

## **II. Late Cretaceous tectonic evolution of the Deep Creek Range-Kern Mountains block, eastern Nevada and western Utah: Magmatically induced large-scale folding, dynamothermal metamorphism, and ductile strain at mid- to upper-crustal levels in the Sevier hinterland**

### **Introduction**

The Kern Mountains and Deep Creek Range (KMDCR), situated on the Nevada-Utah border in the heart of the Northern Basin and Range, display a rich Late Cretaceous history of metamorphism, magmatism and deformation. The position of these ranges to the west of the east-vergent Sevier fold-and-thrust belt (Armstrong, 1968), and the overlapping age(s) of the Late Cretaceous magmatism, metamorphism and penetrative strain in the hinterland with shortening in the foreland (e.g., DeCelles & Coogan 2006; Miller & Bradfish, 1980; Douce et al., 1990) have led most workers to conclude that the hinterland tectonism is a direct manifestation of the same Mesozoic retroarc shortening that produced the better known thrust belt to the east. One perspective is that the isolated metamorphic/magmatic culminations in the hinterland provide windows into the Late Cretaceous lower to middle crustal mush/migmatite zone of broadly distributed penetrative deformation and thickening, prograde metamorphism and anatexis (e.g., Price & Mountjoy 1970; Miller & Gans, 1989) – effectively the middle to lower crustal accommodation of upper crustal shortening to the east. The alternative view is that these culminations are isolated features, perhaps reflecting areas of localized crustal thickening (e.g., Coney & Harms, 1984; Wrobel et al. 2021), lower crustal diapirism (e.g., Zuza & Cao, 2022), or lithospheric delamination (Wells & Hoisch, 2008). Although the Sevier fold-and-thrust belt is one of the best-studied in the world, its hinterland is much less well-understood with many fundamental questions remaining

regarding the amount of shortening and the precise relationship between magmatism, metamorphism, and deformation in this region.

The single large tilt block represented by the KMDCR provides an exceptional place to investigate these topics. The  $\sim 40^\circ$  of westward tilting associated with slip on the major range-bounding normal fault on its eastern margin provides an intact cross section of the pre-extensional upper to middle crust, exposing a broad spectrum of late Mesozoic structures. Although this study specifically focuses on the KMDCR, it has implications for several interrelated broader topics on Cordilleran tectonics, including:

- a) *What is the magnitude, style and timing of shortening in the hinterland of the Sevier belt?* The lack of a significant angular unconformity between Paleozoic rocks and the Cenozoic section as well as the observation that Cenozoic rocks are almost exclusively deposited on the upper Paleozoic units has led some to argue that the middle to upper crust in the hinterland was only weakly deformed during the Mesozoic as it was transported eastward above a basal décollement without undergoing much internal deformation (e.g., Miller et al., 1983). However, the presence of large-scale shortening structures and well as metamorphic assemblages that suggest deep tectonic burial suggests that at least locally there was significant shortening in the middle to upper crust (Greene, 2014; Harris et al., 2007; Long, 2015; Wrobel et al., 2021).
- b) *What was the precise interplay and genetic relationships between metamorphism, magmatism and deformation in the Sevier hinterland?* The hinterland crust experienced both regional and local dynamothermal metamorphism during the Late Cretaceous (Miller et al., 1988) as well as the emplacement of numerous

leucogranite plutons (e.g., Lee et al., 1981) that are often closely associated with increases in both metamorphic grade and penetrative strain. Are the leucogranites best viewed as a cause of the observed metamorphism or as a consequence of the same regional crustal thickening event? Similarly, are the well-developed tectonite fabrics and folds associated with these metamorphic culminations a localized strain—perhaps associated with pluton emplacement or diapirism, or do they document regional shearing and crustal thickening associated with Sevier age hinterland crustal shortening?

This study addresses these topics by integrating detailed geologic mapping, mesoscopic and microscopic structural analysis, petrography, and igneous and metamorphic geochronology of key localities in the KMDCR. Specifically, this paper focuses on:

- 1) What are the ages, magnitude and character of mesoscopic to map-scale deformation and metamorphism in these range?
- 2) What are the spatial and temporal relationships between map-scale and outcrop-scale structures, tectonite fabrics and metamorphic mineral growth?
- 3) What are the spatial and temporal relationships between the metamorphic and deformational features described above and various intrusive bodies exposed in these ranges, and what do these relationships indicate regarding the role of plutonism vs. regional tectonics in producing these observed deformational and metamorphic features?

Of particular interest is the Water Canyon Anticline (WCA), a large recumbent fold in the southern DCR that was previously interpreted to reflect west-directed Sevier age

shortening in the hinterland (Rodgers, 1987). Here, we present an entirely different interpretation that this fold and associated fabrics are instead primarily the result of emplacement of a large Late Cretaceous pluton, the Tungstonia Granite (TG). This paper presents a detailed geologic map of a ~35 km<sup>2</sup> area in the southern DCR spanning the overturned limb of the WCA, as well as detailed maps of the ~7 km<sup>2</sup> northwest and ~16 km<sup>2</sup> southwest flanks of the KM along the margins of TG. This mapping was accompanied by detailed mesoscopic structural analyses of folding, bedding and cleavage orientations, and assessment of strain magnitudes and orientations. Petrographic analysis of samples from both the southern DCR and western KM shed additional light on the nature and conditions of penetrative strain and metamorphism, their relationship to each other and how both are related to map-scale structures. These field and petrographic observations are supplemented with LA-ICP-MS U-Pb geochronology of metamorphic monazite from the southern DCR that constrains the ages of two overprinting Late Cretaceous metamorphic aureoles as well as U-Pb zircon geochronology of eight samples from various locations within TG that constrains the crystallization and emplacement history of this pluton. Together, these datasets document the magmatic, metamorphic, and structural histories of these two ranges with a focus on discriminating thermal and deformational events related to regional tectonism from those more closely associated with the emplacement of the plutons.

### **Regional Geologic Setting**

Prior to Mesozoic deformation, the Sevier hinterland was the site of prolonged Neoproterozoic to Triassic shallow marine deposition along the western margin of Laurentia, resulting in a westward thickening wedge of >15km of passive margin

siliciclastic and carbonate rocks that underlie most of eastern Nevada and western Utah (Stewart, 1976). During the Mesozoic, eastward subduction of the Fallon plate beneath North America resulted in the development of the retroarc Sevier Orogen, characterized by major crustal shortening inboard of the magmatic arc, and broadly analogous to the modern Andes (Armstrong, 1968; Burchfiel & Davis, 1975; Royse et al., 1975). At the latitude of the KMDCR, the Sevier fold-and-thrust belt is located ~150 km to the east in central Utah and is characterized by several large east-directed thrust sheets and associated folds that affect upper-crustal miogeoclinal rocks and are interpreted to merge at depth with a gently west dipping detachment. Estimates of total shortening exceed ~220 km which likely resulted in upper crustal thickening of  $\geq 15$  km (DeCelles & Coogan, 2006). In the foreland, these thrusts are highly influenced by stratigraphy, with characteristic ramp flat geometries and slip along rheologically weak horizons. They are “thin-skinned” and detached from the underlying basement. The timing of thrusting is constrained by analysis of synorogenic foreland basin deposits and thermochronology to have begun as early as Late Jurassic but is almost entirely Cretaceous in age and migrated progressively eastward through time, eventually transitioning into Laramide style deformation during the Paleocene (e.g., Armstrong & Oriel 1965; Burtner & Nigrini, 1994; DeCelles et al., 1995; DeCelles & Coogan, 2006; Fouch et al., 1983; Heller et al., 1986). Upper crustal shortening in the foreland fold-and-thrust belt is interpreted to have been accommodated to the west by mid-to lower crustal shortening and thickening in the hinterland (Miller & Gans, 1989).

Although crustal thickening in the hinterland is geometrically required to accommodate upper-crustal shortening in the foreland fold-and-thrust belt, subsequent large-scale extension during the Cenozoic and limited exposures of deeper (mid-crustal) levels has

made unraveling this earlier contractional history difficult. One endmember model for hinterland deformation is that eastward translation of the middle to upper crust was facilitated nearly entirely by a subhorizontal or gently west dipping mid- to lower crustal shear zone, with little to no deformation in the overlying rock column. This hypothesis is supported by the observation that in many places the earliest Cenozoic rocks in eastern Nevada are deposited on the youngest units of the Paleozoic section with little angular discordance, suggesting minimal structural relief in the upper crust prior to Cenozoic extension (Armstrong 1968, 1972; Gans & Miller 1983; Long, 2012). However, a number of major shortening structures have been identified in various locations within the Sevier hinterland. Immediately to the south of the KM in the footwall of Northern Snake Range metamorphic core complex, the east vergent O'Neill Peak recumbent anticline and syncline affect the entire Middle to Upper Cambrian section and accommodated almost ~5 km of structural thickening during the Cretaceous (Wrobel et al., 2021). When combined with associated supracrustal shortening structures in the hanging wall of the detachment fault in the Confusion Range of western Utah, total shortening appears to be  $\geq$ 10 km with  $\geq$ 7 km of structural burial and is likely responsible for the kyanite grade metamorphism in the footwall of the Northern Snake Range décollement (Greene, 2014; Wrobel et al., 2021). Farther west in the hinterland, the central Nevada thrust belt comprises a zone of upper crustal shortening characterized by east vergent thrust faults and map-scale folds that accommodated ~10 km of shortening during the Cretaceous (Bartley & Gleason, 1990; Long et al., 2014; Taylor et al., 2000).

Perhaps the most extensive record of hinterland shortening and tectonic burial is from the Ruby/East Humbolt/Pequop/Wood Hills metamorphic core complex in

northeastern Nevada, where Cenozoic exhumation by detachment faulting has exposed large areas of mid-crustal rocks. Integration of thermobarometry and geochronology with mapping of contractional structures suggests multiple episodes of tectonic burial and metamorphism throughout the Late Jurassic/Early Cretaceous and Late Cretaceous (Camilleri, 1998; Camilleri & Chamberlain, 1997; Hallett & Spear, 2015; Hudec, 1992). These burial events were separated by at least one period of extensional exhumation, possibly resulting from steep topographic gradients related to crustal thickening (Hodges et al., 1992). Late Cretaceous metamorphism was characterized by higher temperatures and the emplacement of syntectonic leucogranites, likely as a result of the progression from a colder to hotter geotherm (McGrew et al, 2000). Work in the Albion/Raft River metamorphic core complex in southeast Idaho reveals a similar history of major tectonic burial, exhumation, and metamorphism throughout the Cretaceous (Cruz-Uribe et al., 2015; Harris et al., 2007; Kelly et al., 2015). These studies highlight the complex and multiphase nature of deformation and metamorphism in the Sevier hinterland.

Crustal shortening and thickening in the Sevier hinterland was accompanied by both regional and localized metamorphism and crustal anatexis that peaked in the Late Cretaceous at ~80 Ma (Miller et al., 1988; Miller & Gans, 1989). Regional greenschist facies metamorphism is observed at the deepest stratigraphic levels in many of the ranges in eastern Nevada. However, there are also numerous more localized upper-greenschist to amphibolite facies metamorphic culminations that typically have steep vertical and lateral temperature gradients and are spatially associated with the emplacement of leucogranite plutons (e.g., the Papoose Flat Pluton in the Inyo Mtns., the Lexington Creek Pluton in the Southern Snake Range, and the Trout Creek Intrusive Complex in the DCR; De Saint-

Blanquat et al., 2001; Law et al., 1992; Lee et al., 1983; Monroe et al., 2023; Paterson et al., 1991; Sylvester et al., 1978;). These Late Cretaceous leucogranites are strongly peraluminous and have an isotopic composition that indicates they are nearly pure crustal melts (Barton & Anderson, 1990; Best et al., 1974; Farmer & DePaolo, 1983; Lee et al., 1981; Lee et al., 2003; Lee & Christiansen, 1983; Miller & Bradfish, 1980, Gottlieb & Miller, 2022). However, the mechanisms for melting in the hinterland and whether the emplacement of these leucogranite plutons is the cause or consequence of mid-crustal metamorphism are debated. Eastward migration of subduction-related magmatism from the main arc into the hinterland is a possibility (Miller & Gans, 1989). Thermal relaxation following crustal thickening has also been invoked by some workers as the primary cause of this metamorphism and anatexis (Douce et al., 1989; Wright & Wood, 1991). However, this model predicts that metamorphism and crustal anatexis would be widespread throughout the hinterland, not localized. This has led some workers to argue that delamination and foundering of a lithospheric mantle and the replacement with hot asthenosphere was the primary driver for these Late Cretaceous thermal anomalies (Blackford et al., 2022; Wells et al., 2012; Wells & Hoisch, 2008). An additional hypothesis is that melting was a consequence of contractional “A-type” subduction, where underthrusting of supracrustal fluid-rich sediments leads to volatiles fluxing into the hot anhydrous overlying hanging wall, resulting in partial melting (Gottlieb et al., 2022).

During the Cenozoic, the overthickened crust of the Sevier hinterland was extended approximately east-west, thinning the crust to its current thickness of ~30 km (Benz et al., 1990; Gans, 1987). Extension may have begun as early as the Late Cretaceous and is hypothesized to have initially been facilitated by slip along low angle detachment faults

(e.g., Coney & Harms, 1984; Davis & Coney 1979). During the middle Miocene the style of extension transitioned to more typical widely spaced high-angle fault systems and block rotation, forming the present topography of the Basin and Range (Stewart, 1971). The geology of the KMDCR reflects this rich geologic history of the Sevier hinterland, and the rocks exposed in these ranges provide insight on the thermal and deformational architecture of the hinterland crust during the Late Cretaceous.

### **Geologic Framework of the Deep Creek Range and Kern Mountains**

The KM and DCR are not separated by any major structural discontinuities and comprise a single structural block with stratigraphic units that can be traced continuously from one to the other (Fig 1). This block was tilted to the west during slip along the Reilly Canyon Fault which bounds both ranges to the east and likely continues southward to merge with the Northern Snake Range Décollement. (Bick, 1966; Miller et al., 1999; Misch & Hazzard, 1962). This fault has an estimated cumulative 25 km of displacement and is interpreted to have formed at a higher angle (~50-60°) and rotated to its current dip of ~15° during progressive slip and westward tilting of both the hanging wall and footwall blocks, such that paleodepth increases to the east (Gans et al., 1990; Rodgers, 1987).

The eastern part of the DCR is underlain by the Neoproterozoic Trout Creek and McCoy Creek groups, which are interpreted to have been deposited during active rifting and early rapid subsidence on the newly formed western margin of Laurentia (Misch & Hazzard, 1962; Stewart, 1976). The Trout Creek Group is ~3.2 km thick and is composed of

interbedded quartzite, schist, metasiltstone, metadiamictite, and minor marble that have been divided into six mappable units (Fig 9; Rodgers, 1984). This stratigraphy is only exposed at deep structural levels in the DCR, so it is unclear if these units were deposited in an isolated rift basin or if they are relatively continuous throughout the region beneath the present exposure level. The McCoy Creek Group overlies the Trout Creek Group and is composed of a ~2.3 km thick succession of interbedded quartzite, schist, metasiltstone and minor marble and is divided into six mappable units (Fig 9). These units are laterally continuous and are present throughout eastern Nevada at deeper levels of exposure but display significant changes in lithology and unit thicknesses between localities (Misch & Hazzard, 1962).

Approximately 8 km of Paleozoic stratigraphy depositionally overlies the McCoy Creek Group and comprises most of the bedrock exposed in the western DCR. It is composed of lower Cambrian quartzite and shale overlain by a

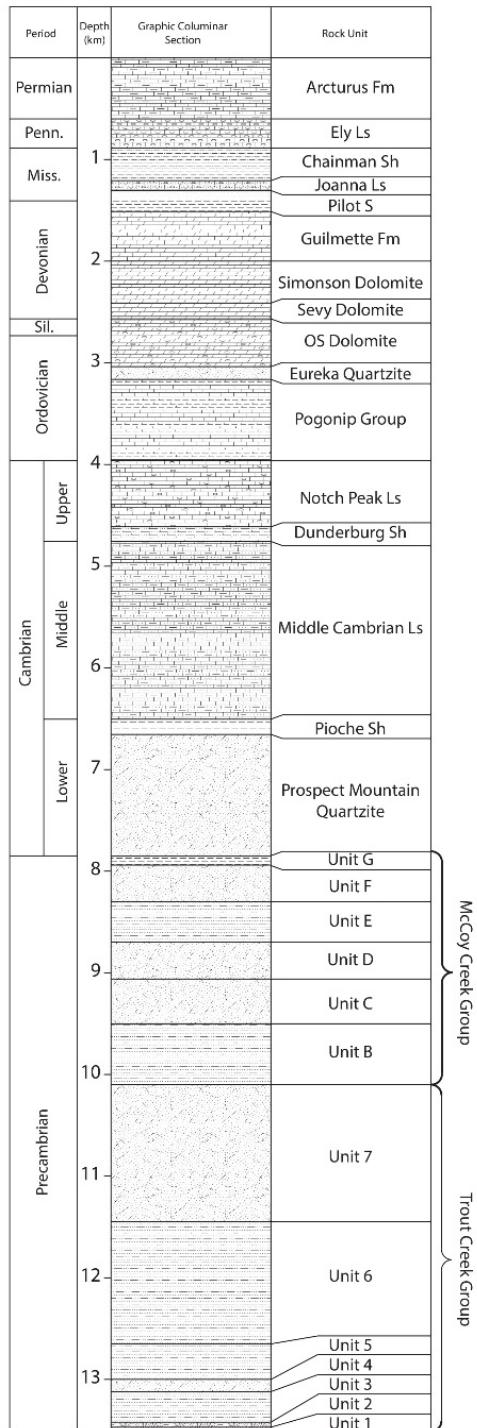


Figure 9: Stratigraphic section of the rock units exposed in the Deep Creek Range. Modified from Rodgers (1987).

succession of middle Cambrian to Pennsylvanian carbonates with minor siliciclastics (Fig 9). The carbonates are dominated by limestone except for the upper Ordovician to Middle Devonian section which is composed primarily of dolomite. These units were deposited slowly on the continental shelf and are laterally continuous for hundreds of kilometers across eastern Nevada. In the westernmost DCR, a succession of Eocene volcaniclastics, ash-flow tuff and andesitic lava flows unconformably overlie the uppermost Paleozoic section with little angular discordance (Nutt & Thorman, 1992). Cenozoic conglomerate and Eocene volcanic rocks are also exposed east of Pleasant Valley in the hanging wall of the range bounding Reilly Canyon fault (Gans et al., 1990).

There are both large plutons and many small undated intrusions in the KMDCR, but all appear to be either Late Cretaceous or Eocene. TG is the largest with an area of  $>100 \text{ km}^2$  and forms the core of the KM. It is a strongly peraluminous leucogranite that was emplaced at  $\sim 70 \text{ Ma}$  (U-Pb zircon; Gottlieb et al., 2022; Lee et al., 1986; this study), during the latest stages of crustal shortening in the Sevier hinterland. The Trout Creek Intrusive Complex is exposed on the eastern flank of the DCR at deep structural levels over an area of  $\sim 2 \text{ km}^2$  as a few small stocks surrounded by numerous dikes and sills. It was emplaced at  $80 \pm 2 \text{ Ma}$  (U-Pb zircon, Monroe & Gans, 2023) and is a typically aplitic leucogranite with a well-developed solid-state deformational fabric around its margins that is continuous with the country rock and forms the core of a structural dome. The  $39 \pm 1 \text{ Ma}$  (U-Pb zircon; Rodgers, 1987) Ibapah Pluton underlies the central DCR, has a surface exposure of  $\sim 80 \text{ km}^2$ , and is composed of coarse-grained biotite granite to quartz monzonite. Numerous small, isolated outcrops of granite with a similar mineralogy and texture are scattered throughout the southern DCR. The  $37 \pm 8 \text{ Ma}$  (Rb/Sr; Best et al., 1974) Skinner Canyon Granite ( $\sim 10 \text{ km}^2$ )

and the undated but likely Eocene Uvada Granite ( $\sim 1 \text{ km}^2$ ) are exposed in the northeastern KM. All three of these Eocene plutons have sharp and irregular contacts and only narrow static metamorphic aureoles with little to no penetrative deformation along their margins.

Two deformation events affected rocks in the southern DCR during the Late Cretaceous. The first is reflected in a west dipping cleavage ( $S_1$ ) that is also present in many other nearby ranges and is interpreted to have formed as a result of east-directed layer parallel shear (Miller et al., 1988; Rodgers, 1987). During the second event, rocks on the southern flank of the range were folded into the WCA, a large recumbent fold that closes to the west and has a gently north plunging fold axis. A locally developed cleavage ( $S_2$ ) that in some areas appears to be axial planar to the WCA also developed during this event. Metamorphism increases down section from unmetamorphosed Paleozoic carbonates in the west to upper greenschist facies within the stratigraphically lowest units and locally to amphibolite facies in several metamorphic culminations.

The overturned limb of the WCA continues southward across Pleasant Valley into the eastern KM, where the stratigraphy dips to the northwest, is overturned, highly attenuated and parallels the margin of TG. This pluton has a well-developed deformational aureole around its margins and intrudes mid-crustal rocks to the east and upper-crustal carbonates to the west. Country rocks in the western KM have structures that appear to be related to both Mesozoic tectonic shortening and deformation associated with pluton emplacement, as well as a variety of normal faults associated with Cenozoic extension.

In order to interpret the original geometry of Cretaceous structures exposed in the KMDCR, it is important to critically evaluate the estimated magnitude and direction of subsequent westward tilting of the ranges during the Cenozoic. Evidence for westward

tilting includes: 1) The general westward dip of stratigraphy with progressively higher stratigraphic units exposed to the west. 2) A systematic increase in metamorphic grade west to east, grading from unmetamorphosed upper-crustal rocks on the western flanks of the ranges to upper-greenschist and locally amphibolite facies mid-crustal rocks along the eastern flanks. 3) The Eocene unconformity and overlying volcanic rocks exposed in the western DCR typically dip westward. 4)  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology of potassium feldspar and mica in both TG and the Ibapah Pluton show systemic younging from west to east, with ages that indicate that the western parts of the ranges were exhumed prior to the eastern flanks (P.B. Gans - unpublished data). 5) The present gentle eastward dip of normal faults in the western DCR and consistent bedding to fault angles of 50-60° suggests they formed at a higher angle and were rotated to their present low angles during westward tilting of the ranges. Although the KMDCR is clearly tilted to the west, the magnitude, direction and timing of tilting are only broadly constrained. Rodgers (1987) estimated that the ranges were tilted to the WNW about a horizontal axis with an azimuth of ~030°. This is based on 1) the orientations fault striae, 2) the strike of normal faults, 3) the strike of tilted Eocene volcanic rocks, and 4) the trend of Pleasant Valley (interpreted as a re-entrant or mullion along the Reilly Canyon fault). Rodgers estimated the magnitude of tilting was ~40° based primarily on the average dip of bedding in the Paleozoic section and very limited orientations on volcanic rocks in the western DCR. However, there is significant uncertainty in both the orientation of the axis of tilting and the magnitude of tilting, which could be as little as 20° or as much as 60°.

## Previous Work

Early work in the KMDCR by Nelson (1959, 1966, 1969), Misch et al. (1957), Misch & Hazzard (1962), and Bick (1966) first described the stratigraphy, identified the major intrusions, recognized metamorphism, and made initial interpretations on the structural history of the ranges, and their work served as an important framework for later research. Rodgers (1987) focused on the structural and thermal history of the southern DCR by characterizing the geometry of the WCA, describing the character and distribution of cleavages and metamorphism, and conducting  $^{39}\text{Ar}/^{40}\text{Ar}$  geochronology on metamorphic hornblende from the southern flank of the range that suggested metamorphism was Late Cretaceous. He interpreted the WCA to be a major west vergent fold that formed during the Late Cretaceous as a result of tectonic shortening associated with the Sevier Orogeny. He hypothesized that the fold formed over a west-directed ductile shear zone at the base of the overturned limb which resulted in the observed penetrative strain and ductile attenuation of stratigraphy. However, this interpretation is not consistent with several peculiar characteristics of the WCA that will be discussed further.

In the KM, Best et al. (1974) conducted a petrologic study of the Tungstonia, Skinner Canyon and Uvada plutons that characterized their general map relationships, mineralogy, texture, ages, whole rock chemistry and  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic composition. The high  $\text{Sr}^{87}/\text{Sr}^{86}$  from TG reported by Best et al. (1974) suggests that it formed primarily from a crustal source with little to no mantle input, whereas the Eocene Skinner Canyon and Uvada plutons likely have a significant mantle contribution. Sayeed (1973) and Sayeed et al. (1977) provided a preliminary petrologic, geochemical and structural analysis of TG and surrounding country with similar conclusions as Best et al., (1974). Ahlborn (1977) focused

on the structural history of the KM and provided a framework for the overall deformational history of the range. Extensive unpublished mapping throughout the KM by Gans et al. (1990) documented many of the deformational structures and map relationships in the country rock surrounding TG and was instrumental in guiding the mapping in the western KM presented in this paper.

More recent work in the KMDCR includes a study that focused on the upper-crustal thermal structure of the Sevier hinterland and used Raman spectroscopy of carbonaceous material thermometry and conodont alteration indices to indicate that the southern DCR had elevated thermal gradients of  $49 \pm 7^{\circ}\text{C/km}$  (Blackford et al, 2022). Gottlieb et al. (2022) used zircon petrochronology to investigate the petrogenesis of TG and the lithology and structure of the basement and argues that TG was sourced from cratonic basement that was underthrust westward during Sevier shortening.

## **Deformation and metamorphism in the southern Deep Creek Range**

### *Map relationships and field observations*

A geologic map of a  $\sim 35 \text{ km}^2$  area on the southeastern flank of the range was produced to build on Rodgers' mapping by documenting in more detail the orientations and character of cleavages, the distribution of map units, the geometry of mesoscopic folds, and the distribution and character of metamorphism (Fig 10). The first period of deformation to affect rocks in the southern DCR is reflected in a cleavage ( $S_1$ ) in Neoproterozoic to lower Cambrian rocks that dips west with respect to horizontal bedding and increases in intensity and metamorphic grade down section and to the south (Figs 11 & 12a). This cleavage is present throughout the southern DCR in both the upright and overturned limb of the WCA.

Later folding into the WCA resulted in the cleavage having a variety of orientations within the map area, but in general it dips moderately to steeply to the northwest in the upright limb (Fig 11-Z1), gently to moderately to the northwest in the overturned limb in the western half of the map area (Fig 11-Z2-Z5), and moderately to the northeast in the overturned limb in the eastern part of the map area (Fig 11-Z8). The intersection lineation with bedding plunges gently to moderately, with trends ranging from northwest to northeast.

A similar west-dipping cleavage is present in many of the surrounding ranges and thus appears to reflect a relatively widespread deformational event in the Sevier hinterland (Miller et al., 1988, Miller & Gans 1989). Previous workers interpreted this cleavage to be a result of east-directed layer parallel shear when the section was approximately flat lying

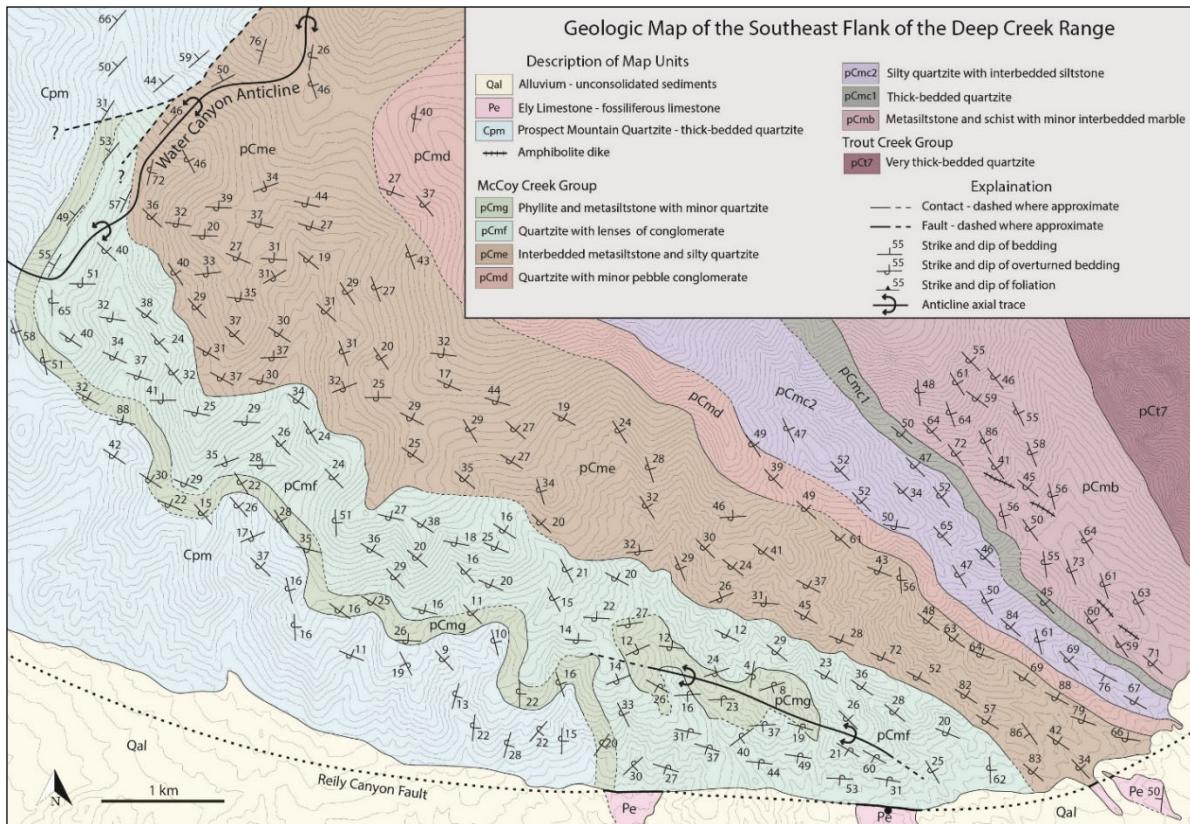


Figure 10: Geologic map of the southeastern flank of the DCR.

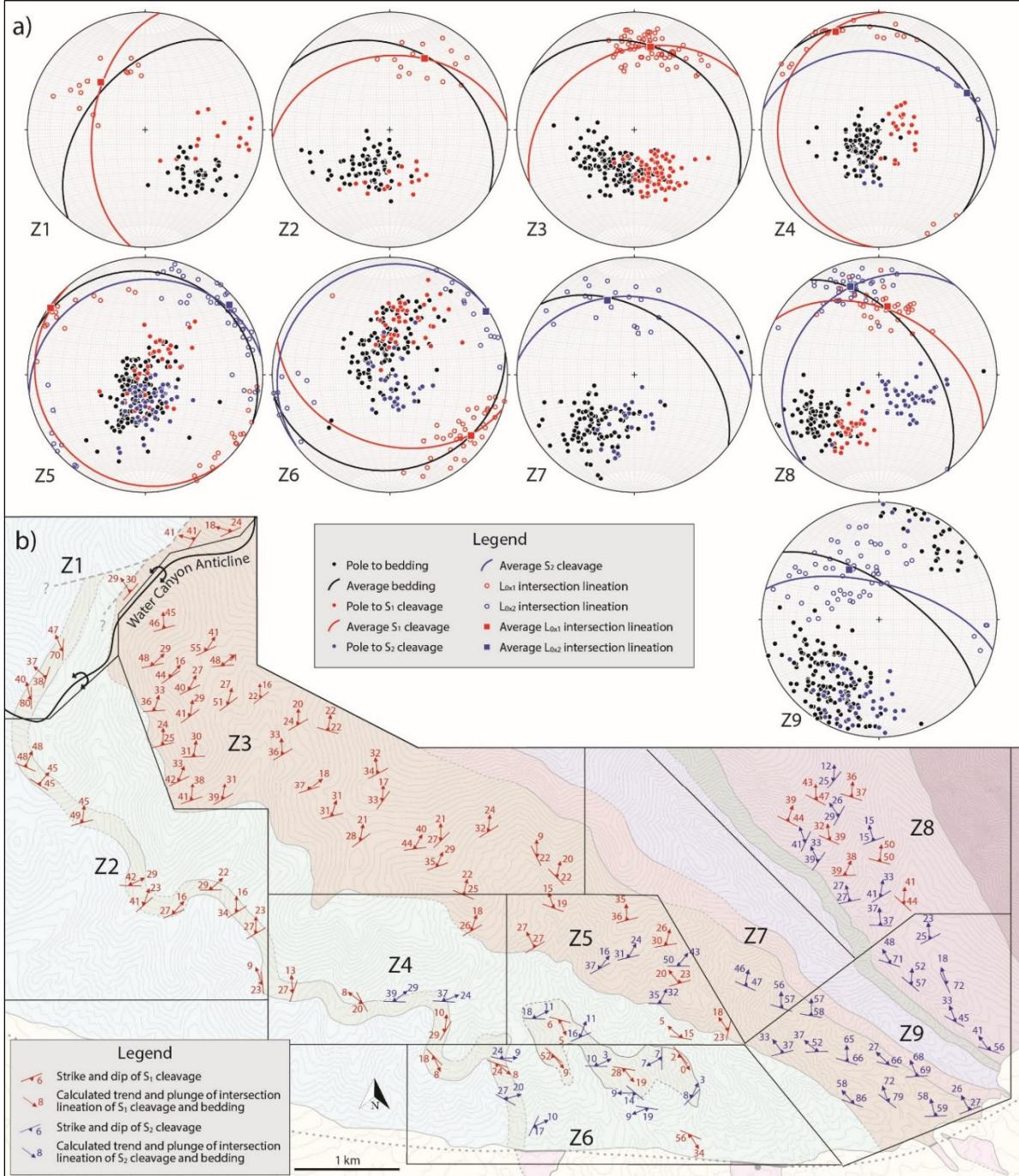


Figure 11: a) Lower hemisphere stereonet projections of poles to bedding and cleavages, intersection lineations and folds in different domains throughout the map area. Great circles illustrate the average bedding and cleavage attitude for each domain (Allmendinger, 2023). b) Map showing outlines of the structural domains summarized in the stereonets (a) and representative orientations of the  $S_1$  (red) and  $S_2$  (blue) cleavages, and intersection lineations.

based on the observations that 1) the cleavage is consistently more west dipping than

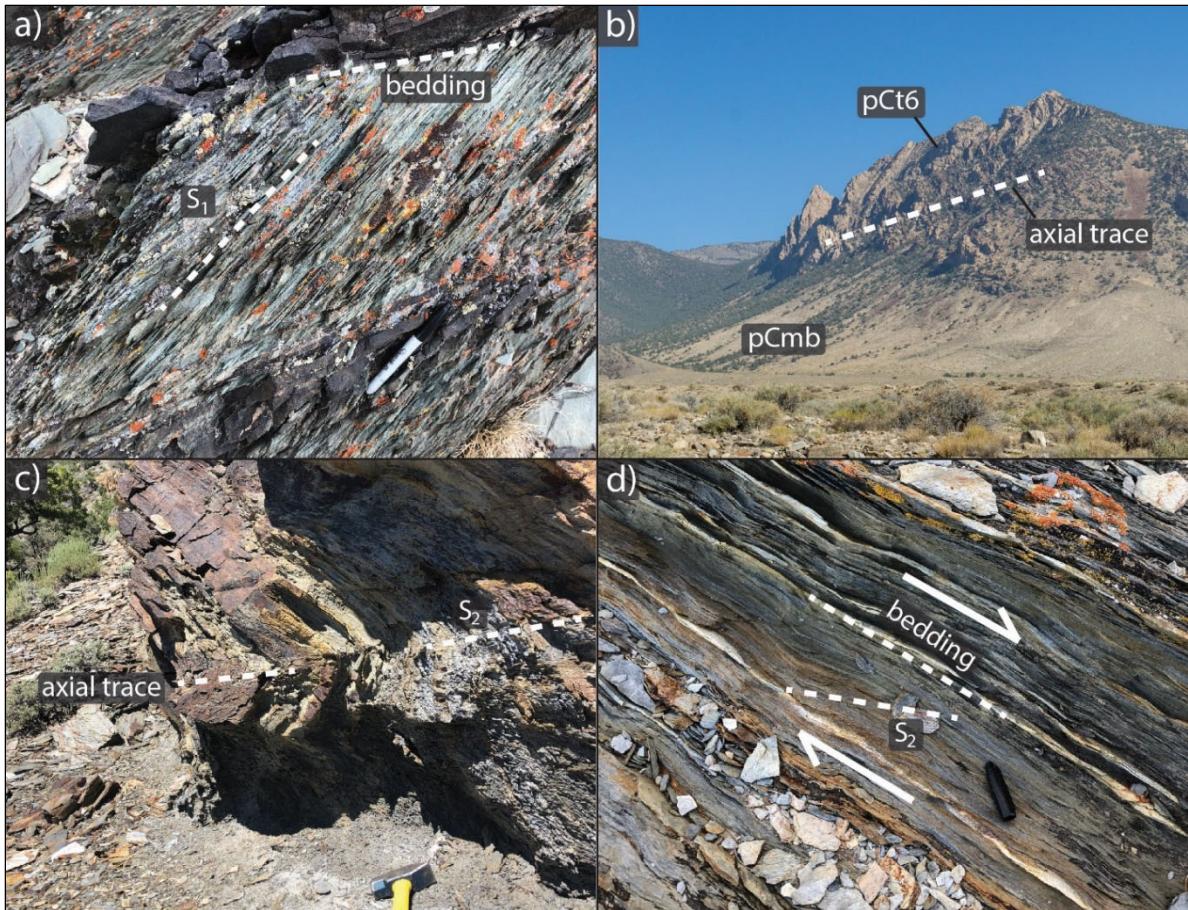


Figure 12: a) Well-developed  $S_1$  cleavage at a moderate angle to bedding in pCme in the northwestern part of the map area. View facing north. b) View of the WCA looking north up the canyon on the eastern side of the map area, approximately parallel to the fold axis. The large cliffs are underlain by thick-bedded quartzite of the upper Trout Creek Group and the valley is underlain by less resistant phyllite and schist of pCmb. c) Outcrop scale fold in pCmb with an axial planar  $S_2$  developed in pelitic layers on the right side of the image. View facing NNW. d) Steeply dipping  $S_2$  cleavage at a low angle to bedding. The relative orientation of bedding and cleavage is consistent with right lateral bedding parallel shear.

bedding and generally intersects bedding at an angle of less than 45 degrees, 2) the cleavage becomes better developed and the intersection angle with bedding decreases with depth, and 3) folds associated with the cleavage are rare, suggesting that bedding was never at a high angle ( $>45^\circ$ ) to the principal shortening axis. (Miller et al., 1988; Miller & Gans, 1989; Rogers, 1987).

One of the most conspicuous features in the southern DCR is the WCA, which is a major “range-scale” recumbent fold that closes to the west and affects Neoproterozoic to Mississippian strata in the southern DCR and northeastern KM (Figs 1 & 10). Stratigraphy in the upright limb in the northwest part of the map area dips moderately to the northwest (Fig 11-Z1) and as beds roll through vertical in the overturned limb, which is only exposed in the southern DCR and northeast KM, stratigraphy dips gently to steeply to the northeast (Fig 11-Z2-Z8). The calculated fold axis plunges gently to the

north and the axial surface dips gently to the north or northwest (Fig 13a). The fold has a subangular hinge with an interlimb angle of ~60° where the hinge is exposed in the northwestern part of the map area. The hinge is more rounded and has an interlimb angle of ~80° farther east, where it is spectacularly exposed in a ~500-meter-high cliff of quartzite of the uppermost unit of the Trout Creek Group (Fig 12b). This fold appears to be relatively local as it cannot be traced northward through the rest of the exposed ~40 km DCR or south into the Northern Snake Range, nor can an offset segment of the fold be identified in the

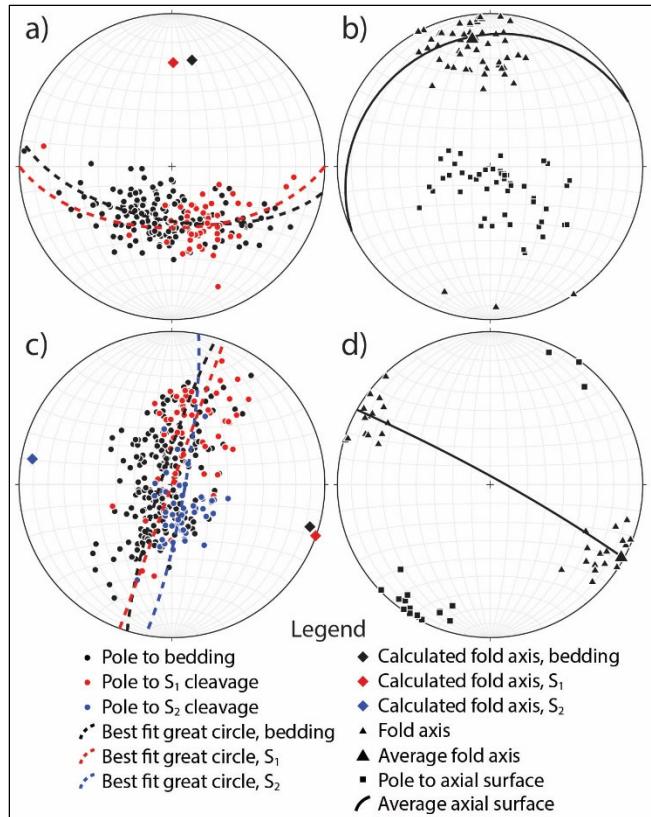


Figure 13: a) Orientations of bedding and the  $S_1$  cleavage around the hinge of the WCA in the northwest part of the map area. b) Orientations of  $D_2$  mesoscopic folds. c) Bedding,  $S_1$ , and  $S_2$  orientations from the NNW-ESE trending anticline in the southern part of the map area. d) Orientations of mesoscopic folds associated with the development of the NNW-ESE trending anticline in the southern part of the map area.

presumed hanging wall of the Reilly Canyon Fault in the northern Confusion Range (Greene, 2014; Wrobel et al., 2021).

Middle Cambrian to Mississippian strata in the overturned limb of the WCA continue southward across Pleasant Valley where the same units are present in the eastern KM, where they are highly attenuated and parallel the northeastern margin of TG (Fig 1b). These units have been thinned to as little as 10% of their original stratigraphic thickness and have a strong bedding parallel foliation that parallels the contact of the pluton (Gans et al., 1990). The observation that the intrusive contact follows approximately the same overturned stratigraphic unit over nearly 7 km and that this coincides with the zone of highest strain suggests a genetic relationship between deformation and pluton emplacement or possibly that the pluton was emplaced along a high strain shear zone at the base of the overturned limb. This relationship will be explored further in the following sections.

Pennsylvanian and younger rocks also continue southward from the southern DCR into the western KM but are deflected towards the west, the opposite direction as Mississippian and older strata (Fig 1b). Bedding in the Pennsylvanian Ely Limestone changes from dipping moderately to the west in the southern DCR, to dipping moderately to the NNE in the northern KM, approximately parallel to the margin of TG (Gans et al., 1990). This zone between Mississippian and older rocks and Pennsylvanian and younger rocks thus represents an important discontinuity, where rocks on either side are deflected in opposite directions.

Folding of the WCA was apparently accompanied by the development of a cleavage ( $S_2$ ) in the southern DCR that is only present in the eastern part of the map area and is most well developed in pelitic horizons of pCmb, pCme and pCmg. In pCmb in the northeastern

part of the map area, the cleavage dips gently to moderately to the north or northwest and appears to be approximately parallel to the axial surface of the WCA and is axial planar to outcrop scale folds (Fig 11: Z8; Fig 12c). However, farther south in pCmb and in pCme, the cleavage becomes much more steeply dipping to the north or northeast and has a very different orientation as the axial surface of the WCA. Here, bedding typically dips steeply to the northeast and the cleavage dips steeply NNE, forming an intersection lineation that plunges moderately to the NW (Fig 11: Z9). The relative orientation of bedding and the cleavages is more consistent with bedding parallel right lateral shear than an axial planar cleavage to the WCA (Fig 12d). This zone coincides with the area of synkinematic metamorphism of the amphibole grade Singleton Creek aureole and here the cleavage is more well-developed and nearly completely overprints the S<sub>1</sub> cleavage. Farther to the west, the S<sub>2</sub> cleavage becomes more shallowly dipping due to folding into a younger NNW-SSE trending anticline and has an intersection lineation with bedding that plunges gently to the northeast (Fig 11: Z5 & Z6).

Mesoscopic folds are locally present with axial surfaces and fold axes approximately parallel with that of the WCA and are best developed in intervals consisting of shale with thin sandstone interbeds and are most common in pCmb (Fig 13b). However, these mesoscopic folds are rare in most parts of the map area and are conspicuously absent in places where they would be most expected (e.g., the same rock types within the hinge region of the WCA). Folds typically have wavelengths of 1-10 m, have rounded to subangular hinges and are generally asymmetric and verge toward the hinge of the WCA (Fig 12c). An axial planar younger (S<sub>2</sub>) cleavage is often developed within these mesoscopic folds and is parallel to sub-parallel to their axial surface.

A younger and more localized deformation also affected rocks on the southern DCR and resulted in the formation of a map-scale WNW-ESE trending upright anticline in the southernmost part of the range (Fig 11: Z5 & Z6). This fold has a calculated fold axis of 05, 120, a nearly vertical axial surface, an interlimb angle of ~90°, and a rounded hinge (Fig 13c). Bedding and both the S<sub>1</sub> and S<sub>2</sub> cleavage are folded, indicating that the fold postdates the formation of both cleavages. Mesoscopic folds with nearly identical fold axes and axial surfaces to the main fold are relatively common, and typically have rounded to sub-rounded hinges, interlimb angles of 70-120°, and wavelengths of 3-10 m (Fig 13d). Rodgers (1987) interpreted these structures to be drag folds related to slip on the Reilly Canyon fault; however, their orientation isn't consistent with what would be predicted with models for drag folding. The folding more likely reflects a period of younger NNE-SSW shortening, likely associated with the late-stages of emplacement and ballooning of TG (see below).

#### *Microstructures and metamorphism*

Petrographic analysis of deformational fabrics and metamorphic assemblages was performed to characterize the mineral assemblages and porphyroblast-matrix relationships of the S<sub>1</sub> and S<sub>2</sub> cleavages, identify how they change throughout the map area, and determine their relationship to two overprinting amphibolite facies metamorphic aureoles, the Wood Canyon aureole and Singleton Creek aureole. The S<sub>1</sub> cleavage is present throughout the map area but varies greatly in both degree of development and metamorphic grade and is most well-developed in pelitic rocks and absent in quartzites and conglomerates. In the northwestern part of the map area in the upright limb and hinge region of the WCA, S<sub>1</sub> is present as a weakly to moderately well-developed slaty to phyllitic cleavage defined by

aligned microcrystalline micas and a weak grain shape foliation in quartz (Fig 14a). This cleavage becomes more coarse-grained and well-developed to the south, with pelitic rocks on the southern flank of the range having a penetrative  $S_1$  defined by aligned medium- to coarse-grained micas and a weak grain shape preferred orientation in quartz (Figs 14b & 14c). The  $S_1$  cleavage is commonly crenulated by the  $S_2$  cleavage and is nearly completely overprinted by it on the southeastern flank of the range in the zone of metamorphism of the Singleton Creek aureole.

The Wood Canyon aureole was first described by Rodgers (1987) and has isograds that cut across formation contacts and indicate increasing grade to the southeast (Fig 15). The aureole has porphyroblastic biotite, garnet, staurolite, andalusite, and plagioclase, and reaches amphibolite grade along the southern flank of the range. Biotite is medium- to fine-grained, commonly altered to chlorite, and has abundant quartz inclusions that are either randomly oriented or form an internal foliation that is continuous with the external  $S_1$  foliation, indicating growth during or after development of  $S_1$ . (Figs 14c & 14d). Garnet is medium- to fine-grained, equant and has aligned trails of quartz and oxide inclusions that are typically subparallel to and occasionally continuous with the  $S_1$  cleavage, suggesting growth happened during or after cleavage development. Garnet is retrograded to aggregates of randomly oriented biotite and chlorite that either form rims or completely replace the garnet porphyroblasts. Relict staurolite is rare but is inferred to have been more common based on abundant staurolite pseudomorphs up to ~5 cm long composed of aggregates of fine-grained quartz and micas that are darker than the matrix. These pseudomorphs are typically subparallel with the  $S_1$  cleavage, suggesting that they are syn- to post-kinematic. Plagioclase occurs as fine-grained equant porphyroblasts with rounded margins and the relative timing

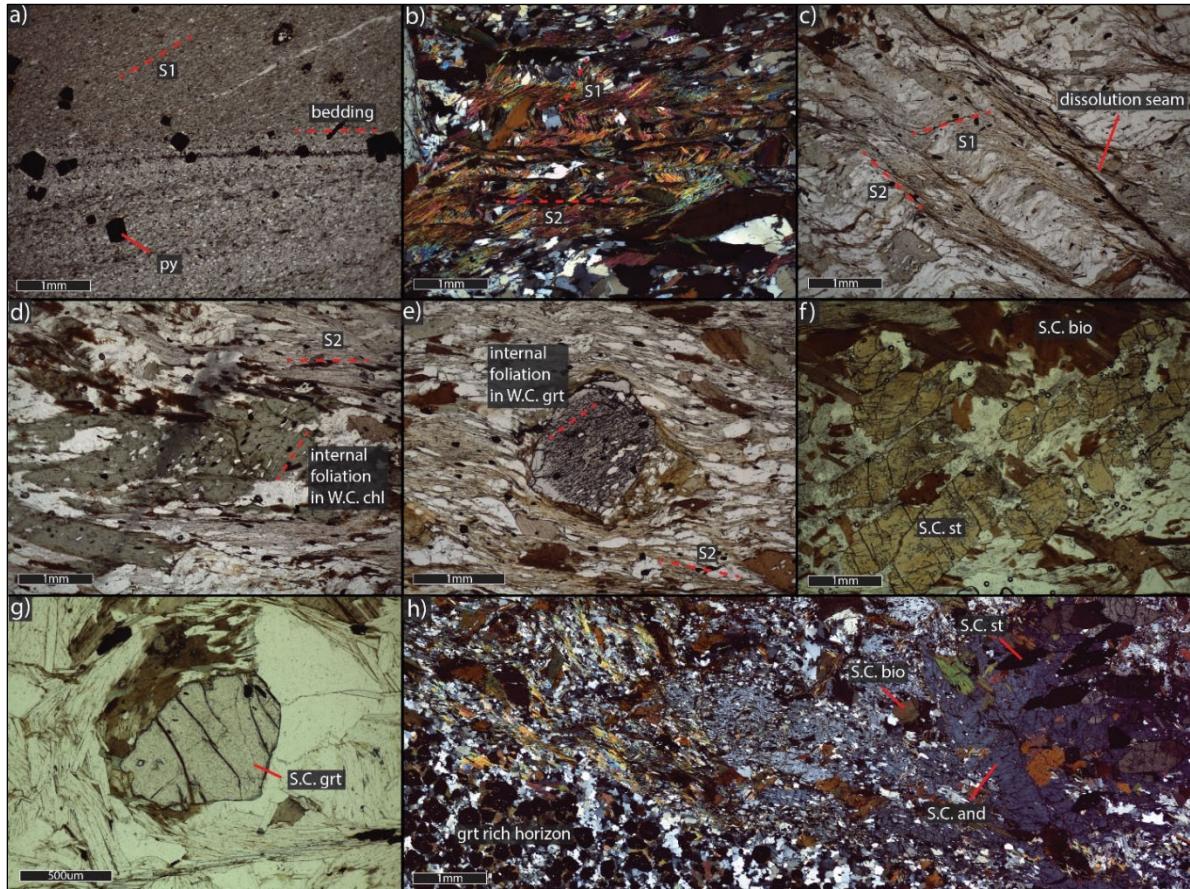


Figure 14: a) pCmg from the western part of the map area with a fine-grained slaty  $S_1$  cleavage and porphyroblasts of pyrite (PPL). b) Schist from pCmb with a well-developed  $S_1$  cleavage defined by penetrative mica growth crenulated by the  $S_2$  cleavage (XPL). c)  $S_1$  cleavage crenulated by the  $S_2$  cleavage. Dissolution seams are present along cleavage domains of the  $S_2$  cleavage (PPL). d) Chlorite from the Wood Canyon aureole with an internal foliation defined by aligned inclusions of quartz that is interpreted to reflect the  $S_1$  foliation (PPL). e) Garnet from the Wood Canyon aureole with an internal foliation defined by aligned inclusions of quartz (PPL). f) Porphyroblasts of staurolite and biotite from the Singleton Creek aureole (PPL). g) Garnet porphyroblasts from the Singleton Creek aureole. h) Schist from pCmb with porphyroblasts of garnet, andalusite, biotite and staurolite from the Singleton Creek aureole (XPL).

of growth and cleavage development is unclear. The Wood Canyon aureole is interpreted to be synkinematic with the  $S_1$  cleavage based on these porphyroblast cleavage relationships and the fact that the  $S_1$  cleavage becomes more coarse-grained and well-developed within the Wood Canyon aureole. However, it is possible that the Wood Canyon aureole formed

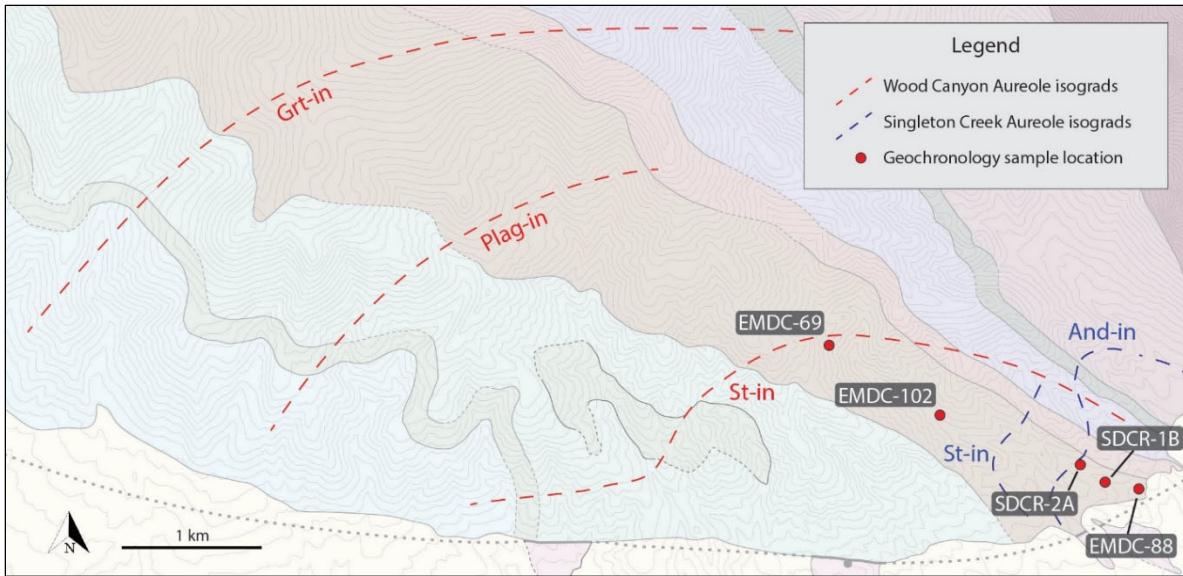


Figure 15: Map showing isograds of the Wood Canyon and Singleton Creek aureoles from Rodgers (1987) and sample locations for monazite geochronology.

after development of the  $S_1$  cleavage and the observed porphyroblast cleavage relationships are due to mimetic growth.

The  $S_2$  cleavage is present in the eastern part of the map area and is variably well developed. Outside the area of synkinematic metamorphism of the Singleton Creek aureole, the  $S_2$  cleavage crenulates  $S_1$ , forming a spaced cleavage characterized by asymmetric microfolds of the  $S_1$  cleavage (Figs 14b & 13c). Cleavage domains are typically spaced 1-2 mm and are formed by partial to complete dissolution of quartz on the shorter limbs of these microfolds. In some samples, more extensive dissolution of quartz forms discrete planar to wavy dissolution seams with concentrations of insoluble material (Fig 14c). In the southeastern flank of the range in the area of synkinematic metamorphism of the Singleton Creek aureole, the  $S_2$  cleavage is upgraded and forms a penetrative foliation defined primarily by highly aligned micas (Figs 14d & 14e). In this area, the  $S_2$  cleavage partially to completely overprints  $S_1$ , which is only evident as aligned trails of inclusions in garnet and

biotite porphyroblasts of the Wood Canyon aureole or as faint zones of aligned micas in microlithons of the S<sub>2</sub> cleavage (Fig 14d).

Rocks in a narrow zone along the southeastern flank of the DCR are distinctly upgraded to amphibolite facies in the Singleton Creek aureole, which was first identified and described by Rodgers (1987). This aureole is coincident with the highest-grade part of the Wood Canyon aureole, has porphyroblastic biotite, garnet, staurolite, andalusite, and cordierite, and has isograds that cut across formation contacts and indicate increasing grade toward the fault bounded southeastern flank of the range (Rodgers, 1987; Fig 15). Biotite is fine-grained, fresh, has little to no inclusions, and is either randomly oriented or is parallel with S<sub>2</sub>, suggesting that it is syn- to post-kinematic (Figs 14f & 14g). Garnet is fine-grained, equant, fresh, hypidioblastic to idioblastic, and contains no inclusions (Figs 14g). It is usually randomly distributed throughout the rock volume but occasionally forms thin garnet-rich layers (Fig 14h). Staurolite is fine-grained, fresh, idioblastic and lacks inclusions (Figs 14f & 14h). It is typically randomly distributed throughout the rock volume but occasionally forms clusters and is sometimes present as inclusions in andalusite (Fig 14h). Andalusite is very coarse grained, fresh, and contains abundant aligned inclusions of quartz and oxide that are parallel with the S<sub>2</sub> foliation, indicating it is syn- to post-kinematic (Fig 14h). The Singleton Creek aureole is interpreted to be synkinematic with development of the S<sub>2</sub> cleavage based on these porphyroblast-cleavage relationships and the fact that the S<sub>2</sub> cleavage becomes penetrative and more well-developed within the aureole. However, it is also possible that it is post-kinematic and the observed porphyroblast-cleavage relationships are due to mimetic growth.

### *Summary of deformation and metamorphism in the southern Deep Creek Range*

Rocks on the southern flank of DCR were affected by an early regional deformation that produced a west dipping cleavage ( $S_1$ ) in Neoproterozoic to lower Cambrian rocks that is low greenschist grade but is upgraded abruptly towards the south in the amphibolite grade Wood Canyon aureole. Subsequently, the Neoproterozoic to Permian stratigraphy (including the  $S_1$  cleavage in the older stratigraphic units) were clearly folded into the WCA, a recumbent fold that closes to the west and has a fold axis that plunges gently to the N-NNW and a highly attenuated lower (southern) limb. A younger ( $S_2$ ) cleavage appears to be axial planar to the WCA but becomes more steeply dipping towards the southeast where it is very well-developed and nearly completely overprints  $S_1$ . Here, syn- to post-kinematic amphibolite facies metamorphism affected a localized area along the southeastern flank of the range (Singleton Creek aureole). Stratigraphy in the overturned limb of the WCA continues southward into the northeastern KM where it is highly attenuated and parallels the intrusive contact of TG. New constraints on the timing of metamorphism in the southern DCR are discussed below.

### **Deformation and metamorphism in the western Kern Mountains**

The western KM expose the western portions of TG in contact with upper-crustal Ordovician to Pennsylvanian country rock on the northwestern and southwestern flanks of the range. The pluton has a conspicuous deformational and metamorphic aureole around its margins in both the country rock and the marginal parts of the pluton that coincides with a transposition of stratigraphy into parallelism with the intrusive contact. Integration of geologic mapping and structural analysis with petrographic observations of tectonites from

within the pluton's deformational aureole indicate that both penetrative deformation and the transposition of stratigraphy occurred synchronously with and was a direct result of emplacement of the pluton.

#### *Map scale structures and relationships*

Detailed geologic maps and cross sections of areas immediately adjacent to the pluton where it is in a clear intrusive relationship were made to characterize pre-, syn- and post-pluton emplacement structures in TG's country rock (Figs 16 & 17). Because of westward tilting of the range, these maps are intended to cover the upper sides and roof of the pluton. Here, TG intrudes upper-crustal dolomite, limestone and siltstone that now display evidence for multiple deformational events, including folds, faults and penetrative strain, at least some of which is associated with the emplacement of the pluton. There is a conspicuous deformational aureole along the margins of TG with a foliation in both the pluton and country rock that decreases in intensity and eventually dies out approximately 1 km outward from the contact, and within a few hundred meters inward into the core of the granite. This foliation is always parallel to the pluton margins and systematically tracks the intrusive contact around the western side of the range, outlining the shape of the pluton (Fig 18: P1-P6). In the distal parts of the aureole, a cleavage is only weakly developed and is at a high angle to bedding in the country rock, but towards the margin of the pluton, bedding is transposed into parallelism with the intrusive contact within a few hundred meters of the pluton, forming a single bedding-parallel high-strain fabric.

The oldest structures exposed in the western KM appear to be N to NE trending map-scale folds that have been subsequently deflected by emplacement of TG and cut by faults. The most obvious of these is the north-trending upright anticline in the southern map area (F5) that separates an eastern limb composed of a conformable section of OS through Dg that dips moderately to the east from a western limb of Dsi, OS, and Dse that dips moderately to the west but has been dismembered by two high angle faults (Fig 16: F5; Fig

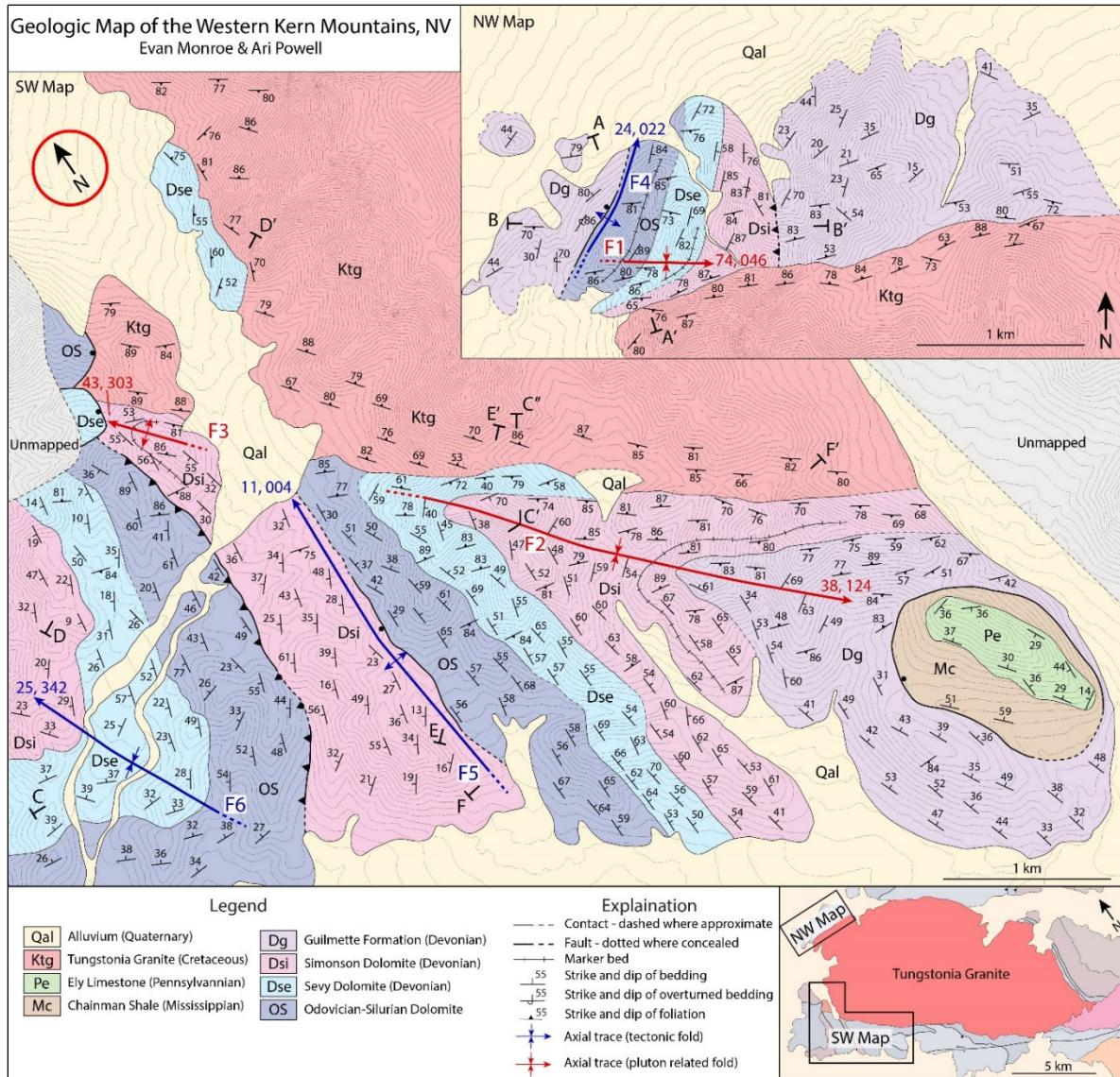


Figure 16: Geologic map of the northwestern and southwestern flanks of the KM. The location of each map area is shown in the inset map in the bottom right corner.

17: C-C'"). This fold has a fold axis of 11, 004, a subvertical axial surface and an interlimb angle of  $\sim 90^\circ$  (Fig 18: S3). Prior to westward tilting of the range during the Cenozoic, the western limb would have been approximately horizontal and the eastern limb approximately vertical or overturned, and the fold would have had an axial surface that dipped to the west (i.e., east vergent), similar to other asymmetric folds that have been recognized in the

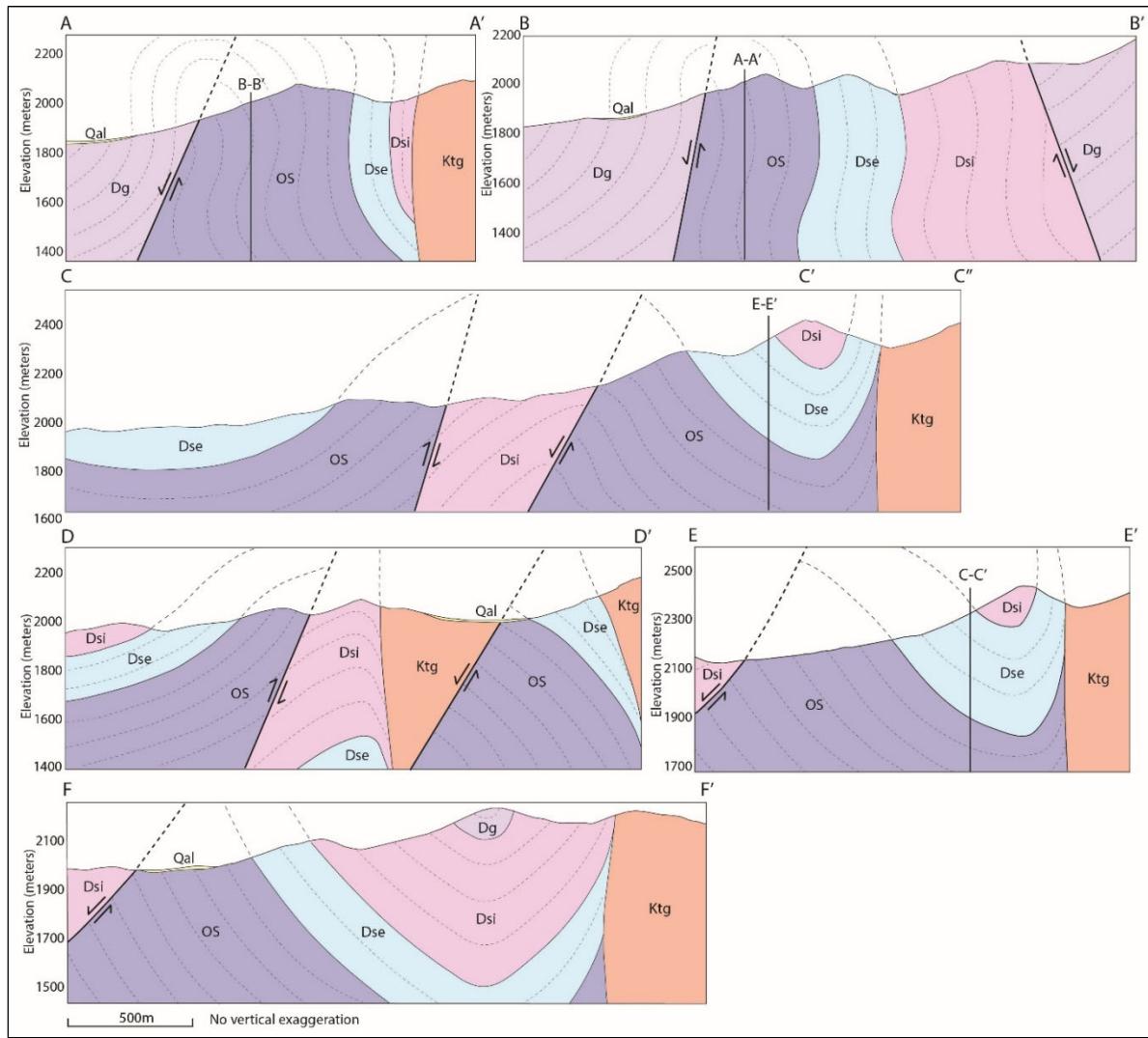


Figure 17: Cross sections from maps of the northwestern (A-A' and B-B') and southwestern (C-C'' through F-F') map areas.

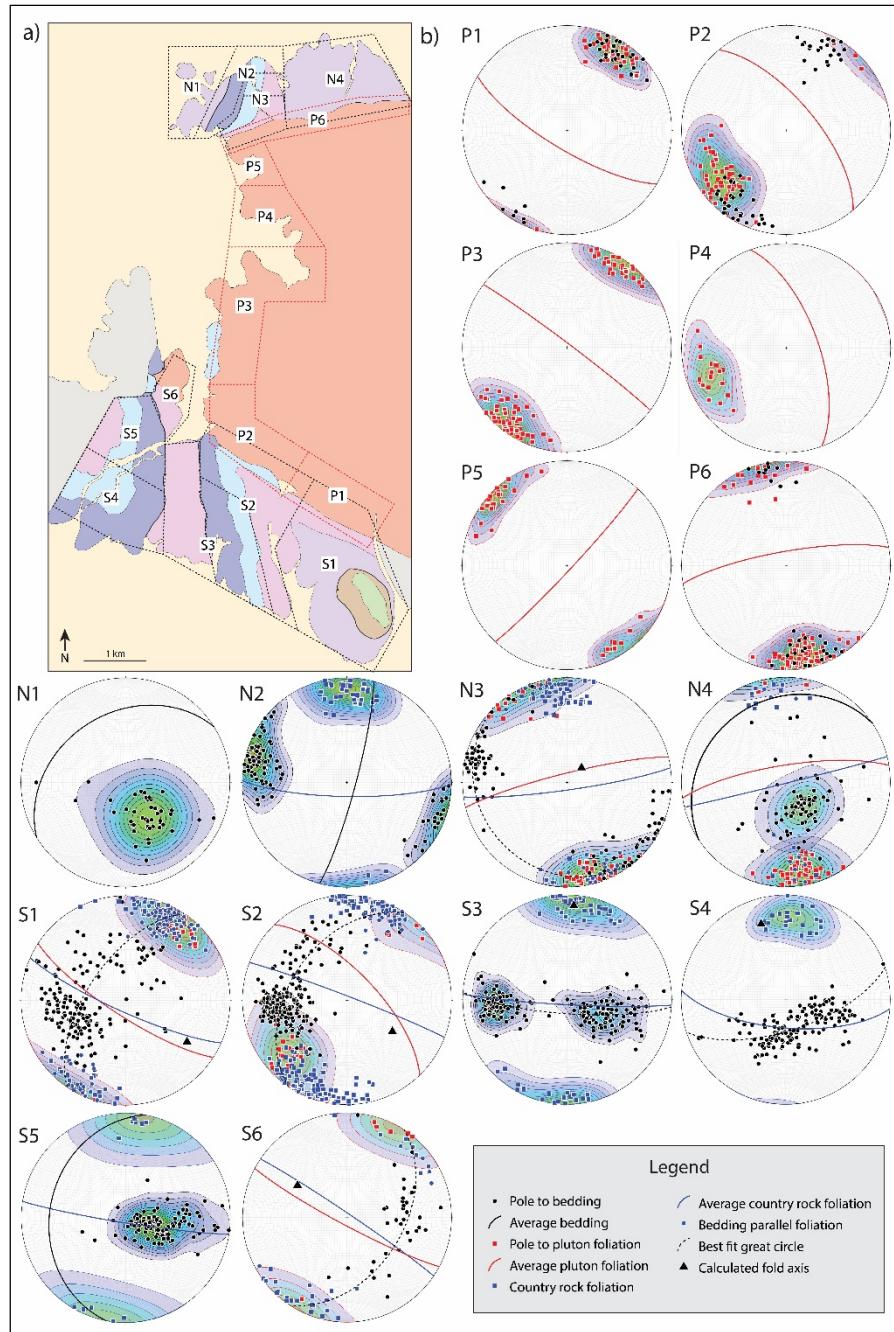


Figure 18: a) Map showing the geographic extent of stereonets. b) Zoned stereonets showing orientations of bedding, foliation, and folds in the northwest and southwest map areas and intervening exposures of TG.

Confusion Range and Snake Range. The geometry of the hinge is obscured by two high angle faults—one that is interpreted as a west-dipping thrust fault that was perhaps synchronous with folding, and the other that is interpreted as a younger west-dipping normal

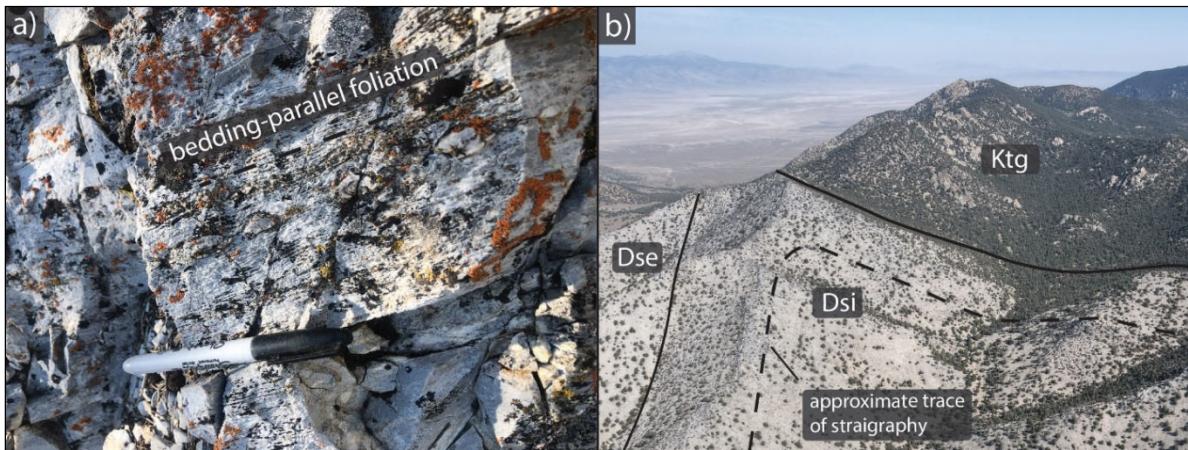


Figure 19: a) Bedding-parallel foliation in Dse ~150 m from the intrusive contact. View facing north. b) Drone image looking north across part of the southern map area. Stratigraphy rotates from being at a high angle to the pluton margin to being sub-parallel to it within a few hundred meters of the contact (F3).

fault. A similar anticline is present in the northern map area (F4) that has a fold axis that plunges gently to the NNE, with bedding of the Guilmette formation in the western part of the map area dipping moderately to steeply to the west and beds to the east of the Ordovician through Devonian dolomites dipping steeply to the east (Fig 16: F4; Fig 17: A-A' & B-B'; Fig 18: N1 & N2). On the eastern side of the northern map area, exposure is poor and bedding is inconsistent but appears to primarily be dipping to the northwest (Fig 18: N4), likely due to the synclinal closure of the associated anticline to the west. However, these folds have been obscured by subsequent normal faulting so their precise geometry is difficult to determine. TG cuts both of these early folds so folding must have occurred prior to emplacement. A gentle syncline (F6) is exposed in the southwestern corner of the southern map area that has a fold axis that plunges gently to the northwest (Fig 16: F6; Fig 17: C-C''; Fig 18: S4). It has a similar orientation to folds exposed in the southwestern DCR (Rodgers, 1987) and is interpreted to be unrelated to pluton emplacement.

Perhaps the most interesting map patterns of the western KM are the conspicuous deflections of stratigraphy into parallelism with the pluton margins. Stratigraphy rotates from being at a high angle to the pluton contact to being sub-parallel to the contact within 100-500 m of the pluton. These abrupt deflections spatially coincide with the zone of penetrative deformation and development of a high strain tectonite fabric near the pluton margins, with the limbs that are adjacent to the pluton being highly strained and attenuated.

In the southern map area, there are two map-scale folds with distinct orientations that reflect the deflection of bedding into parallelism with the pluton contact. The largest of the two is a southwest plunging syncline (F2) that affects the east-facing section of OS through Dg and underlies most of the eastern part of the map (Fig 16: F2; Fig 17: C-C'', E-E' & F-F'; Fig 19b). Bedding orientations around this deflection yield a calculated fold axis of 38, 124, a subvertical axial surface that strikes NW-SE, an interlimb angle of ~50°, and a rounded hinge (Fig 18: S1 & S2). The axial surface of this fold and the pluton margin have a ~10° difference in strike, such that the limb adjacent to the pluton increases in thickness from ~100 m to ~500 m from west to east. Prior to westward tilting of the range, the fold axis and both limbs would have been approximately vertical with the N-S trending limb of the older anticline (F2) being deflected eastward (i.e., dextrally; Table 1).

The second deflection of stratigraphy in the southern map area is a northwest plunging anticline (F3) exposed near the western edge of the map immediately south of the westernmost exposure of TG. Here, Dsi rotates from dipping moderately to the west to dipping very steeply to the northeast, approximately parallel to the pluton margin and foliation, over a distance of ~100 m (Fig 16: F3; Fig 10: D-D'). This anticline has a fold axis of 43, 303, an axial surface that dips steeply to the southwest and an interlimb angle of ~80°

(Fig 18-S6). Prior to westward tilting of the range, the fold axis would have been approximately horizontal, with the limb away from the pluton dipping gently to the southwest or subhorizontal and the deflected limb dipping vertically and striking NW-SE (Table 1). The difference in orientation between the two pluton-adjacent folds in the southern map area clearly reflects the preexisting structure from the earlier N-S trending anticline, such that the eastern fold was affecting rocks that were near vertical and the western fold was affecting rocks that were approximately horizontal. The sense of deflection in both cases is dextral or downward in a pre-tilt orientation. The spatial coincidence of all three folds with the pluton margins and the zone of ductile deformation suggests they formed in response to emplacement of TG.

In the northwest map area, the steeply east-dipping OS through Dsi stratigraphy north of the pluton is deflected to the west starting ~200 m from the intrusive contact and is transposed into parallelism with the

<b>Fold Number</b>	<b>Fold Axis</b>	<b>Transposed Bedding</b>	<b>Limb away from Pluton</b>
F1	74, 046	260, 88	014, 84
F1 Pre-tilt	52, 325	264, 64	191, 58
F2	38, 124	298, 79	352, 54
F2 Pre-tilt	78, 135	306, 80	000, 88
F3	43, 303	302, 89	171, 48
F3 Pre-tilt	03, 303	122, 89	122, 28

Table 1: Orientations of the three folds that transpose bedding into parallelism with the intrusive contact in both their present-day orientation and orientation after restoring for westward tilting of the range. A 40° rotation about a horizontal axis trending 030° was used as a best approximation to restore tilting, however there is significant uncertainty in this estimate. The “Transposed Bedding” column shows the average strike and dip of bedding in the limb adjacent to the pluton, which is approximately parallel to the intrusive contact and foliation. The “Limb away from Pluton” column shows the average strike and dip of bedding in the other limb. The locations of each fold are shown in Fig 9.

WSW striking pluton margins and foliation within ~100 m of the pluton (Fig 16: F1). The fold produced by this deflection (F1) is very steeply plunging with a calculated fold axis of 74, 046 (Fig 18: N3), an axial surface that dips steeply to the north, an interlimb angle of ~130°, and a sub-rounded hinge. Prior to westward rotation of the range during the Cenozoic, this fold would have plunged moderately to the northwest and been defined by an abrupt upward deflection of moderately west-dipping stratigraphy adjacent to the more steeply dipping pluton margins (Table 1). To the east in the Guilmette formation, bedding is inconsistent away from the pluton due to smaller scale folds but still becomes approximately parallel with the pluton margins within 100-400 m of the contact.

At least two distinct normal faulting events affected rocks in the western KM. The earliest period of normal faulting is reflected in a gently east-dipping normal fault exposed in the eastern part of the southern map area that juxtaposes Mississippian Chainman shale in the hanging wall against Devonian Guilmette limestone in the footwall omitting the entire Mississippian Joanna Limestone and Pilot Shale and likely some of the Guilmette as well. The fault is approximately parallel to bedding in both the footwall and hanging wall and possibly represents a bedding parallel segment of an old normal fault with a ramp-flat geometry. This fault projects into TG and the same fault is well-exposed to the north of TG (Gans et al., 1990), indicating it must predate emplacement and likely formed as a somewhat higher angle east-dipping normal fault that rotated to its present low angle during westward rotation of the KMDCR. Younger ~N-S striking high-angle normal faults are also present in both the northern and southern map areas and likely reflect a late-stage extensional event that occurred after emplacement of TG and either during or after westward tilting of the range.

### *Tectonite fabrics in the deformational aureole of the Tungstonia Granite*

TG has a conspicuous deformational aureole around its margins in both the country rock and within the marginal part of the pluton that decreases in intensity inward and outward from the contact. At deeper structural levels in the northeastern KM, this fabric strikes NW and dips moderately to the NE, is parallel to bedding in the overturned limb of the WCA and is continuous throughout all exposures of the country rock northward into Pleasant Valley. At shallower structural levels in the western KM, the cleavage is much more localized and dies out rather abruptly away from the pluton into undeformed Paleozoic carbonates and clastic rocks. Excellent exposures of both the marginal parts of the pluton and the country rock in this area allow for a detailed investigation of the nature and distribution of this strain.

Nineteen oriented samples of carbonate country rock and granite were collected along two transects perpendicular to the pluton margin in the northwest and southwest map areas, as well as a variety of other samples, to assess how the magnitude, mechanisms and conditions of strain vary within the pluton's deformational aureole (Table 2). In hand specimen, most samples within the deformational aureole have a strong foliation and occasionally a very weak lineation, and thin sections were cut where possible perpendicular to the foliation and parallel to the lineation (X-Z face). When no lineation was evident, a

best approximation of the X-Z cut was made by estimating the relative strength of the foliation from various angles.

Samples of country rock were collected from the Devonian Sevy Dolomite and Simonson Dolomite, which are the main wall rocks to the western exposures of TG.

<b>Sample</b>	<b>Distance from Contact (m)</b>	<b>Rock Unit</b>	<b>Average Grain Size (um)</b>	<b>Estimated X/Z</b>	<b>Bedding Orientation</b>	<b>Foliation Orientation</b>
N1	190	Dse	12	1.1	014, 83	086, 78
N2	147	Dse	26	1.7	062, 88	062, 88
N3	126	Dse	21	1.7	066, 87	066, 87
N4	115	Dse	159	1.3	233, 88	233, 88
N5	106	Dse	136	1.8	233, 88	233, 88
N6	86	Dse	25	1.9	245, 82	245, 82
N7	64	Dsi	61	1.9	237, 88	237, 88
N8	50	Dsi	94	3.0	239, 82	239, 82
N9	1	Dsi	138	3.0	246, 78	246, 78
S1	565	Dsi	45	1.1	010, 51	098, 84
S2	300	Dse	14	2.1	333, 55	297, 75
S3	201	Dse	15	2.0	307, 80	307, 80
S4	58	Dse	42	2.2	299, 78	299, 78
S5	5	Dse	41	2.4	317, 61	317, 61

Table 2: Samples collected from TG's country rock in the northern (N) and southern (S) transects. Four samples from TG were also collected from 1 to 50 m from the contact in the northern transect and one sample of TG from ~5 m from the contact in the southern transect.

Undeformed and unmetamorphosed Sevy has an average thickness of 180-200 m and is composed of very fine-grained (10-15 um) light-gray dolomite with thin laminations. Beds typically range in thickness from 20 to 50 cm and occasional coarse-grained horizons are present as well as a few distinct marker horizons that contain abundant detrital quartz. The Simonson Dolomite is 150-175 m thick, has highly variable color (dark brown to light grey), bedding thickness (thin to massive), and grain sizes, and can be divided into three sub-members. The lowest member is ~30 m thick and is composed of light gray to brown, thick-bedded, medium- to coarse-grained dolomite that forms small cliffs and ledges. The dominant member is a thin- to medium-bedded medium- to coarse-grained dolomite with well-developed planar laminations defined by alternating light and dark brown bands. The uppermost part of the Simonson has uniform, very well-developed planar laminations. Minor clay and silt are common throughout both the Sevy and Simonson.

Outside of the pluton's deformational aureole, the country rock is undeformed and unmetamorphosed and is indistinguishable from typical Sevy and Simonson found in other parts of eastern Nevada. In the distal parts of the pluton's deformational aureole, up to 1.5 km from the intrusive contact, a spaced disjunctive pressure solution cleavage begins to appear that is at a high angle to bedding and produces parting planes that are approximately parallel with the pluton margin. In the microlithons between the cleavage domains the rock is largely undeformed. The foliation becomes more pronounced within a few hundred meters of the pluton contact and is defined by both pressure solution seams and the development of a continuous grain shape foliation. Within 100 to 150 m of the pluton contact, the foliation becomes well developed, the dolomite is more coarsely recrystallized, and bedding is transposed into parallelism with it. This foliation increases in grade toward the pluton

margin and is defined by a strong grain-shape-preferred orientation of elliptical dolomite grains, growth and alignment of metamorphic micas, pressure solution seams and compositional layering.

The country rock samples examined for this study are composed primarily of dolomite (~80-98%) with minor to trace amounts of both diagenetic minerals (calcite, quartz, pyrite, oxides) and metamorphic minerals (tremolite, phlogopite, muscovite). Average grain size of dolomite within each carbonate sample ranges from 12-160 um and greatly increases with proximity to the pluton, with the grain size of samples far from the pluton reflecting the original diagenetic recrystallized grain size and samples proximal to the pluton reflecting metamorphic recrystallization (Figs 20a, 21a, 21b & 21c). However, two samples are more-coarse grained than expected for their distance from the pluton. The Sevy Dolomite is known to have conspicuous horizons of more coarse-grained material and it is likely that these anomalously coarse-grained samples are from an originally coarse-grained horizon. Also, the three samples closest to the contact in the northern transect are from Dsi so some of this increase in grain size may reflect the original diagenetic grain size. Some of the samples have a bimodal grain size distribution, with pods and lenses of coarse-grained dolomite occupying 5-20% of the rock volume in a groundmass of fine-grained recrystallized dolomite (Fig 21e). Many of these pods and lenses appear to have originally been carbonate veins that were extensively folded and boudinaged so that they are now disaggregated, or were areas where fluids affected the recrystallized grain size. For these bimodal samples, only the finer grained groundmass was used to measure grain size and ellipticity.

To estimate the magnitude of strain, the ellipticity of ~100 recrystallized dolomite grains per sample was measured from enlarged photomicrographs using the measuring tool in Adobe Illustrator. The average ellipticity ranges from approximately 1 to 3 (long axis over short axis) and increases with proximity to pluto (Fig 20b). It is important to emphasize that these ellipticities are an absolute minimum estimate of the total accumulated strain because of the probability that continuous recrystallization occurred during

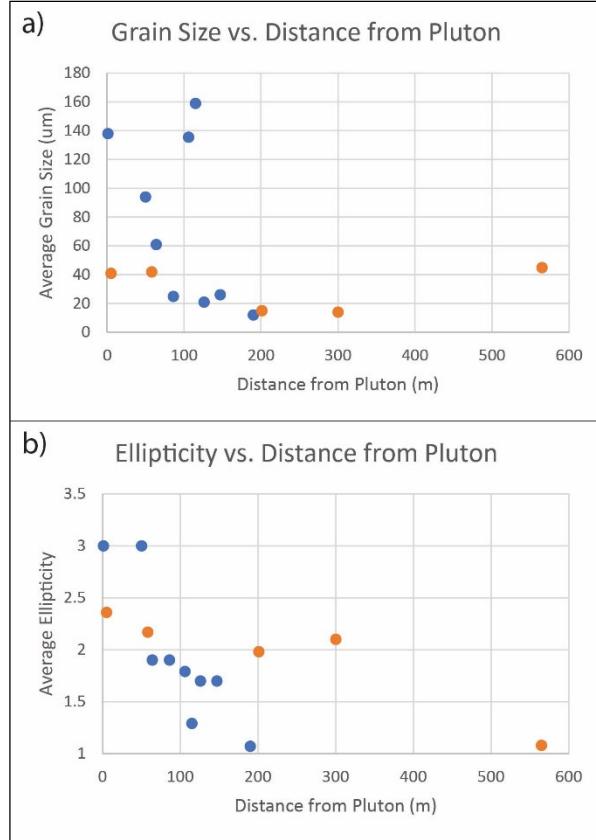


Figure 20: a) Plot showing the average grain size of recrystallized dolomite grains from the northern (blue) and southern (orange) transects plotted against distance from the pluto margin. b) Plot showing the average ellipticity of recrystallized dolomite grains from both transects.

deformation. This strain estimate only reflects the penetrative grain shape foliation and does not account for volume loss shortening perpendicular to the foliation by pressure solution. In addition, it is unlikely that all thin sections are perfectly parallel to the X-Z face so many of these ellipticities have likely been calculated from an oblique cut of the strain ellipsoid. However, they still provide a rough indication of the magnitude of strain and the strain gradient, which dramatically increases towards the pluto margin. Most highly deformed samples have a well-developed foliation but not an obvious lineation and we suspect that much of the strain is well into the flattening field. However, marbles that are deformed at

high metamorphic grade typically to not preserve well-developed lineations so it is possible that strain was closer to pure-shear but that the lineation was not preserved.

Dolomite grains within this suite of samples have a variety of textures. For most samples, grains have relatively straight or slightly rounded margins, with well-developed polygonal grain boundaries that typically increase in development toward the pluton margin, indicating that deformation occurred at elevated temperatures towards the intrusive contact, with thermal recrystallization outpacing deformation (Figs 21d). Both type I and type II twins are relatively common and pervasive in the two samples that are proximal to the pluton margin in the northern transect (Fig 21c). Weak to moderate sweeping and patchy undulatory extinction is sometimes present but decreases with distance from the pluton margin. It is common for adjacent grains to have similar/sweeping extinction angles, indicating that they are separated by subgrain boundaries. Incipient subgrain boundaries within larger relict grains are also occasionally present. Many of the coarser grained pods of dolomite have highly irregular/ameboid grain shapes, suggesting a component of grain boundary migration (Leiss & Barber, 1999). These textures indicate that deformation was occurring at elevated temperatures which could only have been caused by heat from TG.

Metamorphic tremolite is present in eight of the samples and makes up 2-10% of the rock volume (Fig 21f). It occurs as euhedral to subhedral porphyroblasts up to 1 cm across but more commonly 200-1000 um and is variably retrograded to very fine-grained aggregates of dolomite, quartz, oxides and muscovite. It occasionally forms radiating and randomly oriented aggregates that cut the foliation but more commonly occurs as isolated porphyroblasts which are usually parallel or subparallel to the foliation but occasionally cut it. Quartz is present in eleven of the samples and typically comprises up to ~8% of the rock

volume, but usually less than 2-3%. Phlogopite and muscovite are present in most of the samples and comprise up to ~4% of the rock volume. Micas are typically very-fine grained

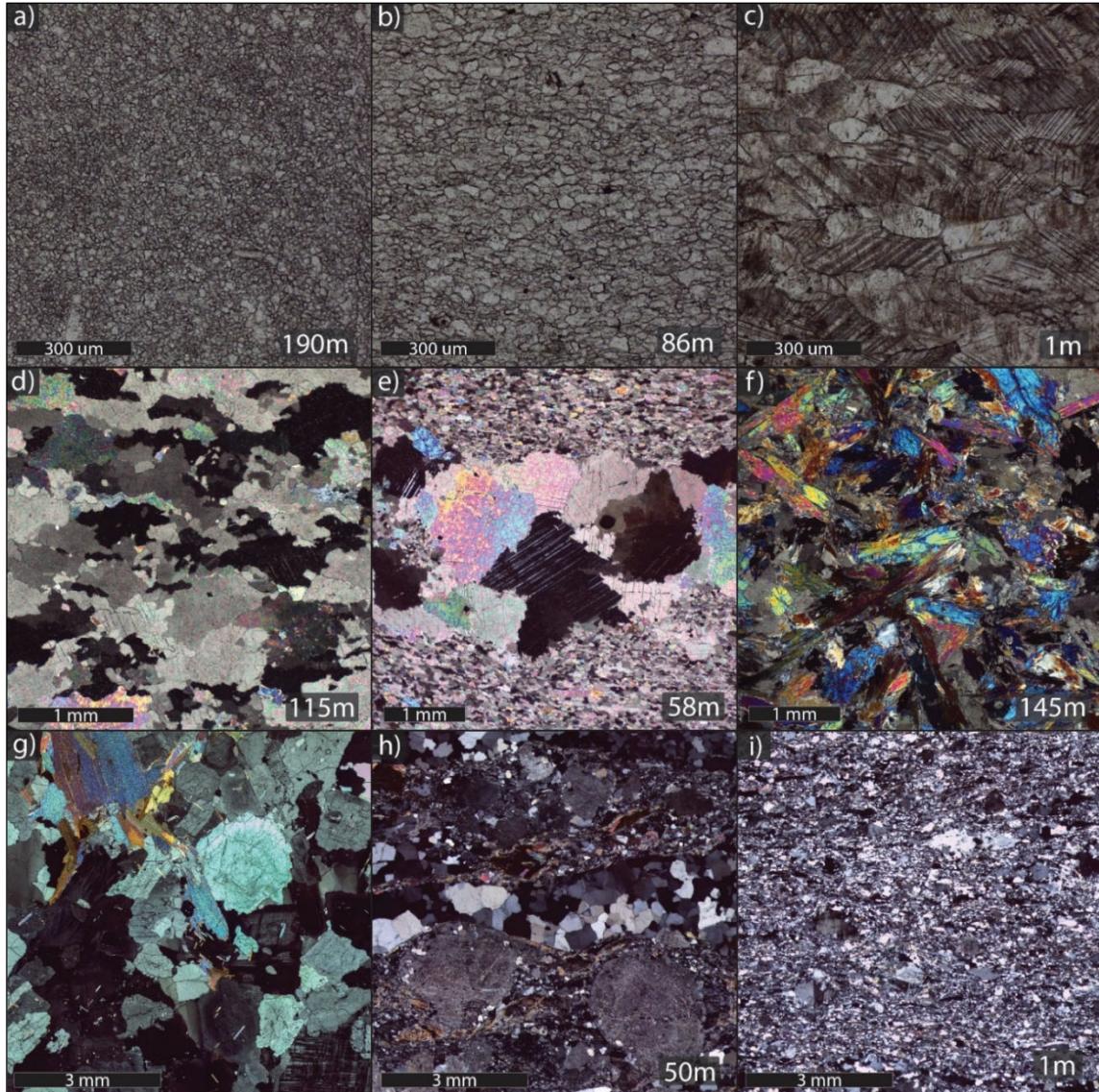


Figure 21: Photomicrographs of rocks from TG's deformational aureole. Distance from the intrusive contact is indicated in the lower right corner of each photo. a) Very fine-grained dolomite with no deformational fabric (PPL). b) Medium-grained dolomite with a weakly developed deformational fabric (PPL). c) Coarse-grained dolomite with a well-developed deformational fabric and pervasive deformation twinning (PPL). d) Coarse-grained dolomite with highly lobate grain boundaries, suggesting grain boundary migration (XPL). e) Fine-grained dolomite with a pod of coarse-grained material. f) Coarse-grained metamorphic tremolite (XPL). g) Undeformed TG from the interior of the pluton (XPL). h) TG collected 50 m from the pluton contact with a moderately well-developed foliation (XPL). i) Highly deformed TG collected 1 m from the pluton contact (XPL).

and occur as platy porphyroblasts, most of which are aligned with the foliation. Small, isolated feldspar grains are present in some of the samples and are usually associated with quartz-rich horizons. Trace oxides are present in nearly all the samples and typically occur as <30 um anhedral grains dispersed throughout the rock volume as well as along dissolution seams.

The unstrained interior of TG is a coarse-grained two-mica granite with an average composition of 40-50% plagioclase, 20-30% potassium feldspar, 25-30% quartz, 3-5% muscovite, 2-3% biotite, and trace oxides, garnet, zircon, titanite, monazite and apatite (Fig 21g). Euhedral books of muscovite up to 5 cm and phenocrysts of perthitic potassium feldspar up to 4 cm are set in a somewhat finer grained matrix of quartz, feldspar and micas displaying a seriate grain size distribution from less than 100 um to 2-3 cm. The interior of the granite has a typical hypidiomorphic granular texture and is isotropic except for occasional aligned books of muscovite, showing no evidence of subsolidus deformation other than undulatory extinction and occasional deformation lamellae in quartz and feldspar.

TG grades from its unstrained interior to a highly strained tectonite near its margins over a distance of ~100-300 m. In the inner portion of the aureole, strain is minimal and primarily accommodated by quartz with little deformation of feldspar. With increasing proximity to the pluton contact, the mesoscopic foliation becomes progressively more well developed and is defined by a strong grain shape preferred orientation of recrystallized quartz ribbons, alignment of synkinematic micas, and an aggregate shape preferred orientation of recrystallized feldspar (Fig 21h). Within a few meters of the contact, the granite is intensely foliated, with highly elongated quartz ribbons, a strong alignment of micas, extensive strain and recrystallization of feldspar, and drastic reduction in

recrystallized grain size (Fig 21i). Some of this reduction in grain size might reflect an original quenching of the granite towards the intrusive contact but the extensive development of quartz ribbons and feldspar porphyroclasts with highly elongated tails showing clear dynamic recrystallization into much smaller subgrains suggests that this conspicuous decrease in grain size associated with the development of an intense tectonite fabric was produced by subsolidus (albeit high temperature) strain and dynamic recrystallization. A qualitative assessment of strain in the most deformed parts of the granite based on ellipticities of quartz ribbons and transposition of aplite dikes is that X/Z is likely >5. Shear sense indicators are relatively ambiguous but asymmetrical tails around feldspar porphyroclasts typically suggest right lateral shear on the northern margin of the pluton and left lateral shear on the southern margin. Because of westward tilting of the range, these shear-senses are pluton-up prior to tilting.

In deformed TG, feldspar occurs as relatively undeformed porphyroclasts surrounded by very fine-grained recrystallized feldspar aggregates which are most common in strain shadows. Larger porphyroclasts are commonly fractured and pulled apart parallel with the foliation. Quartz ribbons range in size from 1 mm to over 5 cm across and commonly have aspect ratios >5 and sometimes > 10. These ribbons used to be single large equant grains prior to deformation and have been stretched out into their current shape. They are now composed entirely of subgrains that have well-developed polygonal boundaries, but are sometimes lobate or ameboid shaped, indicating GBM recrystallization. Muscovite and biotite occur as relatively continuous thin seams or individual grains that commonly wrap around feldspar grains to form an anastomosing network with an average orientation parallel with the foliation.

*Relationships between deformation, metamorphism and pluton emplacement in the western Kern Mountains*

Analysis of map relationships and petrographic observations in the western KM reveals a few important conclusions regarding the relationships between deformation, metamorphism and the emplacement of TG. First, the tectonite fabrics, localized metamorphism, and deflection of bedding into parallelism with the intrusive contact are interpreted to be synchronous with and directly related to the emplacement of the granite, where deformation in the wall rocks served mainly to make space for the granite and accommodate its upward ascent. In other words, this is not a younger “tectonic” shear zone localized along the margin of a pluton. Second, the types of relationships observed here—high strain fabrics, map-scale folding, abrupt lateral increases in metamorphic grade—are simply smaller-scale versions of what we observe occurring on a much larger scale along the southern flank of the DCR and in the embayment of metasedimentary rocks in the overturned limb of the WCA in the eastern KM. The specific lines of evidence that support these conclusions are:

- 1) Deformation is restricted to the immediate vicinity of the intrusive contact and decreases rapidly away from that contact in both the pluton and country rock.
- 2) The tectonite fabrics are dominated by a foliation that appears to be mainly in the flattening field and everywhere parallels the sharp intrusive contact, even though this contact wraps around the western end of TG, such that it ranges from NW to N to ENE striking.

- 3) The strain in the country rocks is synkinematic with prograde metamorphism whose grade increases abruptly from completely unmetamorphosed country rocks to upper greenschist or amphibolite facies over less than a kilometer towards the exposed contact with the pluton—a metamorphism that can only be interpreted as contact metamorphism.
- 4) The tectonite fabric in the marginal part of the pluton dies out rapidly inward and is everywhere a high-temperature subsolidus fabric characterized by dynamic recrystallization of feldspar and extensive high-temperature recovery textures including grain boundary migration and complete polygonization of quartz within quartz ribbons. Intensely foliated hand specimens are often disappointing in thin section because of their recrystallized granoblastic texture, with the only evidence for the foliation being the conspicuous alignment of biotite and muscovite grains.
- 5) A final piece of evidence that this contact is clearly an intrusive contact is that the abundance of leucocratic veins of aplite and pegmatite increases dramatically towards the contact—from quite rare within the interior of TG to an impressive network of dikes and sills within a hundred meters of the contact. Most of these dikes and sills become largely transposed into parallelism with the contact in the intensely foliated area close to the margin, but there are also numerous examples of late aplite dikes cutting across previously deformed and transposed dikes, thereby providing compelling evidence that the emplacement of the shallow levels of the granite was synchronous with the deformation in its marginal facies and contact aureole.

One of the most peculiar attributes of the intrusive contact is the total absence of granite dikes that emanated from the pluton and intruded the adjacent wall rocks, and the lack of any inclusions or pendants of wall rocks within the pluton. We attribute this to the likely very high viscosity of the melt as it was being emplaced largely as a crystal mush and its continued subsolidus ascent to shallower levels driven by the buoyancy of additional magma being emplaced from below—see discussion in following section.

## **U-Pb Geochronology**

U-Pb geochronology was performed to constrain the timing and duration of metamorphism of the Wood Canyon and Singleton Creek metamorphic aureoles as well as the precise age(s) and crystallization history of TG. Both are broadly known to be Late Cretaceous (Gottlieb et al., 2022; Lee et al., 1986; Rodgers, 1987) but it is important to establish more precise ages to determine the duration and timing of both metamorphic and magmatic activity in the area and to assess what relationships, if any, exist between the two. Monazite from five samples of schist from the southern DCR was dated to constrain the age(s) and duration of metamorphism as well as zircon from eight samples from various locations within TG to constrain its crystallization history.

### *Methods*

Analysis took place at UC Santa Barbara’s Laser-Ablation-Split-Stream Geochronology facility following the methods described in Kylander-Clark et al. (2013). Zircon crystals were separated using standard magnetic and density techniques, mounted in an epoxy puck, and imaged using the cathodoluminescence detector on UCSB’s FEI Quanta 400F field emission source SEM prior to analysis. Monazite was analyzed in thin section to

evaluate the petrographic context of mineral growth. Monazite grains were identified using the cathodoluminescence detector on the SEM and UCSB's Cameca SX-100 electron microprobe was used to make quantitative elemental maps of U, Th, Pr, Gd, La, Y, Nd, Sm, Ce and P to identify zoning patterns to help guide laser spot placement. U-Pb isotopes were measured with a Nu Instruments Plasma HR multi-collector ICP for both zircon and monazite, and element concentrations for monazite were measured concurrently using an Agilent 7700X quadrupole ICPMS. The primary reference material (RM) for zircon U-Pb was 91500 (Wiedenbeck et al., 1995), and GJ1 (Horstwood et al., 2016) and Plešovice (Sláma et al., 2008) were employed for accuracy; both standards yielded dates within 2% of their expected values. Monazite 44069 was used as the primary RM for U-Pb normalization, and Bananiera (Palin et al., 2013), FC-1 (Horstwood et al., 2003) and Trebilcock (Tomascač et al., 1996) yielded U-Pb dates within 2% of their expected values. Bananiera (Kylander-Clark et al., 2013) was used as the primary trace-element RM, assuming 12.9% P in monazite. 60-80 spot analyses were performed on each monazite sample and ~60 spot analyses were performed on individual zircons from each sample of TG. Isotope data was reduced using Iolite software and plotted with Isoplot software (Berkley Geochronology Center, 2012; Paton et al., 2011).

#### *Revised ages of prograde metamorphism in the southern Deep Creek Range*

The amphibolite grade Wood Canyon aureole on the southern flank of the DCR contains porphyroblastic biotite, garnet, staurolite, andalusite and plagioclase and has isograds that cut across formation contacts and indicate increasing grade to the southeast (Fig 14). Metamorphic assemblages associated with this aureole are overprinted by the

younger and much more localized Singleton Creek aureole, which is located on the southeastern most flank of the range and also reached amphibolite facies as evidenced by prograde biotite, garnet, andalusite, staurolite and cordierite. Rodgers (1987) analyzed two samples of metamorphic hornblende using the  $^{40}\text{Ar}/^{39}\text{Ar}$  technique to constrain the ages of metamorphism in the Wood Canyon and Singleton Creek aureoles. One was from an amphibolite sill in McCoy Creek unit B that was within the outer portions of the Wood Canyon aureole that yielded an uninterpretable age spectrum. The second sample was from another amphibolite sill in unit B within the outer margin of the Singleton Creek aureole that yielded a plateau of  $72.8 \pm 0.2$  Ma, although most of the gas was released on a single step. It was unclear at this locality whether hornblende was heated beyond its closure temperature during Singleton Creek metamorphism, so its bearing on the age of either of the aureoles is not clear. In any case, the ~73 Ma argon age is best interpreted as a cooling age (or possibly a partially reset older age) and does not likely record the age of peak metamorphism for either event. New U-Pb monazite geochronology on five samples of schist collected along a transect in McCoy Creek unit E was performed in an attempt to determine the ages of both the Wood Canyon and Singleton Creek aureoles. Two samples were collected from within the st + grt zone of Wood Canyon aureole but outside the st-in isograd of the younger Singleton Creek aureole, with three of the samples located within the st ± grt ± and ± cord zone of the Singleton Creek aureole (SDCR-2A, SDCR-1B, and EMDC-88; Fig 23a).

The majority of the monazite grains analyzed are 10-30 um, equant, rounded, and disseminated throughout the rock volume (Fig 22). Rare grains up to 100 um are also present, and multiple spots were put on these larger grains. Elemental maps measured on the EPMA often don't show clear zoning patterns, however some grains—especially the larger

ones—exhibited sector or concentric zoning, which is most evident in Ca and Y. Nearly all the analyses are slightly discordant, indicating a component of common lead which is typical for metamorphic monazite. Projecting these data onto concordia resulted in final dates with errors of  $\pm$  2–4 Ma.

The five samples analyzed have a range of dates from 34 to 108 Ma, with the highest concentration ranging from ~80–90 Ma (Fig 23c).

This spread of dates from 80–90 Ma is present in all the samples and it relatively continuous. Sample EMDC-102 and to a lesser extent EMDC-69 and EMDC-88, also show a cluster of Eocene dates from 35 Ma to 42 Ma. The three samples from within the Singleton Creek aureole (SDCR-2A, SDCR-1B and EMDC-88) have a peak at  $70 \pm 2$  Ma, which is absent from the other two samples. There are a small number of older dates (up to 108 Ma) and intermediate dates (between 50 Ma and 78 Ma).

We interpret the spread of dates from ~80–90 Ma to reflect protracted crystallization and recrystallization of monazite during episodic or protracted heating and fluid flow and likely represents the age of the Wood Canyon aureole. The younger  $70 \pm 2$  Ma peak is only

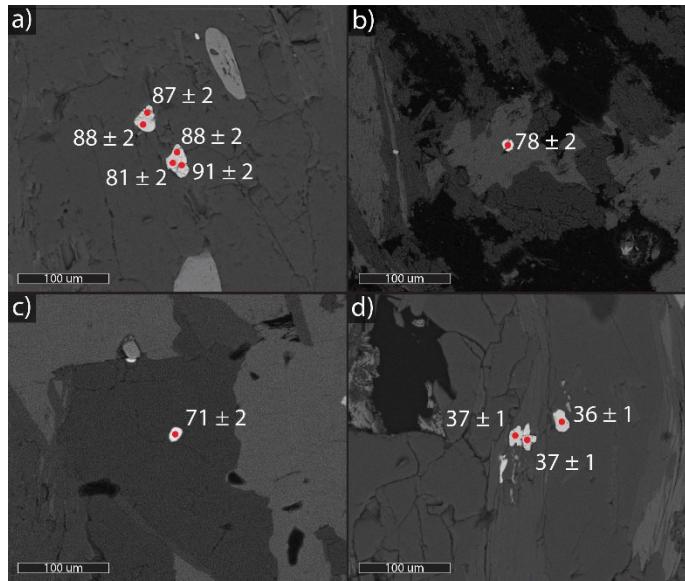


Figure 22: SEM images showing the typical monazite morphologies from the samples analyzed with laser spot locations and associated ages. a) Relatively coarse-grained monazite with multiple Late Cretaceous ages. b-c) Very fine-grained equant monazite that was the most common in these samples. d) Relatively coarse-grained monazite with Eocene ages.

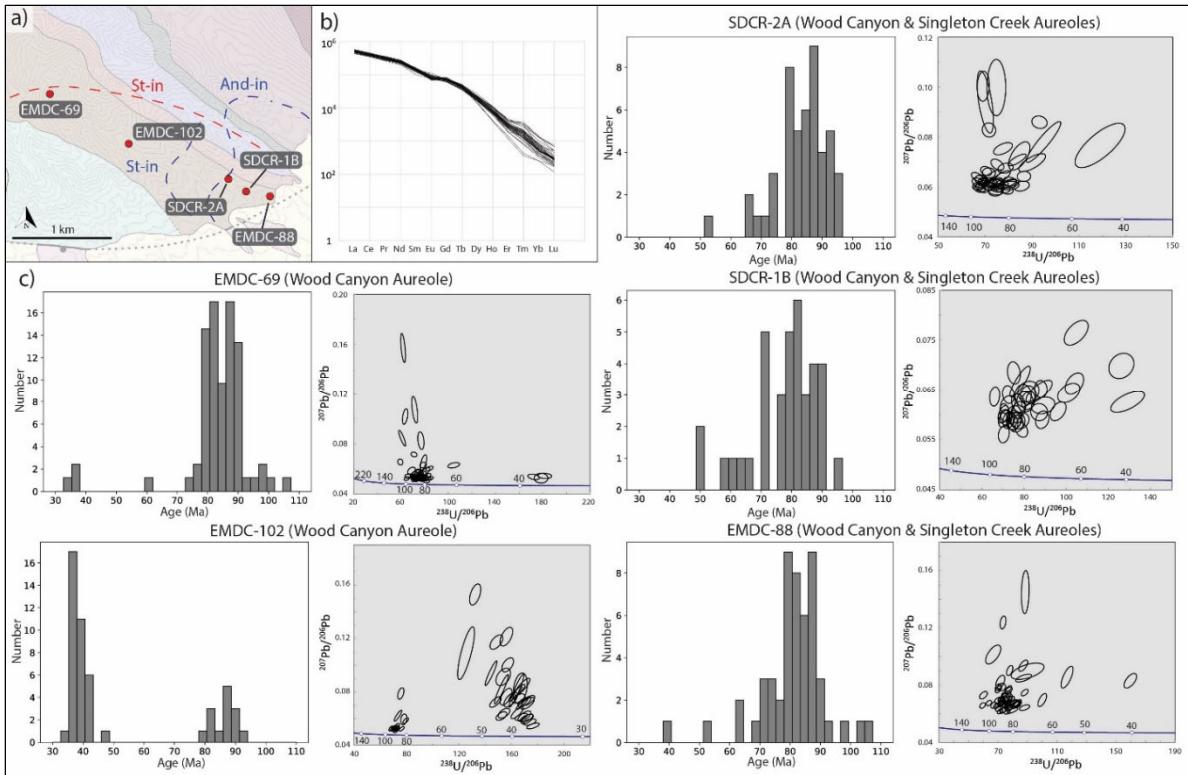


Figure 23: a) Map showing geochronology sample locations and the staurolite-in isograd of the Wood Canyon aureole (red), and staurolite-in and andalusite-in isograds of the Singleton Creek aureole (blue). Isograds from Rodgers (1987). b) Rare earth element spider diagrams for the six samples analyzed. b) Histograms and Tera-Wasserburg concordia diagrams showing the distribution of U-Pb monazite ages from the six samples of schist from the southern DCR that were analyzed. Each age is from a single spot analysis on a monazite grain.

present in samples within the Singleton Creek aureole so we interpret these dates to reflect this younger and much more localized metamorphic event. The Eocene dates overlap with the age of the Ibapah pluton in the central DCR and the Skinner Canyon Granite (and likely the Uvada Granite) in the KM and thus likely reflect heating by Eocene magmas concealed beneath the present exposure surface (Best et al., 1974; Rodgers, 1987). A similar spectrum of Eocene monazite dates was also obtained from the Trout Creek area ~8 km to the north (Monroe et al., 2023). The intermediate dates between the Late Cretaceous and Eocene peaks may reflect minor episodes of monazite (re)crystallization or they could be mixed

analyses between these two domains. Older (~90-105 Ma) dates may represent minor episodes of early monazite (re)crystallization, the significance of which is unclear.

In summary, we interpret with Wood Canyon aureole to represent a protracted period of amphibolite facies metamorphism that occurred over a 10-15 Myr period from ~90 Ma to ~80 Ma. A younger, shorter lived and more localized episode of amphibolite facies metamorphism occurred on the southern tip of the range at ~70 Ma (Singleton Creek aureole). Finally, we see evidence for Eocene monazite (re)crystallization that likely reflects heating and/or fluid flow from Eocene magmas.

#### *Crystallization history of the Tungstonia Granite*

U-Pb zircon geochronology was performed on eight samples of TG to assess the age of final crystallization of the pluton and determine whether it was emplaced and rapidly crystallized at all once or if it represents an amalgamation of multiple distinct intrusions separated by significant time intervals. Samples chosen for analysis were collected from different geographic positions within the pluton, including its western, southern, and northern margins as well as its interior. The zircons from each sample show clear igneous textures with concentric zoning patterns and no evidence for metamorphic overgrowths, and laser spots were typically placed near the rims to reflect the latest stage of zircon crystallization.

U-Pb analysis of the eight samples yielded a wide spectrum of zircon dates ranging from 66 Ma to 2.7 Ga, after filtering out discordant (<0.9 concordance value) dates and zircons with a high uranium content (>10,000 ppm) with the potential for lead loss (Figs 24 and 25). Each sample has a fairly continuous spread of dates from ~70 Ma to 80-90 Ma with no clear age breaks, followed by a variety of older Cretaceous and Jurassic ages, as well as

some Proterozoic ages and one Archean age. Older (Proterzoic/Archean) ages and most of the Jurassic and earlier Cretaceous dates were obtained from xenocrystic cores, whereas the majority of younger dates were obtained from rims with some from the interior of grains.

To calculate our best estimate for the final crystallization age of each sample, the TuffZirc algorithm was used in Isoplot which calculates the youngest population of ages that lie within  $2\sigma$  of each other (Fig 25). Of the seven samples analyzed from the main body of TG, estimated final crystallization ages range from  $68.5 \pm 0.5$  Ma to  $70.1 \pm 1.2$  Ma.

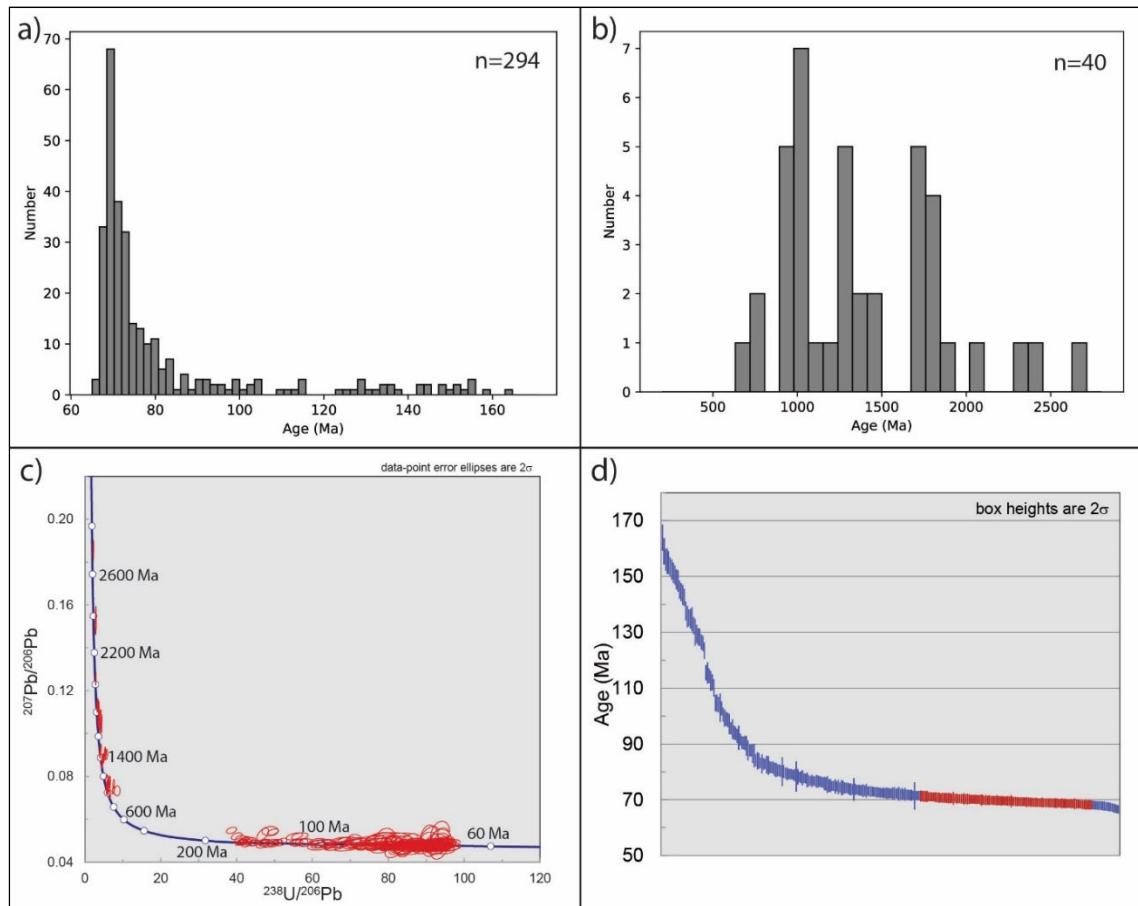


Figure 24: a) Histogram of all ages <200 Ma obtained from the eight samples analyzed from TG. b) Histogram of all ages >200 Ma. c) Terra-Wasserburg concordia plot of all ages from TG. d) Plot showing the spectrum of all ages <200 Ma obtained. Red bars indicate the youngest population that lies within  $2\sigma$  of each other.

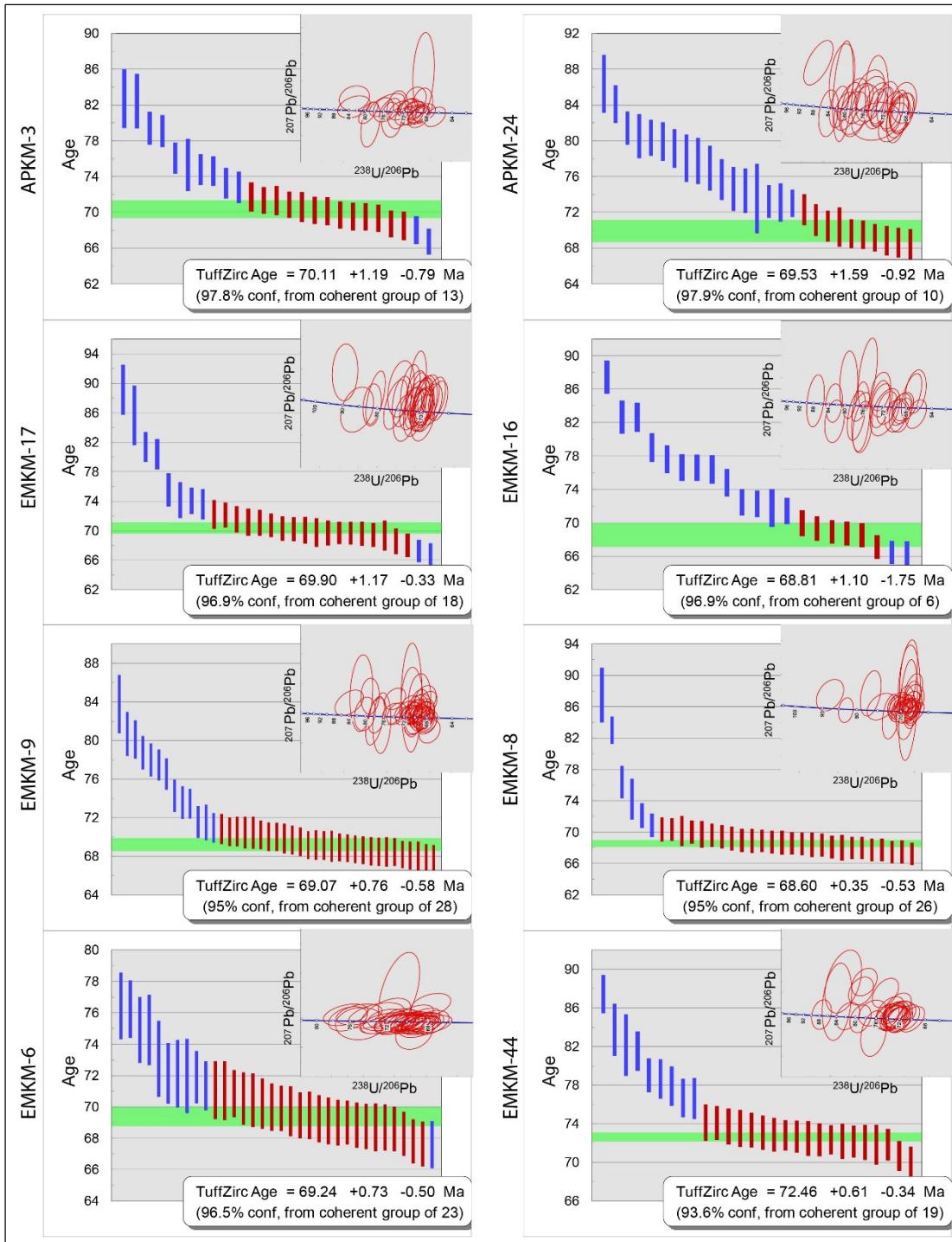


Figure 25: Diagrams showing the ages with errors of individual zircon analyses from each sample of TG. Red bars represent ages that fit within a single population and were used in the final age calculation. Blue bars represent ages that didn't fit into a single population and weren't used in the final age calculation. Tera-Wasserburg concordia diagrams shown on the top right indicate that all U-Pb ratios are concordant or are close to concordia.

Although many of these ages are within error of each other, there is an apparent eastward

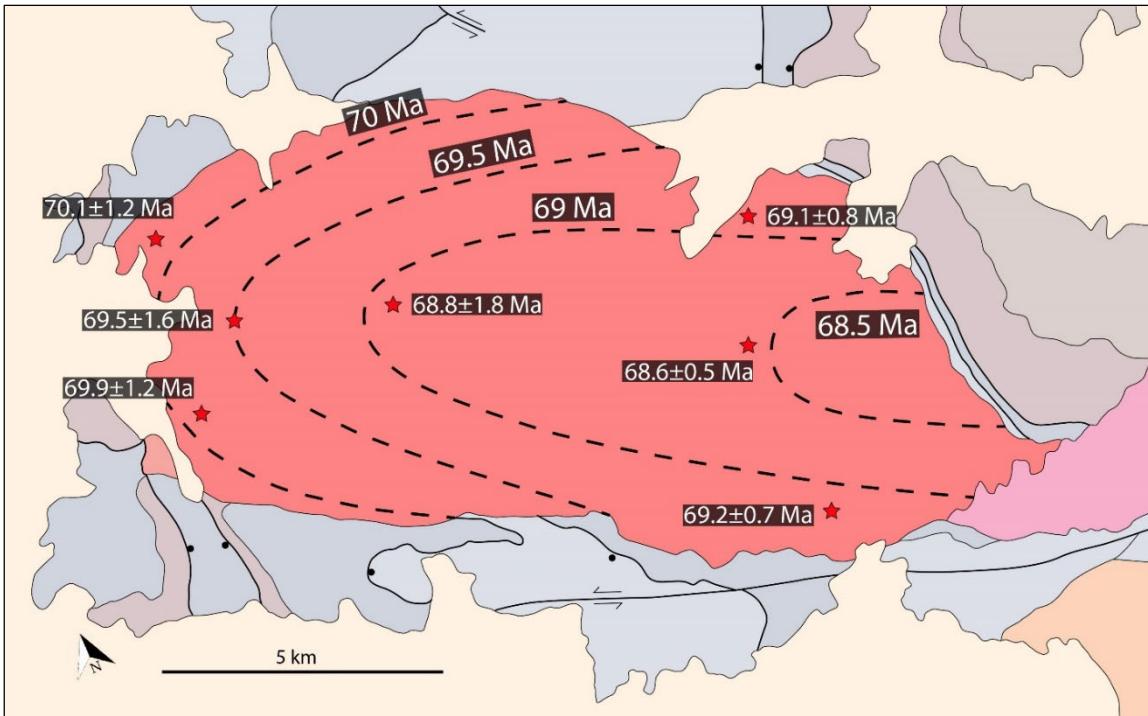


Figure 26: Map of the KM showing the locations and ages of the U-Pb geochronology samples from TG. Interpretive age contours with a 0.5 Ma interval are shown to highlight the inward and eastward younging trend suggested by the ages. Base map modified from Gans et al., (1990).

and inward younging trend within the pluton (Fig 26). Because of westward tilting of the range, this suggests that the uppermost parts of the pluton and margins crystallized before the deeper and interior portions. However, because these ages have significant errors, the precise chronology of emplacement cannot be resolved. In addition to the seven samples analyzed from the main body of TG, a sample from an isolated outcrop of granite that looks both compositionally and texturally identical to the main phase of TG but is located ~10 km to the ESE of the main body (EMKM-24) yielded an age of  $72.5 \pm 0.6$  Ma, ~2 million years older than the ages obtained from the main body.

Given the concentric apparent younging inwards, we believe that TG as it is exposed today reflects the final crystallized product of a prolonged history of melt generation by anatexis and coalescence, crystallization, and ascent of this magma, with final emplacement

at 70 to 69 Ma, perhaps as a crystal mush with a largely crystallized outer rind and still molten interior. This is further supported by the continuous spread in ages from >80 -70 Ma with no clear gaps or inflections, which is interpreted to reflect an even more protracted zircon growth/crystallization history of at least 10-15 million-years, perhaps starting as early as 90 Ma. This crystallization and emplacement history of TG nicely complements the metamorphic history of the southern flank of the DCR, with protracted metamorphism from 90-80 Ma, followed by a ~72 Ma thermal event, perhaps associated with the ascent of TG, and will be explained more in the final discussion.

## Discussion

Previous work treated the Deep Creek Range and Kern Mountains as distinct domains, exposing unique and somewhat unrelated geology, with the DCR representing a large tilt block that exposes a large-scale west-vergent tectonic fold associated with Sevier shortening, as well as some peculiar localized metamorphic culminations, and the KM exposing one of the largest Cordilleran S-type granites with a well-developed deformational aureole. Here, we suggest that these two ranges are not only tied together physically, but that the many disparate magmatic and deformational features observed in the KMDCR are genetically related to each other. Specifically, we believe that these ranges document how metamorphism and anatetic melting at deeper levels in the Sevier hinterland locally produced large magma bodies—diapiric mushes—that rose incrementally to shallow crustal levels, and in so doing produced an array of map-scale structures and dynamothermal metamorphic tectonic fabrics that might otherwise be interpreted as a consequence of regional deformation. Salient features of our hypothesis are:

- 1) The WCA and other folds in the western KM were produced by the downward (or locally upward) deflection of country rocks adjacent to a rising and ballooning pluton.
- 2) High strain fabrics and prograde dynamothermal metamorphism in the KM and southern DCR are also directly a consequence of thermal weakening and channel flow adjacent to a rising pluton/crystal mush.
- 3) The melts that produced TG and their subsequent rise and crystallization occurred over a protracted period of time (~10-15 Ma), with final emplacement of the granite at shallow levels as a mostly solidified crystal mush at ~70 Ma.
- 4) The fairly restricted area now occupied by the Kern Mountains and Deep Creek Range appears to have served as a long-lived ~E-W trending conduit for rising hydrothermal fluids and anatetic melts, derived from deeper crustal levels (>15 km) during Late Cretaceous regional shortening associated with the Sevier Orogeny. A cross-sectional view of this “channel” is now exposed in the KMDCR by Miocene westward tilting and block rotation.
- 5) Structural geologists and field geologists commonly interpret the presence of map-scale and mesoscopic folding, development of penetrative tectonite fabrics and Barrovian style dynamothermal metamorphism as *prima facie* evidence for, and a direct response to regional tectonic shortening events. We do not question that much of the magmatism, deformation and metamorphism observed in the KMDCR is indirectly related to Sevier age horizontal crustal shortening, but argue that most of the thermal and deformational features exposed in these ranges are primarily a

response to the vertical (diapiric) ascent and spatial accommodation of anatetic melts from a much deeper Sevier hinterland mid-crustal mush zone.

#### *A reinterpretation of the Water Canyon Anticline*

A number of peculiar characteristics of the WCA are not consistent with the interpretation by Rodgers (1987) that it formed as a result of tectonic shortening associated with the Sevier Orogeny:

1. The fold closes to the west not the east, whereas observed shortening structures elsewhere in the Sevier hinterland are almost entirely east vergent, including the closest well-documented Sevier age folds and thrusts in the Northern Snake Range, northern DCR, and Confusion Ranges (Bick, 1966; Greene, 2014; Wrobel et al., 2021).
2. It is a profoundly local structure. There is no evidence that the WCA continues northward from its exposures along the southern flank of the DCR, nor to the south of TG.
3. An axial planar cleavage and higher order parasitic folds are conspicuously absent in areas of the WCA where they would be most likely to form (e.g., in the hinge region and rheologically favorable interbedded sandstone and shale intervals). The absence of these associated features would be most peculiar in mid-crustal metasedimentary rocks of this ilk that were undergoing typical layer parallel shortening. Moreover, the orientation of the steeply dipping S<sub>2</sub> cleavage on the southern limb of the WCA appears to be more consistent with right-lateral shear than as an axial planar cleavage.

4. Units in the southernmost overturned limb are highly strained and ductily thinned to ~10% of their original stratigraphic thickness in the northeastern KM, whereas most of the upright limb to the north in the DCR is unstrained and at full thickness. These relations suggest that the WCA primarily reflect a deflection of the southern limb in response to a passive shear folding mechanism, rather than layer parallel shortening and passive amplification. One possibility is that this reflects a superimposed ductile shear zone in the overturned limb, perhaps as a part of a west-directed ductile fault propagation fold. However, the lack of continuity of either the fold or hypothesized thrust along strike make this scenario unlikely, whereas the close spatial and temporal association of this highly attenuated limb with the intrusive margin of TG suggests a different cause.

An alternate hypothesis is that the WCA formed primarily in response to ascent of TG and that folding and strain within its thermal and deformational aureole acted as a material transfer process that made space for the rising magma. When magmas are emplaced into the crust, the volume that is occupied by the resultant intrusion must somehow be accommodated by displacement of the wall rocks (e.g., Hutton, 1996; Patterson & Fowler, 1993). Some hypothesized mechanisms for creating this extra space include fracturing and diking, stoping, ductile flow and tectonic accommodation along dilational faults or ductile shear zones (Clemens & Mawer 1992; Glazner, 2004; Miller & Paterson, 1999). Downward folding of stratified country rock adjacent to intrusive margins has been observed for numerous plutonic complexes, including in the Ruth pluton of Alaska, the Yerington Batholith of west-central Nevada and the Pachalka pluton of southeastern California

(Paterson and Farris, 2008). They are characterized by a downward deflection or folding of the country rock into parallelism with the steeply dipping pluton margins and ductile attenuation of the limbs adjacent to the pluton. The precise cause(s) and mechanisms that are responsible for these abrupt downward deflection of country rocks adjacent to plutonic margins are not always clear. One “scenario” envisions the emplacement of large thin sill-like intrusions at shallow crustal levels followed by the progressive downward growth of a tabular intrusion by additional melt rising incrementally that effectively displaces the country rocks downward and to the side. Another simply invokes downward (reverse) flow of country rocks along the rheologically weakened thermal aureole of an intrusion to occupy the space left behind by the rising melt—akin to the flow-lines predicted adjacent to a rising buoyant diapir in a higher density viscous fluid (e.g., Cruden, 1990; Marsh, 1982). These mechanisms are not mutually exclusive and any deflections in the wall rock stratigraphy may be further accentuated by a component of flattening in the deformation aureole due to ballooning of the pluton.

We here suggest that the abrupt eastward deflection and attenuation of the Mississippian and older stratigraphy along the southern flank of the DCR and northern flank of the KM—i.e., the map-scale folding that created the WCA—is an outstanding large-scale example of the sort of downward bending and flow of country rocks adjacent to a rising pluton. As illustrated in Figure 27 and discussed further below, we believe that all of the mechanisms discussed above (downward growth of the intrusion, channel-flow, ballooning) played a role in the resultant map-scale architecture, which is superbly displayed as a consequence of later Cenozoic tilting of the ranges.

The folds adjacent to TG in the westernmost KM are interpreted to reflect similar processes, where both folding (deflection) of the country rock and ductile attenuation and shear along the pluton margins facilitated mass transfer of the country rock to make space for the ascending (and possibly expanding) pluton. The close spatial association of these folds with the pluton margins and its deformational aureole, and the observation that one of the limbs is always folded or deflected into parallelism with the pluton margin, despite considerable variation in the orientation of this contact, leaves little doubt that these structures formed as a direct result of pluton emplacement. These folds have a variety of orientations due to the pre-existing orientation of bedding prior to emplacement and likely reflect a combination of downward flow and ballooning of the pluton.

Although the WCA is much larger than the folds in the western KM, it shares many of the same characteristics and it is difficult to imagine it has a different origin. We envision the ascent and growth of TG and the development of the WCA as follows: Up to ~20 Myr prior to final emplacement of TG (~90 Ma), prograde metamorphism and anatexis at deep crustal levels was forming a network of small bodies of magma, with fluids associated with these processes likely rising higher in the crust (Fig 27a). Both the monazite data from the southern DCR and the spectrum of zircon ages from TG suggest that melt generation/crystallization was occurring for a prolonged (10-15 Myr) period. By ~80 Ma, these magma bodies began coalescing and rising into the middle crust in a “channel”, resulting in elevated isotherms, thermal softening of the country rock, and perhaps minor downward flow of the country rock. By ~70 Ma, these magmas rose to the upper crust and began feeding a sill-like body along the boundary between the Mississippian Chainman Shale and the Pennsylvanian Ely Limestone (Fig 27c). This geometry is consistent with the

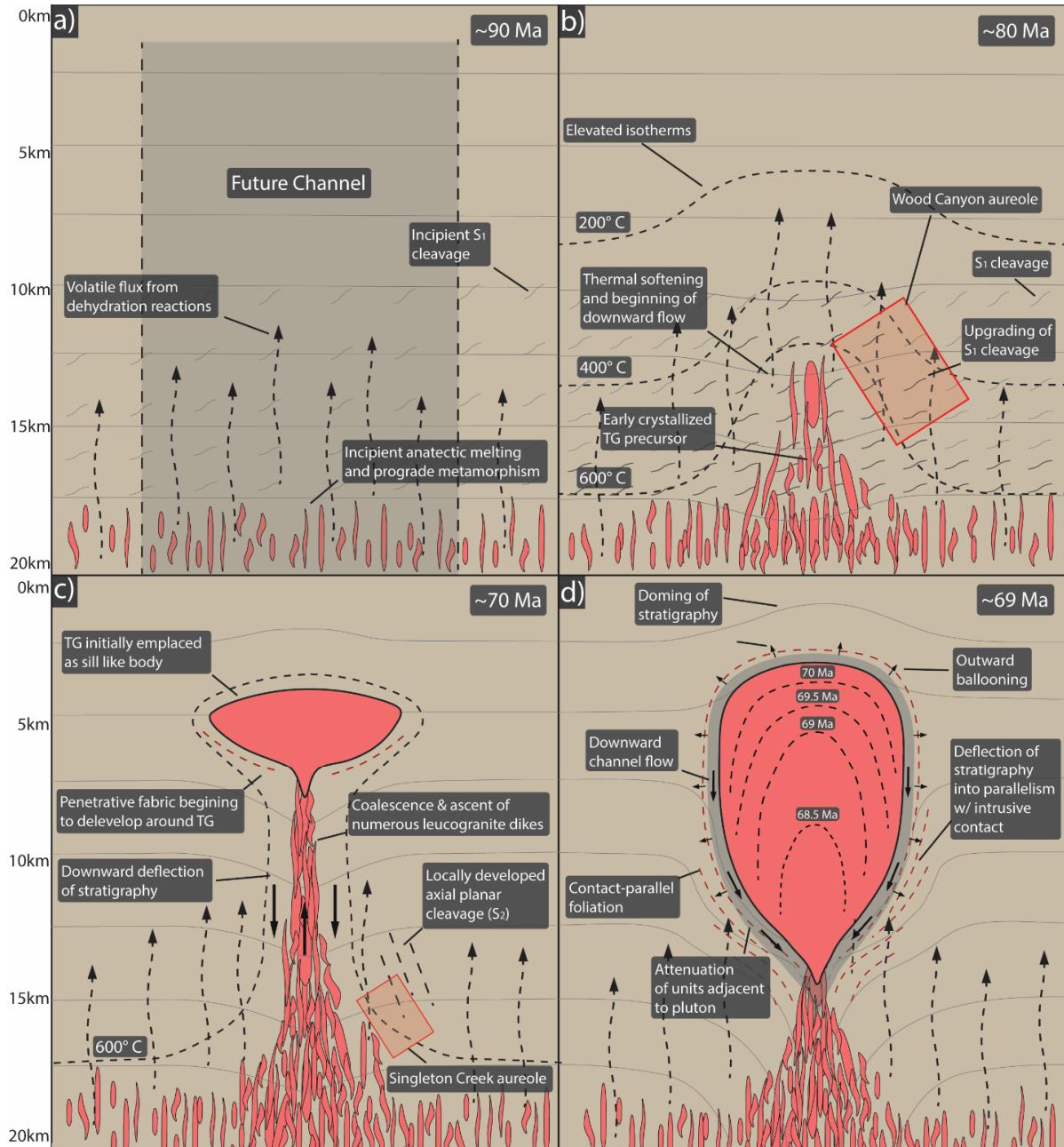


Figure 27: Schematic model of the emplacement of TG. a) 90 Ma - Initial prograde metamorphism and anatexis and melt crystallization at deep crustal levels. b) 80 Ma - Coalescence and ascent of leucogranite bodies to mid-crustal levels. c) 70 Ma - Ascent of magmas to upper-crustal levels and development of a sill-like body. Downward deflection of stratigraphy accommodates the growing pluton. d) 69 Ma - Final stage of emplacement. Progressive downward growth of the pluton transposes stratigraphy into parallelism with the intrusive contact, forming anticlines. Downward channel flow (grey zone) and ballooning result in a high strain fabric and attenuation of units adjacent to the pluton.

observed map relationships in the northern KM and southern DCR, where Mississippian and

older units are deflected to the east (downward) and Pennsylvanian and younger units are deflected to the west (upward). As more magma was injected and the magma body grew downward, the stratigraphy below would have been deflected progressively downward to accommodate the additional volume of the growing magma chamber. Heat from the magma would have reduced the strength of the country rock significantly and localized strain, resulting in a zone of downward channel flow in a narrow zone in the country rock adjacent to the pluton margins. This zone of high strain is reflected in the well-developed contact-parallel foliation around the pluton margins and appears to widen dramatically eastward (downward). Ballooning of the pluton also likely contributed to the high strain fabric, though the importance of this remains unclear. Eventually, after multiple pulses of additional magma and progressive downward growth of the incipient pluton, this sill-like body would have developed into a more spherical/ellipsoidal body and stratigraphy along its northern (and possibly southern) margin would form an anticline (Fig 27d). The overturned limb of the WCA and the northeastern margin of TG restores to being approximately vertical and NW-SE striking after removing ~40° of westward tilting about a horizontal north trending axis. This geometry is consistent with downward folding into parallelism with the approximately vertical side of TG. It is unclear whether a mirror image of this type of large-scale folding occurred on the southern margin of the pluton because younger extensional faulting and eastward directed transport of upper-crustal blocks along normal faults conceals virtually all the southern wall rocks to TG.

The geochronology from the southern DCR and TG provides further support for the general framework outlined above. Correlation of the S<sub>2</sub> cleavage with the Singleton Creek aureole suggests that the WCA formed during this ~70 ± 2 Ma metamorphic event which is

within error of the final crystallization age of TG, suggesting pluton emplacement and folding were coeval. Moreover, the geographic distribution of final crystallization ages within TG suggests the margins of the pluton crystallized first and the interior and deeper portions of the pluton were likely emplaced later as the pluton progressively grew downward while deforming the earlier crystallized outer margins and forcing stratigraphy in the overturned limb of the WCA deeper in the crust.

*Ages and significance of metamorphism and plutonism*

In the western KM, rocks grade from unmetamorphosed upper-crustal carbonates to highly strained and metamorphosed marble, with evidence for high-temperature recrystallization of dolomite and growth of metamorphic tremolite and micas adjacent to the pluton margins. The spatial coincidence of this zone of metamorphism and penetrative strain with the margins of TG and the abrupt decrease in grade away from the intrusive contact to unmetamorphosed upper-crustal rocks clearly indicates that metamorphism was a direct result of heat from the magma/crystal mush. At these upper-crustal levels, the zone of metamorphism is very narrow (<500m); however, at deeper structural levels in the eastern Kern Mountains, metamorphism is much more widespread and is continuous throughout most of the overturned limb of the WCA northward into Pleasant Valley.

Metamorphism in the southern DCR is characterized by widespread low-grade metamorphism that is distinctly upgraded in two amphibolite facies metamorphic aureoles. The low-grade “background” metamorphism increases systematically down-section from lower-greenschist facies in the McCoy Creek Group and higher units of the Trout Creek Group to upper-greenschist facies in lower units of the Trout Creek Group. This low-grade metamorphism is interpreted to reflect the regional geothermal gradient and is likely

representative of the background thermal conditions throughout much of the hinterland at these stratigraphic levels. The McCoy Creek Group where exposed in many of the surrounding ranges shows similar widespread lower- to mid-greenschist facies metamorphism that increases systematically down-section (Miller et al., 1988; Miller & Gans, 1989).

A protracted period of amphibolite facies metamorphism from ~80-90 Ma affected rocks on the southern DCR prior to the formation of the WCA when the section is inferred to have been approximately flat-lying (Wood Canyon aureole). Porphyroblast-cleavage relationships and upgrading of the  $S_1$  cleavage within the aureole suggests that metamorphism occurred while this cleavage was actively developing. Metamorphism was characterized by an abrupt increase in temperature both down-section and to the south, with isograds cutting across formation contacts, indicating a localized heat source(s)—most likely small bodies of magma and/or fluids circulating in the vicinity of magma bodies that were being emplaced to the south periodically over a ~10-15 Myr period. This is also reflected in the spectrum of zircon ages obtained from the TG that range continuously from ~70 Ma to ~80-90 Ma, which indicates a protracted period of crustal anatexis and crystallization. We hypothesize that this prolonged period of prograde metamorphism and crustal anatexis/crystallization in the KMDCR reflects a “channel” where heat was being advected upward in the crust by the ascent of numerous small bodies of leucogranites and hydrothermal fluids associated with them. This advection of heat resulted in localized metamorphism and high lateral temperature gradients that are not reflective of the broader conditions of the Late-Cretaceous mid-crust in the Sevier hinterland.

The culmination of this prolonged period of prograde metamorphism and anatexis in this “channel” was the final ascent and emplacement of the largest S-type granite exposed in eastern Nevada—TG. This final ascent appears to be reflected in the southern DCR by a more localized and shorter-lived period of amphibolite facies metamorphism occurred on the southeastern tip of the DCR at  $\sim 70 \pm 2$  Ma (Singleton Creek aureole). Porphyroblast-cleavage relationships and upgrading of the  $S_2$  cleavage suggests metamorphism was synkinematic with cleavage development and high strain shearing and attenuation, and therefore also likely occurred during folding of the WCA. We propose that this metamorphism reflects heat from TG magma during its final ascent and crystallization. This hypothesis is supported by the nearly identical ages of the final crystallization of TG and the Singleton Creek aureole. Our interpretation that metamorphism in the southern DCR is primarily a result of Late Cretaceous magmatism suggests that perhaps many of the dynamothermally metamorphosed rocks that are locally exposed at deep structural levels in the Sevier hinterland may be more a reflection of localized magmatic process than regional tectonics.

*Summary: A reassessment of the interplay between metamorphism, magmatism and deformation in the Sevier hinterland*

The emplacement of TG had a profound impact on deformation in the surrounding country rock and resulted in a high strain deformational aureole around its margins, including folding of the stratigraphy in the western KM and the formation of the WCA. There are other Late Cretaceous plutons in the Sevier hinterland that show a similar intensification of penetrative strain and peculiar folding relationships around their margins,

including the  $80 \pm 2$  Ma Trout Creek Intrusive Complex in the DCR (Monroe et al., 2023) and the  $94 \pm 2$  Ma Lexington Creek pluton in the Southern Snake Range (Gottlieb et al., 2022; Lee and Christiansen, 1983). However, the deformational aureole around TG at deeper structural levels in the northeastern KM appears to be much more extensive than the others and the WCA is far larger than most other documented pluton related deformational structures in the Sevier hinterland. Interestingly, most Jurassic and Eocene plutons in eastern Nevada only have narrow static metamorphic aureoles, even those that are similar in size to TG and were emplaced at similar or deeper crustal levels (e.g., the Ibapah pluton). These contrasts raise some interesting questions: *What was different during the Late Cretaceous that allowed plutons to more easily deform and metamorphose their country rock? Why did TG specifically have such a profound deformational impact on its country rock?*

The Late Cretaceous plutons of eastern Nevada are all 2-mica leucogranites with an isotopic composition that suggests they are nearly pure crustal melts (e.g. Miller & Bradfish, 1980; Best et al, 1974; Wright & Wooden, 1991). These melts are interpreted to have been largely derived from the prograde metamorphism and melting of sedimentary rocks which would result in magmas with a high volatile content. More speculatively, these magmas were likely rising in concert with fluids released from dehydration reactions in the zone of prograde metamorphism. The presence of abundant fluids associated with the rise of these magmas would have drastically reduced rock strength and would allow a pluton to more easily deform the country rock during emplacement.

In the case of TG, it also appears that prolonged metamorphism and crustal anatexis prior to emplacement also played a key role. If our hypothesis is correct that the area now occupied by TG and the overturned limb of the WCA was a long-lived “channel”, where

smaller volumes of leucogranites and hydrothermal fluids generated by prograde metamorphism and anatexis in the lower crust were rising and advecting heat to mid- and upper-crustal levels, this would have weakened this portion of the crust substantially. By the time TG magmas began moving upward in the crust, the surrounding country rock was likely very weak, allowing TG to more easily deform it. We propose that this combination of thermal and fluid-related weakening by the prolonged emplacement of numerous small bodies of leucogranites and associated fluids through this “channel” is what allowed TG to have such a profound deformational impact on its country rock.

The KMDCR provides a sobering example of how the localized ascent of Late Cretaceous anatectic melts and associated fluids were able to produce map-scale structures and extensive metamorphic tectonite fabrics in the Sevier hinterland—deformational features that appear to be primarily accommodating pluton emplacement rather than tectonic shortening. Without the spectacular exposure of these rocks in the KMDCR, it would be easy to interpret much of the penetrative strain, map-scale structures, and metamorphism as reflecting tectonic deformation/burial. This emphasizes the need for caution when interpreting deformational structures and metamorphic assemblages in mid-crustal rocks in the Sevier hinterland as being reflective of broader deformational/metamorphic conditions.

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