Cenozoic Tectonic Evolution of the Great Basin

M. Claiborne Newton, III*
Tectonex, LLC, Winnemucca, Nevada

ABSTRACT

The Great Basin is an enclosed depression at the northern terminus of the Basin and Range province of the North American cordillera. The Great Basin is a large pull-apart zone composed of smaller nested pull-apart basins that formed at different times and places. The Great Basin developed primarily as a sinistral pull-apart zone due to left-lateral motion on NE-SW lithospheric-scale fault zones. The fault zone on the north side is a wide NE-SW trending zone of spaced discontinuous faults, informally referred to as the Elko Tectonic Zone, analogous to the earlier named and parallel Great Falls Tectonic Zone through Idaho and Montana. The Elko Tectonic Zone ranges from the Walker Lane in western Nevada northeast to Wyoming, and the Yellowstone hot spot track (Snake River Plain) is part of this tectonic zone. The tectonic zone corresponds with the boundary between North American Precambrian continental lithosphere on the southeast side and accreted lithosphere on the northwest side. This upper plate lithospheric-scale break may have influenced the development of a tear fault in the subducted oceanic Farallon plate, causing it to break up, leaving the residual Farallon plate to the south and the Juan de Fuca plate to the north. The residual Farallon plate slowed in its rate of subduction, sank, steepened and rolled back, creating a southwestward migration of the continental arc magmatic front through Cenozoic time. Pull-apart basins developed at the same times and places as the contemporaneous arc magmatic front.

The southern boundary fault system of the Great Basin was also a NE-SW trending sinistral strike-slip fault zone and the sinistral Garlock fault zone in California was an extension of this Great Basin-forming boundary shear zone.

The central part of a pull-apart basin is commonly a ridge system, called a hinge zone, which separates different parts of the basin. The hinge zone experiences the most extension of any region of a pull-apart basin over the life of the basin. A hinge zone may therefore be a site of significant extensional unroofing and metamorphic core complexes may rise to the surface. The probable hinge zone of the Great Basin has been identified in eastern Nevada and is bounded by a set of metamorphic core complexes.

Voluminous felsic ignimbrite eruptions took place from Late Eocene to Early Miocene time and the ash-flow tuffs were deposited on a gently-dipping surface, yet it has been recognized that thick sequences of tuffs abruptly thin and did not cross a topographic barrier in the Toquima and Toiyabe Ranges. Rather than being deposited on a high altiplano-type plateau, the ignmbrites may have been erupted through and laid down on the flat floors of pull-apart basins and the barrier may have been a hinge zone within a pull-apart basin.

The Great Basin formed throughout Cenozoic time from Eocene to mid-Miocene time by accumulated extension in a WNW-ESE (290°) direction by the development

*E-mail: mcnewt3@gmail.com

of nested pull-apart basins, both separate and overlapping in time and space. Most of these basins were sinistral and dominantly controlled by NE-SW structures within or parallel to the Elko Tectonic Zone. After mid-Miocene time, as the Walker Lane NW-SE dextral strike-slip fault zone became established, pull-apart basins in the Great Basin increasingly experienced dextral shear and the accumulated direction of extension changed to WSW-ENE (255°), perpendicular to the northern Nevada rift trends.

Keywords: tectonic evolution, Great Basin, Cenozoic extension, Elko Tectonic Zone, Walker Lane

INTRODUCTION

The Great Basin (Figure 1) is an enclosed depression at the northern terminus of the Basin and Range province of the North American cordillera. Like the rest of the Basin and Range province, the Great Basin is characterized by sinuous ranges generally just tens of kilometers long, separated by gravel-filled basins. The topographic features were famously described by geologist Clarence Dutton as an "army of caterpillars marching toward Mexico." Although having the same type of topography, the Great Basin is unique within the Basin and Range province by having internal drainage, a feature first recognized by the explorer John C. Fremont, who gave the feature its famous name. The reason for the internal drainage of the Great Basin is that it is itself a large compound pull-apart basin, composed of a set of smaller nested enclosed pull-apart basins, each of which also had internal drainage during most of its life.

Extension forming the Great Basin did not start in Miocene time (the beginning usually cited at around 17 Ma ago) as is commonly stated in the literature, e.g. Wernicke, 1992. Indeed, some have suggested that the bulk of extension in the Great Basin took place after 10 million years ago (Colgan and Henry, 2009, 2017). Recent publications suggest that the period from 49–17 Ma was essentially atectonic, when the surface of Nevada was a high-standing gently-sloping Altiplano-type plateau, which became known as the Nevadaplano (e.g. DeCelles, 2004; Best and others, 2009; Henry and others, 2012).

This paper will present the argument that extension, in the form of transtension, took place in the Great Basin throughout Cenozoic time and that overall extension in a WNW-ESE direction was effected by cumulative transtension as nested pull-apart basins formed in various locations at various times. These basins formed on both the west and east sides of a stationary but splitting hinge zone region which had major unroofing and detachment faulting taking place on its flanks as metamorphic core complexes rose. The early Great Basin developed primarily as a sinistral pull-apart zone, spreading away from the central hinge zone region. One of the major structural zones accommodating sinistral strike-slip shearing, herein referred to as the Elko Tectonic Zone, consists of numerous NE-SW trending fault strands, which controlled pull-apart basin location and formation from Eocene to mid-Miocene time.

Extension in the Great Basin earlier than Miocene time has been recognized but not elucidated, e.g. Dickinson, 2006. Extension associated with the Ruby Mountains core complex has been recognized as multi-generational, with major exhumation taking place in mid-Miocene time, around 17 Ma ago, and earlier extension taking place from Eocene to Miocene time (Pape, 2010). The earliest extension in this part of the Great Basin may have been early to middle Eocene (Sullivan and Snoke, 2007) and another early period was mid- to late-Oligocene time (Kistler and others, 1981). Although areas surrounding the core complex, such as the Carlin-Pinion region, may have undergone less extension during these periods, they were still experiencing extensional or transtensional faulting.

Part of the evidence cited to indicate only minor extension during Eocene to early Miocene time is the dearth of exposed coarse clastic sedimentary rocks of this age. However, such rocks are sometimes observed on the range. For example, at Copper Basin on Battle Mountain, 500 meters of Oligocene conglomerate are tilted 25 degrees and unconformably overlain by 16-Ma old rhyolite (Henry and others, 2011), suggesting probable Oligocene-Early Miocene faulting.

As another example, Haynes (2003), in a detailed study of the Eocene Elko Formation, concluded that there were two depocenters at that time separated by a topographic high which hosts the Carlin trend. The eastern sedimentary assemblage has boulder conglomerates at the base, overlain by lacustrine limestone and fine clastic rocks. On the west side of the Carlin trend high, the Eocene rocks are all pebble to cobble conglomerates (Haynes, 2003). Paleocurrent indicators in that area suggest transport from the Carlin trend ridge system to the north and west (Haynes, 2003), from a topographic high into a basin.

Transtensional pull-apart basins, comprising the Great Basin, began forming at least as early as Eocene time. They were instrumental in situating the prolific gold deposits of the Great Basin throughout Cenozoic time and they also were part and parcel of caldera-forming voluminous ignimbritic eruptions from Late Eocene to Miocene time.

Prior to 17 Ma, the dominant sense of shear in the Great

Basin was left-lateral, accommodated by NE-SW faults, concentrated in a zone referred to as the Elko Tectonic Zone, which is parallel to the Great Falls Tectonic Zone to the north. The Elko Tectonic Zone marks several geotectonic structures—a possible major lithospheric break between North American Precambrian continental lithosphere to the southeast and accreted lithosphere to the northwest, the site of a probable tear fault along which the subducted Farallon plate broke apart and the subsequent track of the Yellowstone hot-spot mantle plume. It also appears to have been a major zone of sinistral strike-slip and oblique shearing in Tertiary time and formed the northern boundary of the Great Basin hinge zone and also formed the boundary between multiple sets of pull-apart basins of various ages.

Beginning around 17 Ma ago, NW-SE right-lateral strike-slip faults came to dominate in the Walker Lane region, in the beginning of the transition from a convergent to a transform plate margin. This was also the time that major extension across the Great Basin and rapid exhumation of metamorphic core complexes in the Great Basin hinge zone region took place. Pull-apart basins, at least on the west side of the Great Basin, that had been sinistral, became dominantly dextral. Subduction of the Farallon plate ceased south of the Elko Tectonic Zone tear fault, and the Walker Lane, and associated Northern Nevada Rift zones, formed in the rapid transition to a transform boundary as the Pacific plate impinged on North America.

Fault Systems and Pull-Apart Basins

In Figure 1, it can be seen that there are two main trends of basins and ranges within the Great Basin, the predominant one being NNE-SSW to NNW-SSE and the less dominant direction being NE-SW. A third more minor trend is NW-SE, although

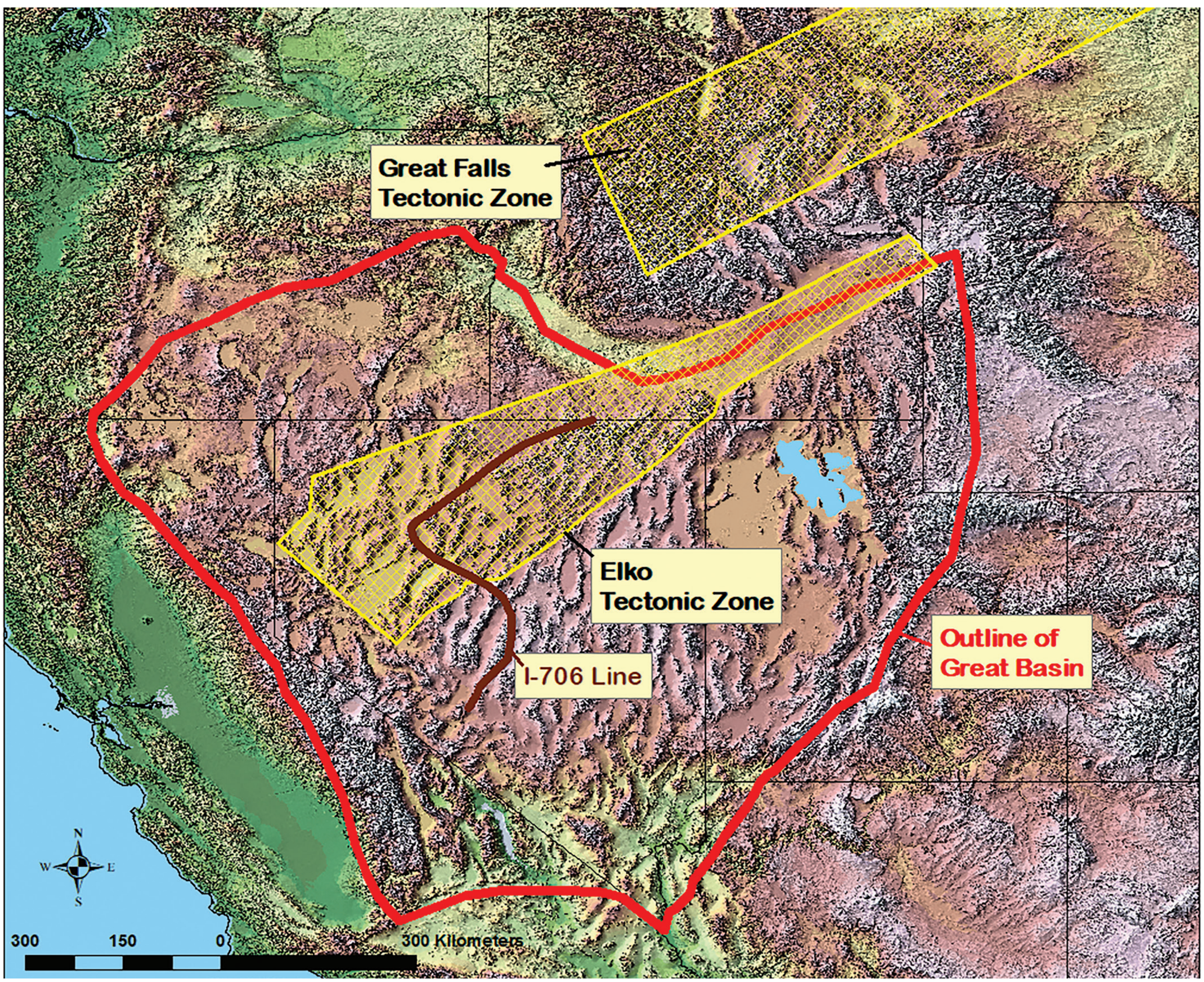

Figure 1. Shaded relief map showing outline of the Great Basin and the tectonic zones.

this trend is dominant in the Walker Lane, on the west side of the Great Basin. The three structural trends reflect three main fault systems. The NNE-SSW to NNW-SSE trends are parallel to normal faults, the NE-SW trends are related to left-lateral strike-slip and left-oblique faults and the NW-SE trends are due to right-lateral strike-slip and right-oblique faults. The NE-SW and NW-SE strike-slip fault zones also experienced normal slip at times during their lives.

In Figure 1, the area labeled Elko Tectonic Zone, in which the NE-SW fabric is particularly noticeable, goes from the western Nevada border northeastward to Wyoming, through the Snake River Plain. This NE-SW structural zone is subparallel to the Great Falls Tectonic Zone to the north through Idaho and Montana (see Figure 1).

The Great Falls Tectonic Zone represents a major lithospheric discontinuity separating two Archean cratonic provinces (Boerner and others, 2011) and had major shearing along it (O'Neill and Lopez, 1985). There is evidence that the Elko Tectonic Zone also represents a major lithospheric discontinuity. For example, the $^{87}Sr/^{86}Sr = 0.706$ line (Tosdal and others, 2000) bends into and remains parallel with the tectonic zone near its northern edge (see Figure 1). This line is commonly taken to mark the boundary between continental and oceanic lithosphere. Sims and others (2005) suggest a large block of Archean-age continental lithosphere, part of their Wyoming Province, under northern Nevada (see Figure 2), and the northwest edge of this block is within the Elko Tectonic Zone.

The Yellowstone hot spot track lies within the Elko Tectonic Zone, also indicating a lithospheric-scale subvertical break. As will be discussed later in this paper, the Elko Tectonic Zone probably also marks a break (tear fault) in the subducted Farallon plate, along which the plate broke into separate slabs, such as the Juan de Fuca plate to the north, which continued to subduct, generating the Cascades volcanic arc. South of the Elko Tectonic Zone, the residual Farallon plate foundered, sank and retreated westward until eventually its subduction ceased. The mantle plume generating the Yellowstone hot spot track is probably a minor player in the overall tectonics of the Great Basin, merely opportunistically rising along a tear fault.

The three main kinematic directions are related to transtensional tectonics as illustrated in Figure 3. In this simple shear model, the pull-apart basins, with parallelogram geometry, are opened by lateral and normal movement along the NE-SW or NW-SE fault systems. A typical pull-apart basin has a central hinge zone that separates the basin into two parts. This feature was recognized and named in the Salton Sea pull-apart basin by Brothers and others (2009). The hinge zone of a pull-apart basin was so-named because, in the early formation of the basin, it remains a stationary high that acts as the hinge of a trap door as the developing basin breaks and drops at the ends of the basin. Later in the evolution of a basin, continued extension across the hinge zone may split it, causing high-angle normal faults and basins within and adjacent to the hinge zone area. A pull-apart basin expands outward by movement along the bounding strike-slip faults, sometimes leaving remnant narrow basins and ranges within it. Over the life of the pull-apart basin, the maximum amount of extension takes place across the hinge zone. It may be unroofed along detachment faults and isostatically rise. It is not uncommon in the Great Basin to find older rocks exposed in hinge zones. In the main hinge region of the Great Basin discussed below, high-grade metamorphic rocks in core complexes were brought to the surface.

In Figure 3, the hinge zone is elongate parallel to the direction of $\sigma1$, the maximum principle stress, and the basin expands outward orthogonal to the hinge zone, parallel to the direction of $\sigma3$, the minimum principle stress. In Cenozoic fault geometries of the Great Basin, if the maximum principle stress direction was oriented more NNE-SSW, the dominant sense of shear was sinistral, with basin opening controlled by sinistral movement along the NE-SW faults. If the maximum principle stress direction was oriented more NNW-SSE, then the dominant faults were NW-SE and the pull-apart basins were mainly dextral.

Figure 4 shows some of the individual fault strands within the Elko Tectonic Zone. The tectonic zone comprises a set of NE-SW sinistral strike-slip faults that form the boundary of several pull-apart basins.

Hinge Zone of the Great Basin

Throughout the life of the Great Basin, the most cumulative extension would have taken place across the hinge zone area. The Great Basin hinge zone is a sinuous NNE-trending zone of basins and ranges with several metamorphic core complexes on the flanks. The major period of exhumation of the core complexes was in the range of 18–14 Ma ago. However, earlier periods of extension in the core complexes have been documented, e.g. Late Eocene—Late Oligocene in the Snake Range (Lee and others, 2017) and Middle to Late Oligocene in the Ruby Mountains-East Humboldt Range core complex (Sullivan and Snoke, 2007; Kistler and others, 1981). The Middle Miocene episode represents a period of rapid extension across the Great Basin with accelerated upper crustal thinning (cover rocks sliding off the hinge zone structural high), triggering the isostatic rise of deeper crustal rocks in the footwalls of detachment faults on the outer edges of the hinge zone. The core of the hinge zone, probably throughout the period prior to, during and after the metamorphic core complex exhumation, continued to experience extension and is currently marked by gravity lows in both complete Bouguer and isostatic residual gravity representations. The isostatic residual gravity anomaly enhances basin and range density contrasts and suggests that at least two deep sediment-filled basins developed in the core of the hinge zone—Steptoe Valley and the southern end of Spring Valley. Ranges adjacent to these basins have been described as extreme extension domains (Long and Walker, 2015). These deep basins and hyper extended range rocks indicate the extreme amount of extension that took place within the hinge zone area.

Although significant extension takes place in the interior of

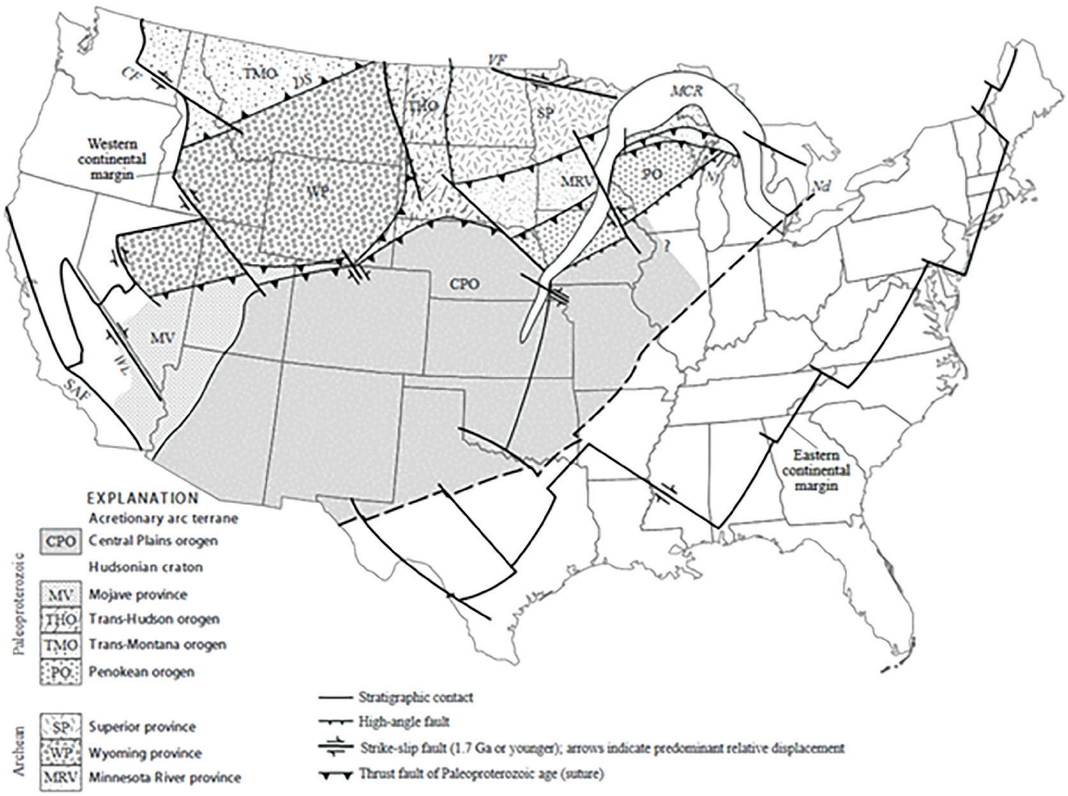

Figure 2A

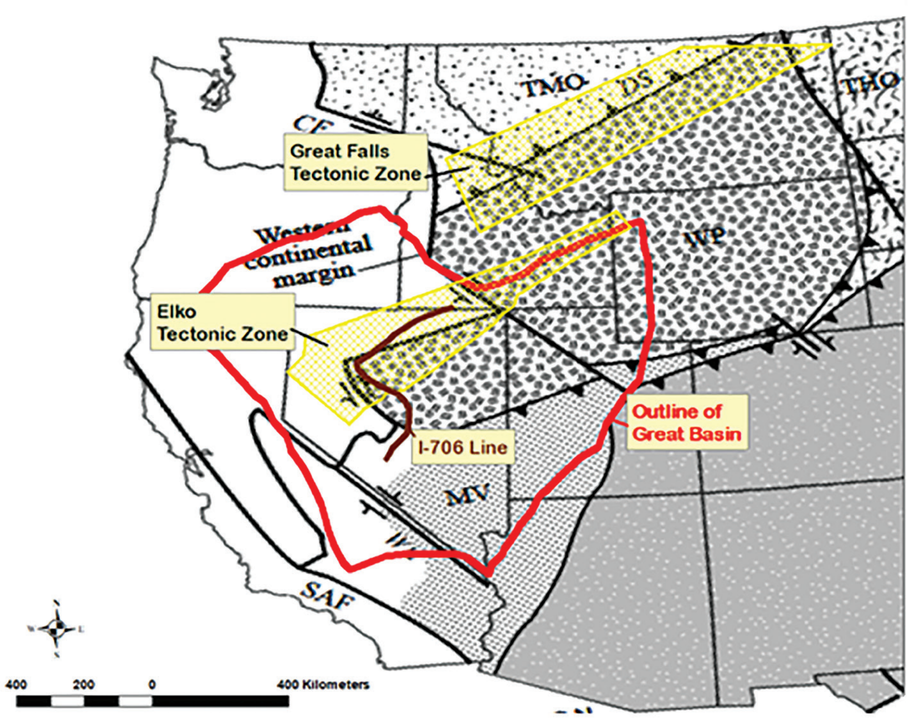

Figure 2B

Figure 2. (A) Map of interpreted Precambrian basement configuration from Sims and others, 2005. (B) Overlay of Elko and Great Falls Tectonic Zones on Precambrian basement map of 2A. Note the northwest boundary of the Archean basement block is within the Elko Tectonic Zone.

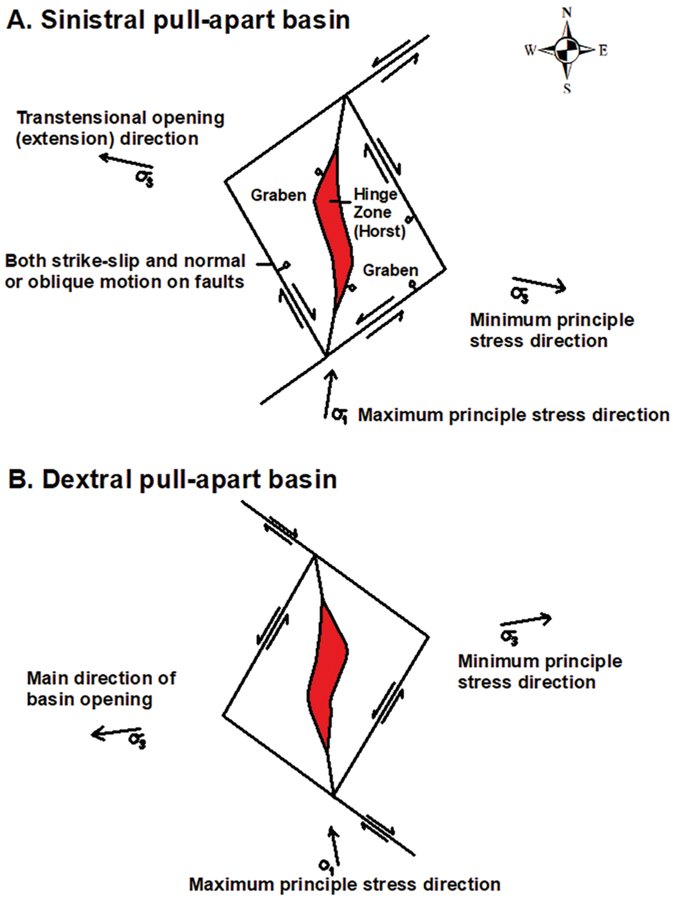

Figure 3. Principal fault directions, senses of shear, principal stress directions and overall extension directions in a simple shear model of pull-apart basins.

a hinge zone region, the distribution of metamorphic core complexes around the edges of the Great Basin hinge zone suggests that the most major unroofing takes place at the periphery of the hinge zone, perhaps from carapace rocks sliding to the outside of a regional welt.

The evidence suggests that at least some metamorphic core complexes are a manifestation of the hinge zones of pull-apart basins, and therefore the location of metamorphic core complexes may lead to the recognition of the hinge zones of pull-apart basins.

Pull-apart Basins Within the Great Basin

The Great Basin developed as a series of nested dominantly sinistral pull-apart basins, that varied in space and time as the overall basin evolved. Figure 5 shows the hinge zone of the Great Basin, bounded by the Ruby Mtns-Grant Range-Snake Range-Albion Range metamorphic core complexes. Older basins may no longer be topographic depressions. However, the two youngest basins, which lie on the western and eastern tips of the Great Basin (see Figure 5), are still rectangular topographic depressions with internal drainage filled with Miocene to Recent volcanic deposits. In post-glacial times, these basins were the sites of enormous lakes now evidenced by multiple high terrace cuts and tufa deposits. Named after the historical lakes, the basins are here referred to as the Lahontan Basin on the west and the Bonneville Basin on the east. The current floors of the basins are relatively flat-lying surfaces underlain by fluvial and playa deposits. Figure 4 shows the outlines of these two pull-apart basins and the NE-trending fault zone that partly controlled their development.

The Lahontan basin started out life, at least as early as Oligocene time, as a sinistral basin and was later (Middle Miocene and later) overprinted, expanded east-west and elongated to the north by dextral transtension as the Walker Lane right-lateral strike-slip fault system became the western boundary of the pull-apart basin. The Bonneville pull-apart basin may also have had both sinistral and dextral periods of dominant shear. This basin is not dealt with extensively in this report.

Round Mountain Basin

Various pull-apart basins formed at different times in different places, generally following the documented sweep of magmatism from NE to SW through Nevada (see Figure 7 below). As the subducted slab continued to sink and retreat to the SW, Oligocene-age basins formed in central Nevada (Round Mountain Basin, Figure 6). The older basins are no longer topographic lows, but the Round Mtn Basin is evident in the gravity data as a low anomaly, probably due to the large volume of low-density felsic volcanic rock within it. The nature of volcanic activity also changed from more effusive andesite activity to felsic caldera-forming ignimbrite eruptions in Oligocene time. These felsic ignimbritic eruptions have been attributed to volcanic arc activity during subducted slab rollback beneath thick continental crust (Best and others, 2016). The extensional setting of similar voluminous felsic ignimbritic eruptions elsewhere has been recognized, such as in the Italian Campania Volcanic Zone (Torrente and others, 2010).

The Round Mountain pull-apart basin was probably experiencing extension from Late Eocene to Early Miocene time, based on the age of calderas within it. It is a rhomboid feature defined by a pronounced gravity low anomaly (see Figure 6), probably due to being filled with light felsic tuff. The outline of the basin is shown in Figure 6 and the probable hinge zone is highlighted in red hatch. The hinge zone includes the Toquima Range and some of the Toiyabe Range (Colgan and Henry, 2017). This is also part of a zone identified by Speed and others (1988) as the Toiyabe Uplift. As is common in hinge zones of pull-apart basins in the Great Basin, there has been sufficient exhumation to expose rocks at least as old as Early Cambrian in the ranges. This zone also was identified by Best and others (2013) as a topographic barrier to ash flows on both the east and west side of the ridge system. It was recognized that abundant calderas formed in a cluster on the east side of this feature, the tuffs were laid down on basically a gently sloping surface and thinned abruptly against the Toquima Range barrier (Best and others, 2013). The clustering of calderas within the basin is shown in Figure 7. The surface the tuffs were deposited on is what has been suggested to be a high plateau similar to the Andean Altiplano, and the concept has become entrenched in the literature, becoming known as the "Nevadaplano" (DeCelles, 2004). Rather than being an altiplano, the gently-sloping surface was probably the floor of a pull-apart basin, the caldera-forming eruptions took place within the basin and the tuffs were largely confined to the side of the basin they erupted in and did not cross the dividing hinge zone ridge. Such caldera-forming eruptions within pull-apart basins along volcanic arcs are documented in younger arcs, such as the Toba Caldera in Sumatra (see Figure 8).

In the Toiyabe Range, Smith (1992) recognized detachment faults and more steeply dipping normal faults and suggested synvolcanic Oligocene extension on the order of 100–200%. Smith (1992) also recognized the presence of basins bounded by steep normal faults with uplifted footwalls and made the cogent suggestion that pre-Miocene Great Basin faulting was similar in style to Miocene to Recent faulting. The other line of evidence from the same area supporting this similarity is the linear topographic high barrier separating tuff basins, reported by Best and others (2013). This Oligocene geometry of basins and ranges indeed mimics present-day geometry and supports that there was significant local extension in Oligocene time.

Another way to determine that there had to be significant extension during this period is that, if Sullivan and Snoke (2007) and Kistler and others (1981) are correct that there was significant mid- to late-Oligocene exhumation of the Ruby Mountains-East Humboldt Range metamorphic core complex, then there probably was also significant concomitant shallow extension. Exhumation means unroofing, and unroof-

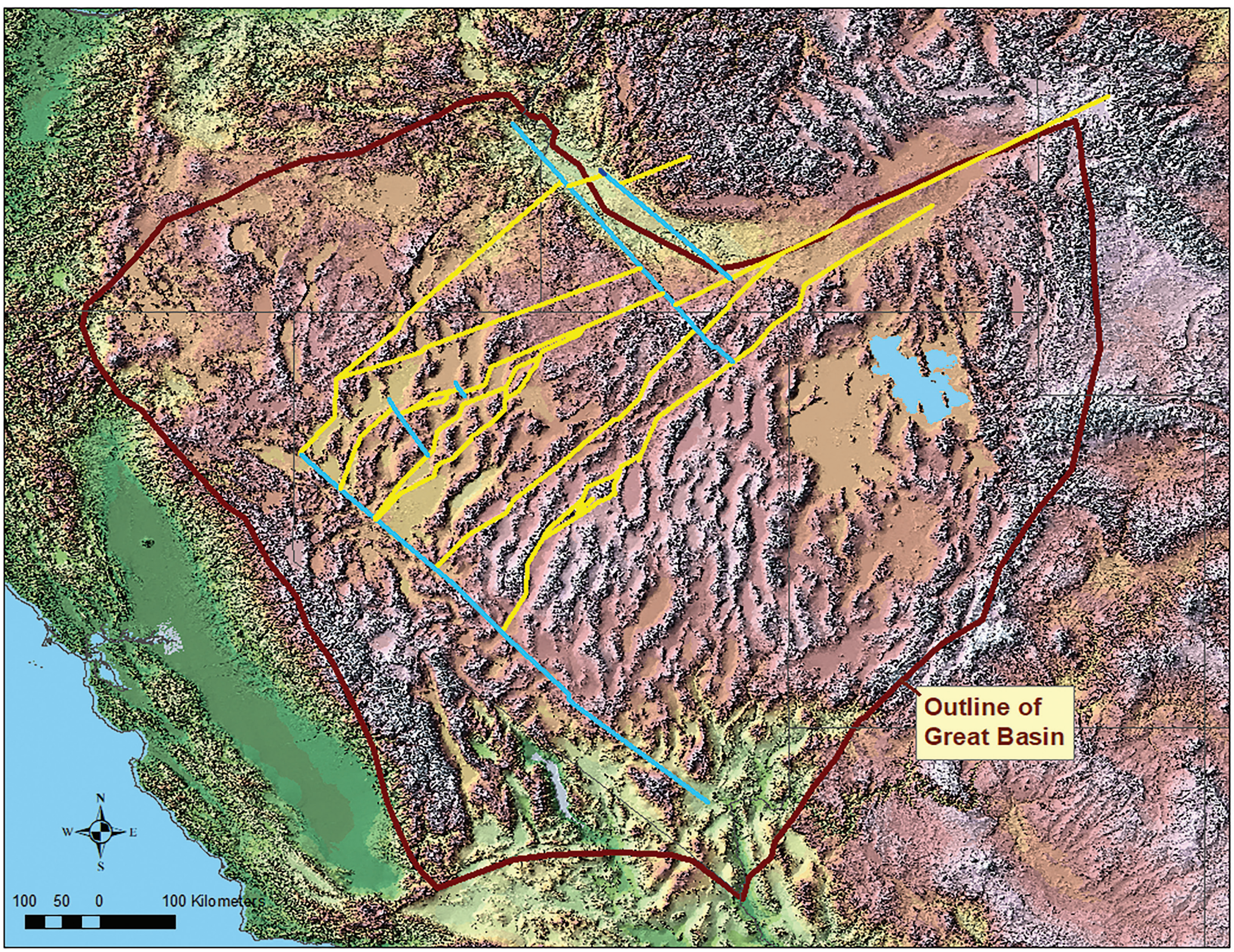

Figure 4. Some individual faults defining Elko Tectonic Zone. Yellow faults are dominantly left-lateral strike-slip, blue faults are dominantly right-lateral strike-slip.

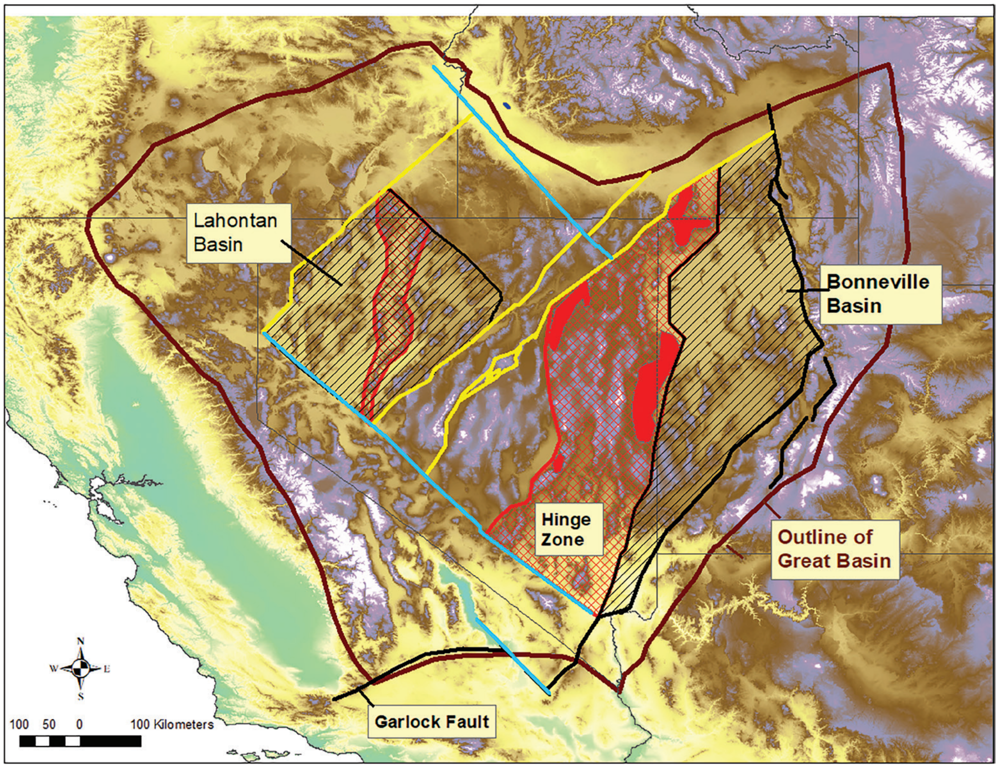

Figure 5. Younger pull-apart basins that are still topographic lows. Red hatch areas are hinge zones, solid red regions are metamorphic core complexes.

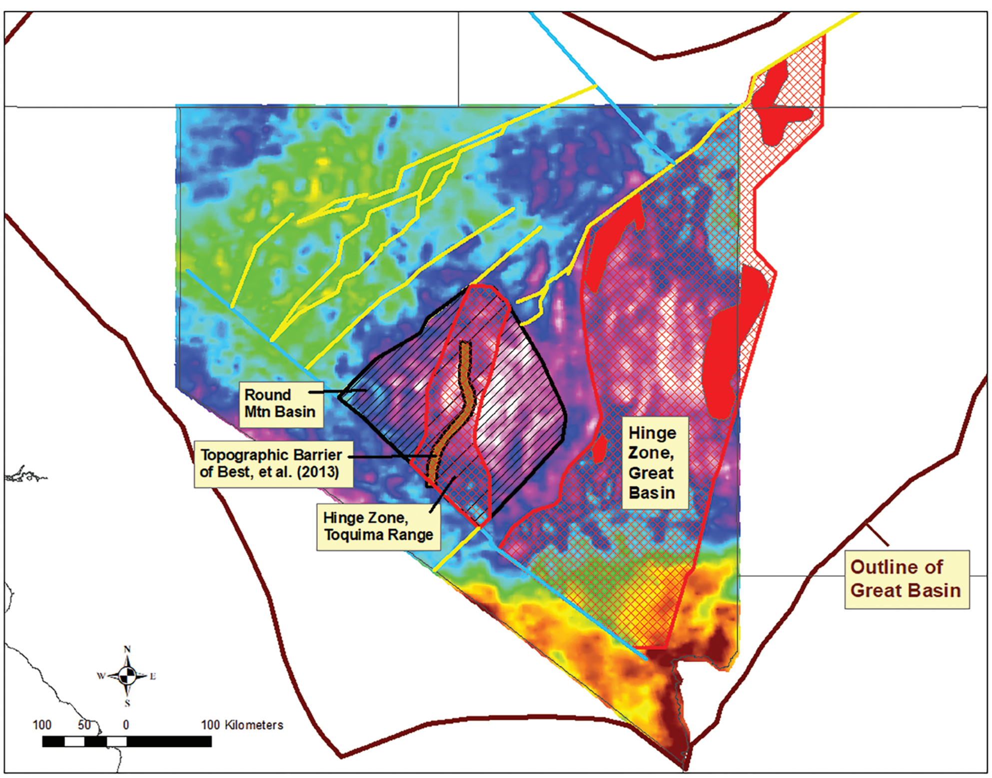

Figure 6. Complete Bouguer Gravity anomaly map showing rhomboid shaped gravity low (pink and white colors) in the Round Mtn Basin, an Oligocene-age pull-apart basin with internal calderas.

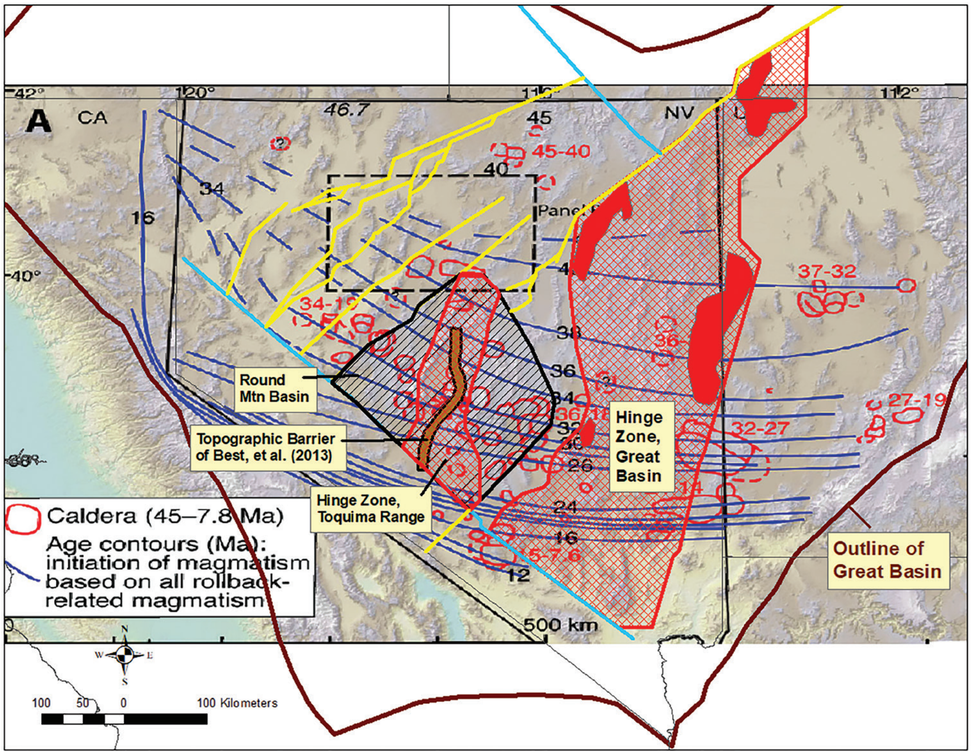

Figure 7. Online figure after Cousens and others (2018) overlain by outline of the Round Mountain pull-apart basin and hinge zone. Red circles are calderas, blue lines are igneous isochrons (successive positions of arc magmatic front through time). Note the cluster of calderas within the pull-apart basin and the topographic barrier of Best and others (2013) coincident with the hinge zone.

ing means crustal extension, and not just lower crustal ductile flow. The top of the metamorphic complex has to come off and those cover rocks have to move laterally away from the core complex.

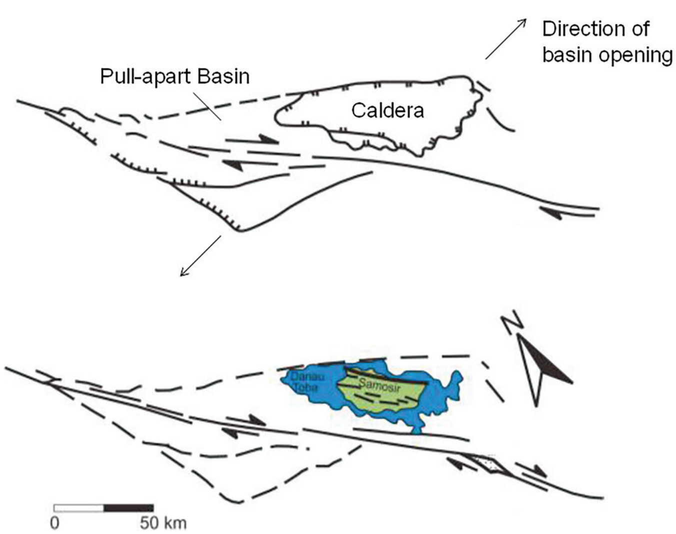

Figure 8. Quaternary example of caldera eruption in a pull-apart basin: 73,000 year-old Toba Caldera formed in a pull-apart basin developing along the Sumatran dextral strike-slip fault within the Sunda volcanic arc (after Putra and Husein, 2016).

Northern Nevada Rifts

Starting about 16 Ma ago, two major NNW-SSE rift zones cut and extended south of the Elko Tectonic Zone, the Kings River Rift to the west and Northern Nevada Rift to the east (see Figure 9). Voluminous basalts along the two rifts are essentially the same age—around 15.5 Ma old. The basalts are locally associated with rhyolitic ignimbrites and effusive rocks.

Northern Nevada rifts suggest an extension direction of around 255 degrees. The bulk of the Great Basin however formed with a cumulative extension direction of around 290 degrees (see Figure 9) related to sinistral transtension. In the Lahontan pull-apart basin, sinistral spreading was replaced by dextral opening as activity along the Walker Lane increased. The Walker Lane is dominantly a set of NW-SE right-lateral strike-slip faults joined by NNW-SSE normal fault segments (dilatant jogs). Normal faulting in the Walker Lane region, starting around 4 million years ago, created the Owens Valley and Salton Sea grabens with the NNW-SSE orientation and facilitated the rise of Sierra Nevada horsts. The southern part of the Sierra Nevada has the NNW-SSE trend, the trend of the northern part is more NW-SE, parallel to the strike-slip faults. The Northern Nevada rifts are essentially parallel to normal fault trends in the Walker Lane, such as the Owens Valley graben. The 255 degree direction of extension, orthogonal to the Northern Nevada rifts, is the direction of opening of the Lahon-

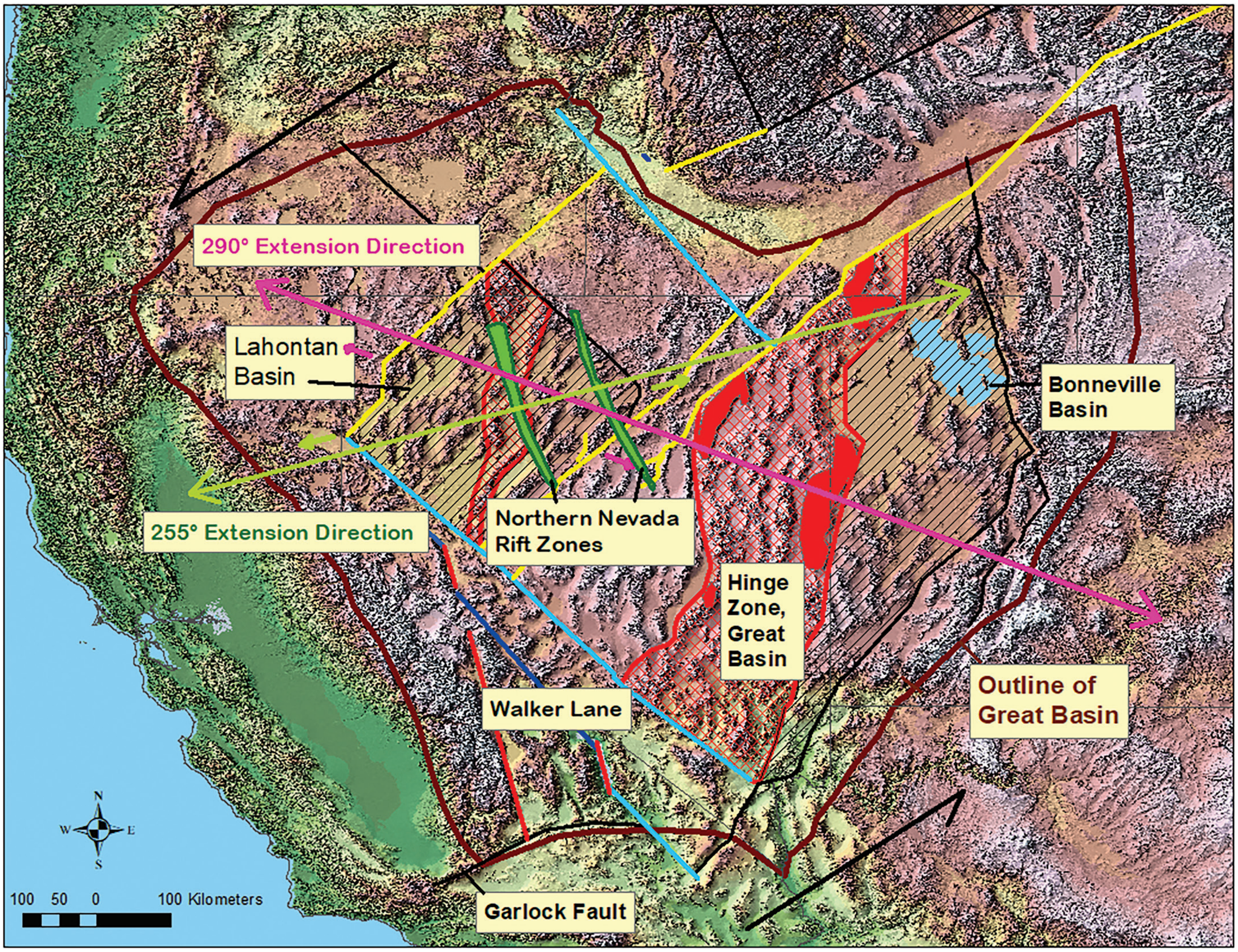

Figure 9. Great Basin showing Miocene-Younger Pull-apart Basins, Hinge Zones and Northern Nevada Rift Zones. Pre-Middle Miocene Extension direction shown in pink, Middle Miocene and younger extension direction shown in green.

tan basin from mid-Miocene time on (see Figure 9). The rifts are normal fault zones kinematically related to Walker Lane-parallel right-lateral strike-slip faults. The rifting may also have been in a back-arc environment, related to the southern terminus of the ancestral Cascades volcanic arc (Du Bray and others, 2014). At any rate, the Northern Nevada rifts were short-lived and were part of the post mid-Miocene rapid transition from a convergent to a transform plate boundary as the Farallon plate was completely subducted and the Pacific plate impinged on North America.

REFERENCES

Best, M.G., Barr, D.L., Christiansen, E.H., Gromme, S., Deino, A.L., and Tingey, D.G., 2009, The Great Basin Altiplano during the middle Cenozoic ignimbrite flareup: Insights from volcanic rocks: International Geology Review, v. 51, p. 589–633.

Best, M.G., Christiansen, E.H., de Silva, S., and Lipman, P.W., 2016, Slab-rollback ignimbrite flareups in the southern Great Basin and other Cenozoic American arcs: A distinct style of arc volcanism: Geosphere, v. 12, p. 1097–1135.

Best, M.G., Gromme, S., Deino, A.L., Christiansen, E.H., Hart, G.L., and Tingey, D.G., 2013, The 36-18 Ma Central Nevada ignimbrite field and calderas, Great Basin, U.S.A.: Multicyclic super-eruptions: Geosphere, v. 9, p. 1562–1636.

Boerner, D.E., Craven, J.A., Kurtz, R.D., Ross, G.M., and Jones, F.W., 2011, The Great Falls Tectonic Zone: suture or intracontinental shear zone?: Canadian Journal of Earth Sciences, v. 35, p. 175-183.

Brothers, D.S., Driscoll, N.W., Kent, G.M., Harding, A.J., Babcock, J.M., and Baskin R.L., 2009, Tectonic evolution of the Salton Sea inferred from seismic reflection data: Nature Geoscience, v. 2, p. 581–584.

Colgan, J.P., and Henry, C.D., 2009, Rapid middle Miocene collapse of the Sevier orogenic plateau in north-central Nevada: International Geology Review, v. 51, p. 920–961.

Colgan, J.P., and Henry, C.D., 2017, Eruptive history, geochronology, and post-eruption structural evolution of the Late Eocene Hall Creek Caldera, Toiyabe Range, Nevada: United States Geological Survey Professional Paper 1832, 44 p.

Cousens, B.L, Henry, C.D., Stevens, C., Varve, S., Wetmore, S., John, D.A., 2018, Igneous rocks of the Great Basin, Battle Mountain area, north-central Nevada: not your usual LIP: Online, Large Igneous Provinces Commission, http://www.largeigneousprovinces.org/18may, accessed February 2020.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland system, western USA: American Journal of Science, v. 304, p. 105–168.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin, Geosphere, v. 2, p. 353–368.

Du Bray, E.A., John, D.A., Cousens, B.L., 2014, Petrologic, tectonic, and metallogenic evolution of the southern segment of the ancestral Cascades magmatic arc, California and Nevada: Geosphere, v. 10, p. 1–39.

Haynes, S.R., 2003, Development of the Eocene Elko Basin, northeastern Nevada: Implications for paelogeography and regional tectonism: Vancouver, University of British Columbia, M.S. thesis, 159 p.

Henry, C.D., Hinz, N.H., Faulds, J.E., Colgan, J.P., John, D.A., Brooks, E.R., Cassel, E.J., Garside, L.J., Davis, D.A., and Castor, S.B., 2012, Eocene-Early Miocene paleotopography of the Sierra Nevada-Great Basin-Nevadaplano based on widespread ash-flow tuffs and paleovalleys: Geosphere, v. 8, p. 1–27.

Henry, C.D., McGrew, A.J., Colgan, J.P., Snoke, A.W., and Bruseke, M.E., 2011, Timing, distribution, amount, and style of Cenozoic extension in the northern Great Basin: *in* Lee, J. and Evans, J.P., eds., Geologic Field Trips to the Basin and Range, Rocky Mountains, Snake River Plain, and Terranes of the U.S. Cordillera, Geological Society of America Field Guide 21, p. 27–66.

Kistler, R.W., Ghent, E.D., and O'Neill, J.R., 1981, Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada: Journal of Geophysical Research, v. 86, p. 10, 591–10, 606.

Lee, J., Blackburn, T., and Johnston, S., 2017, Timing of mid-crustal ductile extension in the northern Snake Range metamorphic core complex, Nevada: Evidence from U/Pb zircon ages: Geosphere, v. 13, p. 439–459.

Long, S.P., and Walker, J.P., 2015, Geometry and kinematics of the Grant Range brittle detachment system, eastern Nevada, U.S.A.: An end-member style of upper crustal extension: Tectonics, v. 34, p. 1837–1862.

O'Neill, J.M., and Lopez, D.A., 1985, Character and regional significance of Great Falls Tectonic Zone, east-central Idaho and west-central Montana: The American Association of Petroleum Geologists Bulletin, v. 69, p.437–447.

Pape, J.R., 2010, Reconstruction of Cenozoic extensional faulting within the southern Ruby Mountains metamorphic core complex and adjacent areas, northeastern Nevada: Tucson, University of Arizona, M.S. thesis, 137 p.

Putra, A.F., and Husein, S., 2016, Pull-apart basins of Sumatran Fault: previous works and current perspectives: in Proceedings, Seminar Nasional Kebumian KE-9, p. 43–60.

Sims, P.K., Saltus, R.W., and Anderson, E.D., 2005 , Preliminary Precambrian basement structure map of the continental United States—an interpretation of geologic and aeromagnetic data: United States Geological Survey, Open-File Report 2005-1029, 31 p.

Smith, D.L., 1992, History and kinematics of Cenozoic extension in the northern Toiyabe Range, Lander County, Nevada: Geological Society of America Bulletin, v. 104, p. 789–801.

Speed, R.C., Elison, M.W., and Heck, F.R., 1988, Phanerozoic tectonic evolution of the Great Basin, *in* Ernst, W.G., ed., Metamorphism and Crustal Evolution of the Western United States: Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 572–605.

Sullivan, W.A., and Snoke, A.W., 2007, Comparative anatomy of core-complex development in the northeastern Great Basin, U.S.A.: Rocky Mountain Geology, v. 42, p. 1–29.

Torrente, M.M., Milia, A., Bellucci, F., and Rolandi, G., 2010, Extensional tectonics in the Campania Volcanic Zone (eastern Tyrrhenian Sea, Italy): new insights into the relationship between faulting and ignimbrite eruptions: Italian Journal of Geosciences (Boll. Soc. Geol. It.), v. 129, p. 297–315.

Tosdal, R.M., Wooden, J.L., and Kistler, R.W., 2000, Inheritance of Nevadan mineral belts from Neoproterozoic continental breakup: *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., and Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond, Symposium Proceedings: Reno, Geological Society of Nevada, v. 1, p. 451–466.

Wernicke, B.P., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C. and others, eds., The Cordilleran Orogen, Conterminous U.S.: Boulder, Geological Society of America, The Geology of North America, V. G-3, p. 553–581.