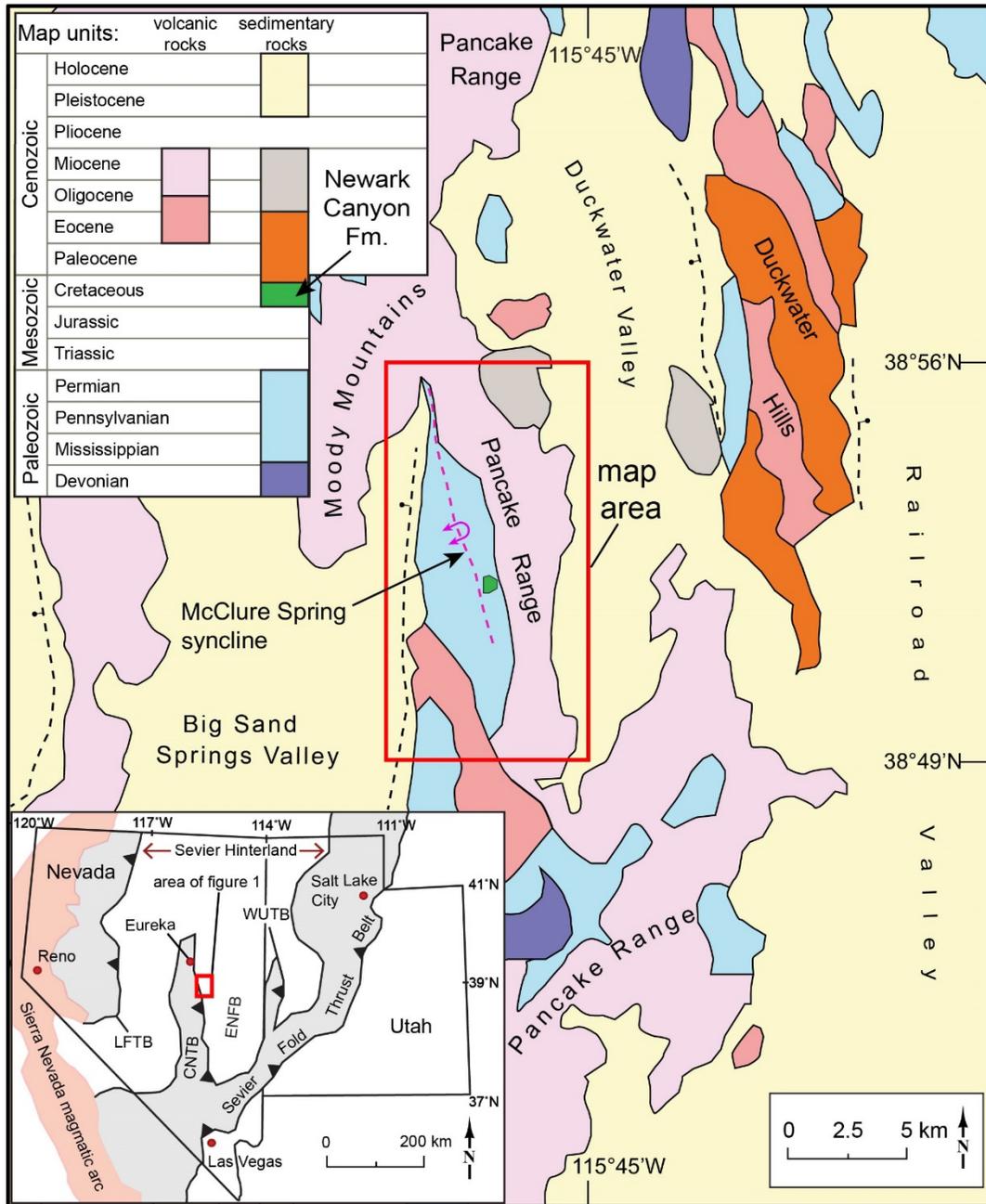


Figure 1. Geologic map of the central Pancake Range, showing the location of the map (modified from Crafford, 2007). Inset map in lower left shows Cordilleran thrust systems of Nevada and Utah (shaded gray) and the Sierra Nevada magmatic arc (shaded red) (modified from Long et al., 2014). CNTB = central Nevada thrust belt; ENFB = eastern Nevada fold belt; LFTB = Luning-Fencemaker thrust belt; WUTB = western Utah thrust belt.

topography. The thickness of Mc is difficult to determine; this unit likely underwent significant intraformational thickening during construction of the McClure Spring syncline due to the low competence of the mudstone compared to underlying and overlying thick-bedded carbonate and clastic units. The Diamond Peak Formation (Mdp) is only exposed along the western edge of the map area, within the overturned western limb of the McClure Spring syncline. It lies conformably beneath the Ely Limestone on the east and is in fault contact with Cenozoic volcanic rocks on the west. The Pennsylvanian Ely Limestone forms most of the exposed bedrock of the overturned western limb of the McClure Spring syncline, comprising the crest of the high topographic western ridge of the central Pancake Range at this latitude.

Permian rocks in the map area are interpreted to be correlative to the Carbon Ridge Formation (Pcr) defined near Eureka (Nolan et al., 1956). Pcr is lithologically distinguishable due to the presence of fluvial clastic intervals and by the presence of fusulinids. In our map, Pcr is split into three units which are conformable and exhibit gradational contacts. Unit Pcr₁ is exposed along nearly the entire length of the overturned western limb of the syncline, and is also exposed within the eastern limb of the syncline where it dips moderately to the west. Unit Pcr₂ is present in the same general location as Pcr₁, but has a greater north-south extent and is confined to the hinge zone of the syncline. Unit Pcr₃ exhibits the smallest aerial exposure of any Permian unit and is found only within the hinge zone at the north end of the syncline.

The NCF is only exposed approximately 200 meters south of McClure Spring near the center of the map, in a series of meter-scale outcrops beneath Cenozoic volcanic rocks in recently eroded washes. The exposed NCF section consists of three distinct lithologies: a lower mudstone, a middle conglomerate, and an upper sandstone. The lower mudstone is poorly exposed, and the middle conglomerate and upper sandstone form resistant ledges and steep hillslopes just below the contact with Cenozoic volcanics. The NCF overlies Permian rocks across a steep angular unconformity and is disconformably overlain by Cenozoic volcanic rocks. The depositional age of NCF is not precisely known, but the lower mudstone has yielded dinosaur bones that indicate deposition in the Late Jurassic or Cretaceous (Perry and Dixon, 1993). In a related study that focuses on the structural geometry and geologic history of the map area (Di Fiori et al., 2021), we dated detrital zircons separated from the basal mudstone and obtained a maximum depositional age (defined by the youngest 5 zircon grains that overlap within error) of 129.2 ± 2.6 Ma, defining the base of the section as Albian or younger. This geochronology, combined with the age range of the dinosaur fossils, defines a permissible depositional age range between ~129 Ma and ~66 Ma (Early to Late Cretaceous).

There are five late Eocene to Oligocene volcanic units in the map area, which unconformably overlie the folded Paleozoic rocks and generally dip shallowly (~10–30°) to

the east. The Stone Cabin Formation (Tsc) is a rhyolitic tuff dated at 34.1 ± 0.9 Ma (K-Ar biotite; Gromme et al., 1972) lying stratigraphically below unit Td (intermediate lavas). It is mainly exposed in the southeastern part of the map area, with a small exposure in the upper northwest corner, where it is overlain by Td and the undivided Pancake Summit Tuff and Windous Butte Formation (unit Tpb). Unit Taft (Tertiary ash-flow tuff) shares a similar stratigraphic position to Tsc, in stratigraphic contact below Td in the northeastern part of the map. Unit Td covers much of the eastern half of the map and is also exposed in the southwestern corner. The Windous Butte Formation (Twb), a rhyolitic tuff deposited at ~31.8 Ma (⁴⁰Ar/³⁹Ar of biotite and sanidine; Taylor et al., 1989), is present in isolated exposures in the center of the map, where it overlies NCF and is in fault contact with Td to the east. Unit Tpb (undivided Pancake Summit Tuff and Windous Butte Formation; 35.36 ± 0.07 Ma to 35.40 ± 0.06 Ma) is widespread and is found in the northwest corner of the map overlying Tsc, in the center part in fault contact with Td, and in the southwestern part in fault contact with Td.

Tertiary rhyolitic lavas and tuffs of Portuguese Mountain (Tq) were defined by Quinlivan et al. (1974) as time-equivalent to unit Tsc (~34 to ~31 Ma), based on an interfingering contact between these two units observed south of the map near Portuguese Mountain. We have divided Tq into three separate units, a lower lithic tuff (Tq₁), an overlying felsic lava (Tq₂), and an upper lava flow margin (Tq₃). Units Tq₁ and Tq₂ are exposed in the southwestern corner of the map where Tq₁ is conformably overlain by Tq₂. Tq₃ crops out in an isolated, NNE-striking linear exposure, adjacent to outcrops of Mj and Mc to the west of the other Tq units.

A single exposure of Tertiary megabreccias (Tes) is present at the northern edge of the map. Tes is composed of meter-scale angular blocks of lithic tuff, compositionally equivalent to proximal Oligocene tuffs and lavas (Kleinhampl and Ziony, 1985). The exact timing of emplacement of these megabreccias is difficult to determine, due to the lack of exposure of contacts with proximal bedrock units.

Quaternary sediments in the map area consist primarily of alluvium. The oldest alluvial deposits are inactive alluvial fans (QTaf), which are topographically elevated compared to younger fans and are exposed in isolated patches along the eastern side of the map. Two younger generations of alluvial fans are also exposed (units Qoaf and Qaf). The majority of the inactive Qoaf exposures are in the northern and southeastern parts of the map. Qoaf deposits are overlain by younger Qaf deposits. Qaf dominates the map outside of the exposed area of bedrock, forming a veneer across the valleys adjacent to the central Pancake Range, while also covering much of the hinge zone of the McClure Spring syncline. These young fans are inset below the older fans and are active depositional surfaces in parts of the map. The youngest and active late Quaternary deposits consist of

hillslope colluvium (Qc) and recent alluvium and alluvial terraces in active washes (Qal and Qalt).

STRUCTURAL FRAMEWORK

The NW-trending McClure Spring syncline dominates the large-scale structural geometry of Paleozoic bedrock. The western limb of the syncline is overturned to the west by an average of $\sim 40^\circ$, though it is locally overturned by as much as 60° and as little as 10° . The eastern limb, though it exhibits a minimal exposure extent compared to the western limb, dips moderately ($\sim 45^\circ$) to the west-southwest, but dips vary locally from 76° to as shallow as 26° . The axial plane defined by these two limbs dips $\sim 45^\circ$ westward. Therefore, with an interlimb angle of nearly 0° , the McClure Spring syncline is an isoclinal fold. Because of this isoclinal geometry, it is difficult to estimate the precise depth of the hinge zone in the subsurface on the cross sections, so a conservative minimal depth estimate is shown.

This east-vergent, kilometer-scale syncline records shortening that can be bracketed between the Permian and the Cretaceous (< 129 Ma to > 66 Ma) deposition of NCF. The NCF dips gently eastward, and projects ~ 1.3 km along-strike to the north to W-dipping Permian rocks in the eastern limb of the McClure Spring syncline, defining an angular unconformity with up to $\sim 70^\circ$ of dip difference. Therefore, deposition of NCF post-dates the construction of the McClure Spring syncline, as well as significant erosion of its eastern limb. Based on this field relationship, folding in the central Pancake Range at this latitude predated the end of the Cretaceous (and perhaps was completed by the Early Cretaceous).

The magnitude of shortening accommodated by construction of the McClure Spring syncline provides useful information for the deformation history of the CNTB at this latitude. By comparing present-day and the pre-deformational lengths of Permian bedding contacts on the cross sections, we estimate that a minimum of ~ 3.2 km of shortening was accommodated by construction of the McClure Spring syncline.

East- and north-striking normal faults with varying offset magnitudes are observed in the map area and cut the folded Paleozoic rocks as well as the east-dipping late Eocene-Oligocene volcanic rocks. This system of normal faults, as well as the gentle overall eastward tilt of volcanic rocks, is attributed to regional, late Cenozoic Basin and Range extension (e.g., Long et al., 2018; Long, 2019). The more significant normal faults in the map area include: 1) a north-striking, down-to-the-west normal fault in the southwestern corner of the map that places Oligocene volcanic rocks against units Mdp and $\mathbb{P}e$; 2) a range-bounding, down-to-the-west normal fault that is inferred to exist outboard and west of the McClure Spring syncline (note that the map does not exhibit any stratigraphic offset or fault scarps to determine its precise location) (Kleinhampl and Ziony, 1985); 3) a series of north- and east-striking normal faults within the hinge zone of the McClure Spring syncline that accommodated ~ 10 's of meters of offset; and

4) multiple east- and north-striking normal faults with approximately tens of meters of offset in the Cenozoic volcanic rocks that surround the folded Paleozoic rocks.

A note on previous mapping of the Cretaceous Newark Canyon Formation and the Permian Carbon Ridge Formation

In past studies in the Pancake Range, there has been disagreement on delineating upper Permian clastic units from the NCF. Kleinhampl and Ziony (1985) mapped queried NCF outcrops adjacent to fluvial clastic outcrops labeled "Ps?" (undivided Permian sedimentary rocks) within the hinge zone of the fold. However, later work by Perry and Dixon (1993) assigned the entirety of NCF exposure to a spatially isolated outcrop of poorly indurated mudstone underlying ledges of carbonate clast conglomerate south of McClure spring. The only depositional age control that Perry and Dixon (1993) discussed for the basal mudstone exposure was the presence of dinosaur bone fragments, which were found by T.D. Fouch and Perry and were identified as Late Jurassic or Cretaceous by Jack Horner via personal communication.

Additionally, contention persisted in previous studies over whether the NCF was folded along with Paleozoic rocks or if deposition of the NCF post-dated folding (Kleinhampl and Ziony, 1985; Perry and Dixon, 1993). We mapped the NCF in one isolated exposure in the center of the map (similar to the mapping of Perry and Dixon, 1993) and documented that it consists of a conformable stratigraphic sequence defined by a basal mudstone, a middle carbonate-clast conglomerate, and a capping, algal mound-bearing sandstone horizon. This stratigraphic package is broadly similar to other NCF exposures that we have examined to the north and northwest in the Fish Creek Range, Diamond Mountains, and Cortez Mountains (Di Fiori et al., 2020, 2021). Our mapping shows that the NCF dips gently to the east, and projects northward ~ 1.3 km to $\sim 45^\circ$ west-dipping Permian rocks within the eastern limb of the McClure Spring syncline. This defines an angular unconformity with up to 60 – 70° of dip difference with Permian rocks, and therefore we interpret that deposition of NCF post-dates construction of the McClure Spring syncline. The NCF exposures originally mapped by Kleinhampl and Ziony (1985) are here interpreted as part of the upper Permian section, specifically unit Pcr_3 , which is a tan to brown sandstone that is conformable with underlying Permian units (Pcr_{1-2}).

GEOLOGIC HISTORY

The central Pancake Range exhibits evidence for multiple episodes of deposition and deformation spanning from the mid-Paleozoic to the present day. During the Neoproterozoic to Devonian, the western U.S. was the site of passive, shallow marine, clastic and carbonate sedimentation (e.g., Stewart and Poole, 1974; Stewart, 1980). During the Late Devonian-Mississippian Antler

orogeny, an obduction event farther to the west in Nevada that resulted in eastward thrusting of slope and basal rocks over the western edge of the continental shelf, clastic sedimentary rocks were shed eastward from highlands in central Nevada into a foreland basin in eastern Nevada (e.g., Speed and Sleep, 1982; Poole et al., 1992; Dickinson, 2004). Mississippian rocks, which are the oldest rocks exposed in the map, record the eastern extent of the Antler foreland basin sedimentation. After the termination of the Antler orogeny, during the Pennsylvanian-Permian, this region again underwent deposition of shallow marine carbonates, followed by a period of fluvial clastic deposition (e.g., Stewart, 1980).

During the Jurassic, an Andean-style subduction system developed off of the western coast of North America, which initiated construction of the Jurassic-Paleogene North American Cordilleran orogenic belt (e.g., Allmendinger, 1992; Burchfiel et al., 1992; DeCelles, 2004; Yonkee and Weil, 2015). During Cordilleran orogenesis, the map lay within the broad 'hinterland' region to the west of the Sevier fold-thrust belt in central and eastern Nevada (e.g., Armstrong, 1968; DeCelles, 2004; Long, 2012; Yonkee and Weil, 2015). Most of the hinterland was characterized by minimal shortening and low-amplitude, long-wavelength folding (e.g., Gans and Miller, 1983; Taylor et al., 2000; Long, 2012; 2015). The central Pancake Range lies within the CNTB, a hinterland structural province defined by E-vergent, N-striking thrust faults and folds that branch northward from the Sevier fold-thrust belt in southern Nevada, which is estimated to have accommodated ~10–15 km of shortening (Taylor et al., 2000; Long et al., 2014). Most of this contractional deformation is interpreted to have occurred after the Pennsylvanian-Permian, on the basis of the youngest rocks deformed by folds and thrust faults (Taylor et al., 1993). In a few localities farther to the south in the CNTB, contractional deformation is interpreted to have ceased by ~85 Ma, on the basis of crosscutting relationships of CNTB structures with undeformed granitic intrusions (Taylor et al., 2000).

The exposure of the Newark Canyon Formation in the map allows us to constrain the timing of CNTB deformation at this latitude. The ~60–70° angular unconformity between Permian rocks in the eastern limb of the McClure Spring syncline and the gently east-dipping NCF indicates that folding pre-dated NCF deposition. The ~129 Ma detrital zircon maximum depositional age calculated from the basal mudstone (Di Fiori et al., 2021) combined with dinosaur fossils that could be as young as the terminal Cretaceous (Perry and Dixon, 1993) brackets construction the McClure Spring syncline between the Late Permian and the end of the Cretaceous.

During the late Eocene and Oligocene, the Sevier hinterland experienced a north-to-south sweep of felsic magmatism known as the 'Great Basin ignimbrite flare-up', which is hypothesized to have been generated by the steepening of the subduction angle of the Farallon plate following the Laramide orogeny (e.g., Humphreys, 1995; Smith et al., 2014). Igneous rocks from this event preserved

in the map area are represented by rhyolitic and dacitic lava flows and ash-fall tuffs, as well as a few felsic dikes. Most of these volcanic units have been dated between ~35 and ~31 Ma by previous workers in studies in the surrounding region (Gromme et al., 1972; Kleinhampl and Ziony, 1985; Taylor et al., 1989).

Regional extension that formed the Basin and Range Province has been attributed to the reorganization of the Pacific-North American plate boundary into a transform system in the Miocene (e.g., Atwater, 1970; Dickinson, 2002, 2006). The map and the surrounding region exhibit evidence for this extension, in the form of multiple dominantly north-striking normal faults, which cut the Paleozoic sedimentary rocks and late Eocene-Oligocene volcanic rocks. The overall gentle eastward tilting recorded by late Eocene-Oligocene volcanic rocks throughout the map is also attributed to Neogene Basin and Range extension.

DESCRIPTION OF MAP UNITS

Quaternary Deposits

Alluvial deposits

Qal Active stream-channel deposits (Holocene) Poorly-sorted, active alluvial sediments. Size ranges from boulders to silt. Deposited in active washes and ephemeral stream channels.

Qc Colluvium (Holocene) Veneer of poorly-sorted, angular, slope-covering sediment deposited over steep slopes, mainly below ridge- and cliff-forming bedrock outcrops. Clasts range in size from silt to boulders.

Qalt Alluvial channel terraces (Holocene) Poorly-sorted, unconsolidated alluvial sediments, with clasts ranging in size from boulder to silt. Deposited directly outboard of active washes and ephemeral stream channels.

Alluvial-fan deposits

Qaf Active alluvial-fan deposits (Holocene) Non-lithified, silty to sandy, pebble to cobble and locally up to boulder-sized clasts deposited in active alluvial-fan systems, which onlap onto older alluvial-fan deposits. Commonly exhibits poorly developed desert pavement and armoring, as well as weak or incipient desert varnish.

Qoaf Inactive alluvial-fan deposits (Holocene to Pleistocene) Abandoned alluvial-fan deposits consisting of non-lithified clasts ranging from silt to boulder sized. Exhibits better-developed desert pavement and surface armoring than Qaf.

QTaf Old inactive alluvial-fan deposits (Pleistocene to Miocene) Composed of fine sand to coarse gravel. Often topographically higher than the other alluvial-fan deposits. Exhibits advanced development of surficial armoring and desert pavement. Exposed pavement rocks exhibit well-developed desert varnish.

Qtes Exotic slide block/megabreccia deposits (Holocene to Miocene) Clast-supported, brecciated body in the northeast corner of the map. Composed mainly of Oligocene tuffs and lavas. Clasts range in size from meter-scale to small gravel. Interpreted by Kleinhampl and Ziony, (1985) to have been emplaced as a mega landslide deposit based on interpretations of tectonic-related brecciation and subsequent alteration (gentle to moderate silicification and argillization).

Tertiary Rocks

Tj Jasperoid breccia (Miocene to Eocene) Red to brown, brecciated and silicified carbonate, exposed in the southwest corner of the map. Map patterns and inherited texture indicate that the protolith is likely the Mississippian Joana Limestone. Forms steep ridges and erodes as large angular blocks.

Twb Windous Butte Formation (early Oligocene) Banded to laminated, red-brown, pink, to light-gray rhyolitic ash-flow tuff. Groundmass is typically light brown and gray but is locally purple and orange. Phenocryst assemblage consists primarily of plagioclase with a lesser abundance of biotite and quartz. Eutaxitic intervals are present but rare. Resistant to weathering, forming moderately steep hills and slopes. Erodes as large blocks. Mean age is ~ 31.8 Ma from $^{40}\text{Ar}/^{39}\text{Ar}$ of biotite and sanidine (Taylor et al., 1989). Thickness ~ 50 – 150 meters.

Tpb Pancake Summit Tuff/ Windous Butte Formation undivided (early Oligocene to late Eocene) Weakly to non-welded red, brown, and gray rhyolitic, crystal-rich ash-flow tuff. Groundmass is dominantly red, brown, gray, and contains phenocrysts of quartz (some smoky quartz), sanidine, and lesser amounts of plagioclase and biotite. Weathers dark brown to red-brown. Erodes as crumbly blocks and forms steep but subdued topography exposed beneath the resistant overlying Td. The timing of Tpb emplacement can be bracketed between 35.36 ± 0.07 Ma to 35.40 ± 0.06 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ sanidine ages from the Pancake Summit Tuff in the Diamond Mountains; Long et al., 2014) and ~ 31.8 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ of sanidine from the Windous Butte Formation in the Quinn Canyon Range; Taylor et al., 1989). Thickness ~ 250 meters.

Td Dacitic-latic lavas (early Oligocene to late Eocene) Brown to red-brown, crystal-lithic lava and lava breccia. Contains local brick-red aphyric horizons. Phenocryst percentage is low, consisting of mostly clear quartz crystals and hornblende. Pervasive groundmass-supported breccia with angular clasts ranging from boulder to pebble size is common. Groundmass is medium-light gray with disseminated mm-scale hornblende phenocrysts. Forms steep cliffs, ridges, and ledges. Erodes as large angular blocks forming steep talus slopes. Age is bracketed between ~ 34.1 and ~ 31.8 Ma by overlying Twb/Tpb and by underlying Tsc. Thickness ~ 100 – 400 meters.

Taft Rhyolitic ash-flow tuff (early Oligocene to late Eocene) White to gray-blue, non-welded, crystal-lithic

rhyolite tuff with interfingering lenses of tuff exhibiting varying degrees of eutaxitic texture, up to vitrophyre. The lower part of the unit is dominated by light-gray lithic-tuff exhibiting cross-stratification. Welding becomes stronger and more prominent in the upper part of the unit and is strongest just below the contact with overlying Td. Phenocryst assemblage is mostly quartz with lesser plagioclase and sanidine and minor biotite. This unit is only exposed stratigraphically below Td in the eastern portion of the map. Forms subdued but moderately steep hillsides and erodes in crumbly blocks. Thickness ~ 100 meters.

Tsc Stone Cabin Formation (late Eocene) Pink to brown, rhyolitic, moderately-welded ash-flow tuff. Abundant lithic and pumice fragments. Grades downward into highly-welded, red-pink, crystal-vitric tuff with rare vitrophyre intervals. Incipient devitrification can be seen in the vitrophyre intervals. Phenocryst assemblage is primarily quartz, with rare plagioclase and biotite. Forms subdued but steep slopes beneath the resistant lavas of Td. Mean age is 34.1 ± 0.9 Ma (K-Ar biotite; Gromme et al., 1972). Thickness ~ 300 meters.

Tq Rhyolitic lava/tuff of Portuguese Mountain Interfingers with the Stone Cabin Formation to the south of the map and therefore is interpreted to be of similar age (~ 34 – 31 Ma; Quinlivan et al, 1974).

Tq₃ Upper unit Light to medium-gray to pinkish-brown, flow-banded rhyolite. Compositionally very similar to Tq₂. Primary difference is pervasive decimeter-scale contorted flow banding. Thickness ~ 200 meters.

Tq₂ Middle unit Light to medium-gray, pink, to red-brown, flow-banded, vesicular, crystal-rich rhyolitic lava with subparallel, dark-gray to black vitrophyric intervals. Vesicles, ranging from mm to cm-scale, are common and are parallel to flow-banding. Vitrophyre horizons exhibit advanced devitrification. Forms steep slopes, ledges, and cliffs. Erodes as large blocks forming steep talus slopes. Thickness ~ 200 meters.

Tq₁ Lower unit Light-gray, tan, and pink-brown, non-welded, pumice-rich, lithic ash-flow tuff. Commonly exhibits fracture-controlled, red-brown silicification. Phenocryst assemblage includes disseminated plagioclase and quartz with lesser abundances of potassium feldspar and biotite. Forms steep, but subdued slopes beneath Tq₂ and erodes and large, crumbly blocks. Minimum thickness ~ 145 meters.

Cretaceous Rocks

Knc Newark Canyon Formation The lower part consists of poorly-exposed, gray-brown to dark-gray claystone and siltstone with fine- to medium-grained sandy horizons and lenses. Contact with underlying Permian units is not exposed; a minimum thickness of ~ 5 meters is estimated. The middle part of the unit consists of gray, well-sorted, pebble to cobble, clast-supported conglomerate.

Clasts are composed primarily of Paleozoic limestone with lesser amounts of sub-rounded to sub-angular black and gray chert. Conglomerate matrix is light-gray to pink-gray, fine- to medium-grained sand of mostly carbonate composition. Gray to pink-gray interstitial horizons of fine carbonate sand overlie the main conglomerate horizon. Outcrops form moderately-resistant horizontal ledges and erode to sand and gravel scree slopes. The upper part of the unit consists of poorly-bedded brown, yellow, and gray sandy siltstone. Brown to red-brown, fracture-controlled iron oxides are pervasive throughout this unit. Laminated, yellow-brown, concentric convex stacks interpreted to be algal mounds comprise most of this unit. Erodes as fine- to coarse-grained sandy hillslope cover. Forms steep to moderate hillslopes from below resistant volcanic rocks. Dinosaur bones bracketed between Late Jurassic and Cretaceous in age have been described from the basal mudstone (Jack Horner pers. comm. in Perry and Dixon, 1993), and the youngest five detrital zircons that overlap within error yield a ~129 Ma maximum depositional age for the basal mudstone (Di Fiori et al., 2021). The cumulative thickness unit Knc (NCF) is ~30 m.

Paleozoic Rocks

Pcr Carbon Ridge Formation (Lower Permian)

Pcr₃ Unit 3 Tan, gray, and light-brown, fine- to coarse-grained cherty sandstone with calcareous siltstone intervals. Grades upward from chert gravel-rich horizons into sand-dominated facies. Sandstone is massive, planar, and cross-stratified. Exposures form resistant, gently to moderately sloping hills. The coarser sand intervals erode as angular platy fragments, while the fine-grained horizons are fissile. The contact with underlying Pcr₂ is gradational. Thickness ~200–300 meters.

Pcr₂ Unit 2 Gray, red, and pink, chert clast-rich, calcareous sandstone and conglomerate. Distinguished from Pcr₁ by the dominance of traction depositional facies. Sandstone intervals are well bedded, with some normal grading, but are primarily massive and cross-stratified (with planar, trough, and low-angle cross-bedding). Conglomerates are both clast supported and matrix supported; both are present in equal abundance. Gravel clasts are mainly composed of chert pebbles of varying colors and minor carbonate clasts. Rugose corals from Pcr₁ are recycled as pebble clasts. Forms ledges and resistant ridges and erodes into small angular blocks. Gradational contacts are observed between Pcr₁ below and Pcr₂ above. Thickness ~200–350 meters.

Pcr₁ Unit 1 Red, pink-tan, and cream wackestone, calcareous mud, and siltstone, which grade upward into silty and sandy wackestone. The upper sandy limestone is composed of multi-colored chert granules. This unit is well-bedded, generally massive and planar, and contains mm-scale silicified fusulinids and abundant cm-scale rugose horn corals. This unit forms steep ridges and

ledges and erodes into large, angular blocks. The appearance of fusulinids demarcates an abrupt lower contact with **Pe**. Thickness ~300–400 meters.

Pe Ely Limestone (Pennsylvanian) Thick, well-bedded, gray to blue-gray, massive, cherty limestone. Chert ranges from black, gray, to red-brown, though red and green are also observed, and is primarily in nodule form, though bedding-parallel stringers are also common. The basal part of the unit is composed primarily of wackestone with clay intervals, which transitions upward into a massive cherty limestone with chert-pebble conglomerate lenses increasing in abundance. Fossil hash consisting mainly of crinoid stem pieces is common, especially in the finer carbonate facies. Forms meter-scale cliffs and ledges. Erodes in large, angular blocks and is flaggy where limestone bedding is thin (~cm scale). Generates steep talus slopes and cones. Underlying contact with Mdp is conformable and relatively sharp. Upper contact with Pcr₁ is relatively sharp as defined by the appearance of fusulinids. Thickness ~500 meters.

Mdp Diamond Peak Formation (Upper Mississippian)

Red-brown, dark-orange, and yellow-brown, coarse silica-cemented sandstone and conglomerate. Surficial dark red to black desert varnish is well-developed in this unit. Consists primarily of well-bedded, fine- to coarse-grained sandstone and pebble-cobble conglomerate. Sandstone facies are tabular and exhibit centimeter to decimeter-scale thicknesses. The sandstone intervals can be massive, planar, and/or trough and planar cross-stratified. Conglomerate is generally clast supported with fine- to coarse-grained sandstone matrix. Gravel clasts are composed primarily of quartzite and black and gray chert, with less abundant carbonate. Interstitial siltstone is less abundant, generally horizontally laminated and commonly contains ripple marks. Wood imprints in fine-grained lithologies are common. Very resistant to weathering, forming steep ridges and cliffs. Erodes into large, angular flaggy blocks forming talus slopes. The lower contact is not exposed in the map. The upper contact is conformable with **Pe**. Thickness ~300 meters.

Mc Chainman Shale (Upper Mississippian) Black to dark gray, thinly-laminated shale and calcareous mudstone with less abundant, intercalated dark-brown to tan, fine- to medium-grained sandstone intervals. Shale commonly exhibits weathered surfaces ranging from yellow to orange-brown. Fine-grained lithologies form gently-dipping hillslopes and muted topography. Erodes as soft, fissile colluvium. The upper and lower contacts are not exposed. Thickness ~600 meters.

Mj Joana Limestone (Mississippian) Thin- to medium-bedded, medium- to light-gray limestone with local lenses of brown, clast-supported, chert pebble conglomerate. Exposures are generally brecciated. Weathers brown, dark brown, and red-brown, with fractured-controlled stockwork jasperoid throughout outcrop. Forms cliffy outcrops with resistant ledges. Erodes as large angular blocks collecting at

the base of the exposure as talus. Lower and upper contacts are not exposed in map. Thickness ~650 meters.

Du Upper Devonian strata, undivided Shown in cross sections only; not exposed at surface within the map boundary.

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