Reactivated Palaeozoic normal faults: controls on the formation of Carlin-type gold deposits in north-central Nevada

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Abstract: Mappable surface structures control linear trends of Carlin-type gold deposits in north–central Nevada. Some of these structures probably resulted from reactivation of Palaeozoic normal faults, linked to underlying basement faults that originated during rifting of western North America during the Proterozoic. These old faults served as conduits for deep crustal hydrothermal fluids responsible for formation of Carlin-type gold deposits in the Eocene. The reactivated structures are recognized by stratigraphic and structural features. Stratigraphic features include rapid facies changes, growth fault sequences and sedimentary debris-flow breccias. Structural features resulted from inversion of the normal faults during the Late Palaeozoic Antler and subsequent orogenies. Inversion features include asymmetric hanging-wall anticlines, flower-like structures, and 'floating island' geometries. Inversion resulted in structural culminations that occur directly over the basement faults, providing an optimal setting for the formation of Carlin-type gold deposits.

North–central Nevada is one of the world's most important gold provinces. More than 6000 tonnes of gold have been produced or identified (Nevada Bureau of Mines and Geology 2004). The vast majority of the gold occurs in deposits known as Carlin-type gold deposits because of similarities to the famous Carlin gold mine. Carlin-type gold deposits are epigenetic, disseminated auriferous pyrite deposits characterized by carbonate dissolution, argillic alteration, and silicification of typically calcareous sedimentary rocks (Hofstra & Cline 2000; Cline *et al.* 2006). They formed during a short time interval in the Eocene between *c*. 42 and 36 Ma (Hofstra *et al.* 1999; Tretbar *et al.* 2000; Arehart *et al.* 2003). The alignment of ore deposits in Nevada has been recognized for many years (e.g. Roberts 1960, 1966). The Carlin and Battle Mountain–Eureka trends are the two best known alignments of Carlin-type gold deposits. The Carlin and Battle Mountain–Eureka trends have been demonstrated to correspond to gross geophysical and isotopic features (see Grauch *et al.* 2003), including gradients in basement gravity (Grauch *et al.* 1995), zones of electrical conductivity (Rodriguez 1998) and initial strontium and lead isotope ratios of Mesozoic and Tertiary igneous rocks (Wooden *et al.* 1998; Tosdal *et al.* 2000). In this paper it is argued that the Carlin and Battle Mountain–Eureka trends correspond to reactivated Palaeozoic normal fault zones that probably had their origins in the Proterozoic during rifting of the western margin of North America, as suggested by Tosdal *et al.* (2000). Mappable geological features that define the Carlin and Battle Mountain–Eureka trends and possibly new trends of Carlin-type gold deposits are described.

Rifting of the western margin of North America resulted in deposition of dominantly quartzite, and siltstone, in latest Proterozoic to earliest Cambrian times. Development of the passive margin sequence continued through the Devonian with deposition of interbedded carbonates and shales on the shelf and, to the west, silty carbonate units along the continental slope. By the end of the Devonian, at least 8–10 km of sediments were deposited (Stewart 1972, 1980; Stewart & Poole 1974; Bond *et al.* 1985; Poole *et al.* 1992). In earliest Mississippian times, deep-water siliciclastic and basaltic rocks (referred to here as the upper plate) were thrust eastward over the shelf-slope sequence (referred to here as the lower plate) along the Roberts Mountain Thrust during the Antler Orogeny (Roberts 1951; see also Poole *et al.* 1992). Subsequent compressional events in the Late Palaeozoic and Mesozoic include the Humboldt, Sonoma, Elko and Sevier orogenies (see Stewart 1980; Thorman *et al.* 1991; Burchfiel *et al.* 1992).

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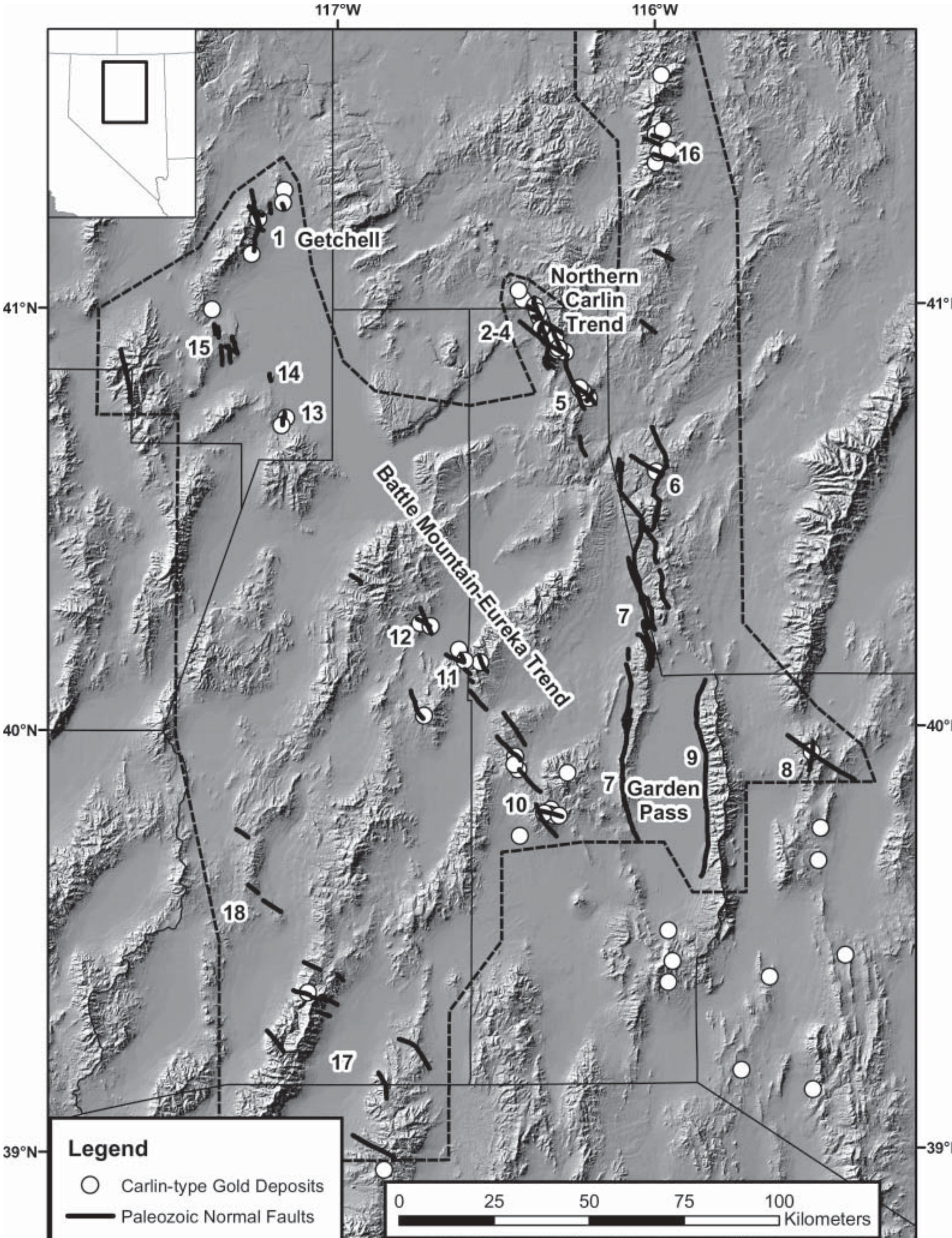

Fig. 1. Shaded relief map of north–central Nevada showing locations of Carlin-type gold deposits and Palaeozoic normal faults identified in this study. The corresponding numbers refer to the list in Table 3. The dashed line delimits the area that was analysed for this study. For reference, the continuous lines outline counties in north–central Nevada.

In the Eocene, north–central Nevada experienced an abrupt shift in tectonic activity from compression to extension and renewed magmatism (see Burchfiel *et al.* 1992; Christiansen & Yeats 1992; Cline *et al.* 2005).

Typically, 'thin-skinned' fold and thrust features that formed during the Late Palaeozoic and Mesozoic orogenies have been described in Nevada (see Stewart 1980). However, inversion of Proterozoic extensional faults during the Late Mesozoic–Early Tertiary Laramide Orogeny has been documented to the east in the Rocky Mountains (e.g. Davis 1978; Marshak *et al.* 2000). 'Thick-skinned' deformation and inversion features, which are typical of deformed cratonic margins worldwide (see Coward 1994), have been only rarely described for Nevada in the literature (e.g. Carpenter *et al.* 1993; Tosdal 2001; Cline *et al*. 2005). Yigit *et al.* (2003) suggested that Palaeozoic normal faults may have controlled gold mineralization in the Gold Bar district in Nevada. However, they interpreted fault-propagation folds and thrust faults, with imbricate splay geometries in the Gold Canyon deposit, to have developed over the tips of major low-angle thrust faults rather than by inversion of a high-angle Palaeozoic normal fault (Yigit *et al.* 2003, fig. 15). A major goal of this paper is to present evidence consistent with inversion and 'thick-skinned' deformation in several localities throughout north–central Nevada. The other goal of the paper is to present a spatial relationship between Palaeozoic normal faults and the location of Carlin-type gold deposits and argue that the faults served as the main conduits for deep auriferous hydrothermal fluids, sourced from the middle to lower crust.

Evidence for Palaeozoic normal faults in north–central Nevada

Based on analysis of published geological maps, field checks, mine visits, review of literature and local detailed mapping, evidence has been found for Palaeozoic normal faults throughout north–central Nevada (Fig. 1). In addition to typical methods of dating earliest movement on structures (offset of units of known age, stratigraphic superimposition), we identified both stratigraphic features (Table 1) and features of fault inversion (Table 2) that suggest the presence of Palaeozoic normal faults.

Features of fault inversion include characteristic fold and fault geometries that form when normal faults are reactivated during compressional orogenies, as summarized by

Table 1. *Sedimentary and stratigraphic relationships used to recognize Palaeozoic normal faults*

(1) Thickening, thinning or abrupt facies changes in Palaeozoic rocks, especially towards faults
(2) Growth fault sequences
(3) Sedimentary breccias with linear boundaries
(4) Reefs or other shallow carbonate sequences forming on the top of tilted fault blocks
(5) Syngenetic barite or sulphide occurrences in the lower plate of the Roberts Mountains Thrust
(6) Local absences of widespread stratigraphic units

Table 2. *Inversion and other structural features used to recognize Palaeozoic normal faults*

(1) Fault propagation folds: fold geometries that involve long, gently dipping backlimbs and short, steep forelimbs
(2) Monoclines
(3) Related kinematics between folds and high-angle faults
(4) 'Flower structures': radiating arrays of faults in the steep forelimb area that root on a master fault (wedge-shaped in section) and are subparallel in trend to the axial plane of the associated anticline
(5) Footwall shortcut thrust faults
(6) 'Floating-island' geometries
(7) Narrow zones of anomalously trending fold axes within a thrust terrain
(8) Refolded or non-cylindrical folded upper plate rocks
(9) Folded thrust faults
(10) Zones of upright to inclined, tight to isoclinal folds in rocks that otherwise have recumbent or open folds
(11) High-angle reverse faults
(12) Folds with anomalous vergence

Williams *et al.* (1989) and Coward (1994). The development of such geometries is schematically illustrated in Figure 2. First, normal faulting results in the formation of a synrift growth sequence (C in Fig. 2a) overlying pre-rift basement and sediments (A and B in Fig. 2a), followed by later deposition of post-rift sediments (D and E in Fig. 2a). During compression, reverse reactivation of the original normal fault causes development of an asymmetric hanging-wall anticline, which forms where hanging-wall rocks are displaced from the original normal fault onto a new higher level along a more gently dipping thrust (Fig. 2b). The synrift growth sequence is folded into a characteristic harpoon shape. The hanging wall anticline in the post-rift sediments has the characteristics of a fault propagation fold. The shortcut thrust may splay

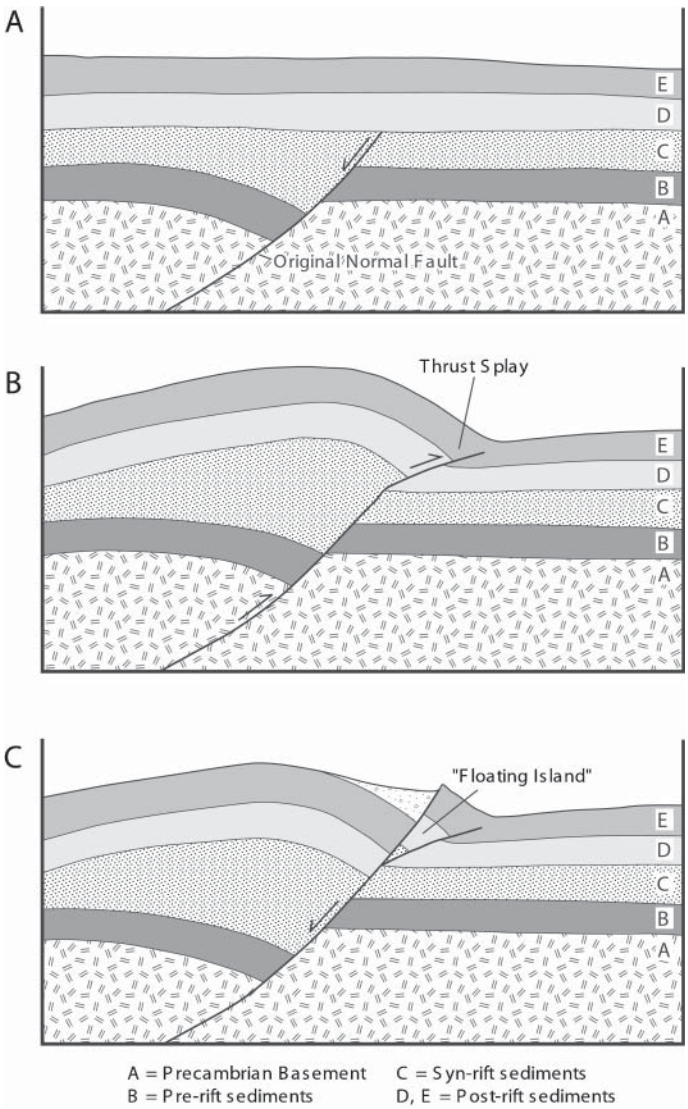

Fig. 2. Schematic cross-sections showing idealized geometries that develop during inversion of a normal fault. (**a**) Normal faulting, deposition of synrift growth sequence (C) over basement (A) and pre-rift sediments (B), and later deposition of post-rift sediments (D, E). (**b**) Inversion and formation of thrust splay and hanging-wall anticline. (**c**) Later extension and formation of 'floating island'. Modified partly from Williams *et al.* (1989).

Table 3. *Interpreted Palaeozoic and older normal faults*

Locality	Evidence	References
(1) Getchell–Twin Creeks	(1) Abrupt linear N70°W boundary to a sequence of sedimentary debris-flow breccias and basalts that were deposited along a monocline, inferred to have formed during extensional reactivation of a buried high-angle WNW-trending normal fault (2) NNW-trending faults (e.g. Getchell Fault) show local folded growth features in their hanging walls, as interpreted from seismic sections (3) Local occurrences of sedimentary exhalative sulphide occurrences (4) Conelea Anticline at Twin Creeks interpreted to be an inversion-related fault-propagation fold that was truncated during emplacement of Roberts Mountain Allochthon (5) Pennsylvanian–Permian Etchart Limestone is substantially thicker in the hanging wall of the Getchell Fault and contains abundant quartzite pebble conglomerate layers that were probably derived during fault growth from Cambrian–Ordovician quartzite in the footwall (6) Narrow zone of tight, symmetrical NNW-trending folds in the Etchart Limestone in the hanging wall of the parallel west-dipping Midway Fault	Breitt *et al.* 2005; Stenger *et al.* 1998; Placer Dome Exploration staff, Pers comm., 1999; Bloomstein *et al.* 1991; this study
(2) Carlin trend (general)	(1) Zone of anomalous fold axes: fold axes in lower and upper plate rocks trend NW within the Carlin trend and trend NE outside the Carlin trend	Evans & Theodore 1978
(3) N5°E to N35°W Post-Gen Fault System; northern Carlin trend	(1) Asymmetric anticlines with fold axes parallel to the Post-Gen Fault System, including the Tuscarora Spur and Post Anticlines; these anticlines precede emplacement of the 158 Ma Goldstrike Stock (2) Shortcut thrust, west-verging asymmetric Ernie Anticline and 'floating island' at Rodeo (3) Reverse faults (e.g. Ridge Fault) and normal faults with reverse drag features (e.g. J series faults) (4) Abundant debris-flow breccias, especially those surrounding the pillar-shaped biohermal Bootstrap Limestone forming at top of tilted fault block in footwall of Post Fault at Meikle (5) Lower plate Devonian sedimentary exhalative sulphide occurrences	Leonardson & Rahn 1996; Armstrong *et al.* 1998; Emsbo *et al.* 1999; Moore 2001; Volk *et al.* 2001; this study
(4) N60-70°W faults; northern Carlin trend	(1) Asymmetric N60–70°W anticlines (West Bazza and Betze Anticlines) (2) Betze Anticline does not involve rocks higher in the section than the lower half of the Devonian Rodeo Creek Fm (3) West Bazza flower structure (4) Abrupt facies boundary extending N60–70°W from Meikle between shelf biohermal and ooloidal limestones of the Devonian Bootstrap Limestone to the north and debris-flow breccias and laminated slope carbonates of the time-equivalent Popovich Fm to the south that strongly suggests synsedimentary Devonian faulting	Leonardson & Rahn 1996; Armstrong *et al.* 1998; Lauha 1998; Griffin 2000; Moore 2001; Bettles 2002
(5) Gold Quarry	(1) N50°W Good Hope reverse fault, interpreted here to be the result of inversion	Harlan *et al.* 2002
(6) Rain	(1) Late Mississippian to Early Pennsylvanian Tonka Fm, which is part of the post-Antler overlap sequence, was deposited on a paleosurface that bevelled different levels of the Early Mississippian Antler fold and thrust belt as well as N60–70°W-striking Early Mississippian normal faults, including the Rain Fault, that cut the fold and thrust belt; the Mississippian normal faults were inverted during late Palaeozoic(?) southward-directed shortening as steeply to moderately dipping reverse faults (2) Flower structure with radiating array of faults that results in a 'floating island' geometry	Williams *et al.* 2000; Tosdal 2001; Cline *et al.* 2005

Table 3. *Continued*

Locality	Evidence	References
(7) Piñon and Sulfur Springs Ranges	(1) Erosional removal of Devonian Devil's Gate Limestone and exhumation of the Devonian Telegraph Canyon Fm as a result of asymmetric, high-angle fault propagation folds, prior to emplacement of Roberts Mountain Allochthon (2) Presence of carbonate debris-flow breccias locally in the lower plate Devonian Telegraph Canyon Fm dolomites, near Union Pass (3) Asymmetric anticlines with N5ºE–N25ºW-trending fold axes that fold the Roberts Mountain thrust (4) Locally sourced angular quartzite fragments in conglomerate of the Permian Garden Valley Fn, which are in hangingwall of high-angle fault with quartzites of the Devonian Oxyoke Canyon Fm in the footwall, near Garden Pass	Carlisle & Nelson 1990; Carpenter *et al.* 1993; This study
(8) Bald Mountain	(1) WNW distribution of: (a) Mississippian Diamond Peak Fm conglomerate facies, (b) Pennsylvanian Ely Fm reef facies, (c) multiple facies transitions in the Permian Arcturas Fm, and (d) Permian Carbon Ridge platform facies, from the Diamond Mountains to the Butte Range (2) Asymmetric N50–60ºW anticline along northeastern flank of NW-aligned late Jurassic Bald Mountain Stock; Cambrian–Ordovician strata in the anticline have lateral facies changes to carbonate debris-flow breccias (3) NNE-trending reverse faults	Cox & Otto 1995; Nutt *et al.* 2000; This study
(9) Diamond Range	(1) Thick Permian conglomerates are interpreted to be recording Permian extension (2) Overturned asymmetric anticline–syncline pairs	Nolan *et al.* 1971; This study
(10) Roberts Mountains	(1) Asymmetric NW-trending anticlines that fold the Roberts Mountain thrust (2) Flower structures in the steep forelimb of the NW-trending asymmetric anticline in Gold Canyon open pit (3) Transverse WNW-trending anticline associated with Gold Bar satellite gold deposits	Murphy *et al.* 1978; Yigit *et al.* 2003; This study
(11) Cortez	(1) Both WNW and NNW-trending asymmetric anticlines that fold the Roberts Mountain thrust in the hanging wall of the Cortez Fault (2) Ordovician Eureka Quartzite unconformably overlies the Cambrian Hamburg Dolomite; nearly 1000 m of Cambrian and Ordovician stratigraphy is missing (Cambrian Dunderberg and Windfall Fms, Ordovician Pogonip Group) (3) West-verging recumbent folds in Horse Canyon open pits, interpreted to be anticlines related to shortcut thrusts in the footwall of the NNW-trending Horse Canyon fault zone	Gilluly & Masursky 1965; Ross 1977; This study
(12) Pipeline–Gold Acres	(1) N15–30ºW-trending asymmetric, east-verging anticline just west of the Pipeline open pit (2) N50–60ºW folds in low-angle shear zone that hosts Pipeline (3) Narrow zone of tight N50–60ºW folds along the northern margin of Gold Acres west of Pipeline open pit	Foo *et al.* 1996*a*,*b*; Wrucke, 1974; This study
(13) Marigold	(1) Truncation of NNW-trending high-angle normal faults by Golconda Thrust (Early Triassic) in the 8 South open pit (2) Abrupt lateral facies changes including thick hanging-wall sedimentary breccias in Pennsylvanian Edna Mtn Fm., which thin away from NNW-trending faults	Marigold mine staff, pers. comm., 1999; McGibbon & Wallace 2000
(14) Lone Tree	(1) Conglomerates of the Pennsylvanian Battle Fm with clasts of quartzite thin considerably away from Lone Tree Hill, which is composed of quartzite of the Ordovician Valmy Fm	Lone Tree mine staff, Pers. comm. 1999

Table 3. *Continued*

Locality	Evidence	References
(15) Edna Mountains	(1) Pennsylvanian Highway Limestone thins out in hanging walls away from NNW-trending faults (2) Conglomerates of the Pennsylvanian Battle Fm thin considerably toward axes of WNW-trending folds, suggesting palaeotopographic high (3) NNW-trending reverse fault that places Cambrian Preble Fm up against Ordovician Valmy Fm	Erickson & Marsh 1974*a*,*b*; This study
(16) Jerritt Canyon	(1) 'Floating island' in the footwall of the WNW-trending New Deep Fault in the Murray Mine (2) WNW faults are filled by 320 Ma andesite dykes (3) WNW faults interpreted as lateral ramps to SE-directed thrusting and duplexing	Hofstra *et al.* 1999; Dewitt 2001; Jones 2005
(17) Austin area (Toiyabe and Toquima ranges)	(1) WNW-trending monoclines that overprint the prominent NNE structural trend in the ranges (2) Cambrian to Early Mississippian strata and structures are cut and tilted by north-dipping normal faults and then bevelled and overlain by Pennsylvanian to Early Permian sedimentary sequences with local mafic lava flows	McKee, 1968, 1976; Smith & Miller, 1990
(18) Ravenswood (southern Shoshone Range)	(1) NW-trending asymmetric anticline and monoclines that overprint the prominent NNE structural trend in the range and fold Roberts Mountain Thrust	This study

into imbricate fans, which can be termed in a descriptive sense a 'flower structure'. Such flower structures in Nevada have commonly been attributed to strike-slip faulting (e.g. Lauha 1998; Williams *et al.* 2000). Thrusts like this can create 'floating islands' (Fig. 2c). When a later phase of normal motion along the inverted fault takes place, as during Teritary extension in Nevada. The hanging wall is dropped down and a wedge of older rocks is created between younger rocks in a triangular-shaped zone of deformation. If a footwall shortcut thrust does not form and movement of the hanging wall along the original normal fault ceases, upright to inclined, tight to isoclinal, symmetrical folds can form in the hanging wall.

Many of the inversion geometries illustrated in Figure 2 and listed in Table 2 are present in north–central Nevada and are described in this paper; namely, fault-propagation folds, flower structures and floating islands. However, none of these features are unique to inversion. As pointed out by Cooper *et al.* (1989), inversion cannot be unequivocally recognized unless folded growth sequences are present. Therefore, except for growth fault sequences, either folded or unfolded, few if any of the features in Tables 1 and 2 prove the existence of Palaeozoic normal faults. This paper does not fully document any folded growth sequences. However, it is believed that the presence of several features in Tables 1 and 2 at given localities in Figure 1 is highly suggestive of a Palaeozoic normal fault, and, at a minimum, Palaeozoic normal faults and subsequent inversion of those faults should be considered as a viable hypothesis to explain the observed features. Table 3 lists the localities numbered in Figure 1 and the corresponding, supporting evidence for Palaeozoic normal faults. Next, more detailed evidence is presented for Palaeozoic normal faults at Garden Pass, in the northern Carlin trend, and in the Getchell district.

Garden Pass

At Garden Pass (Fig. 1), a half-graben bounded by a west-dipping fault contains conglomerates, sandstones and sandy limestones of Permian age (Garden Valley Formation) (Figs 3 and 4). The Permian rocks rest on the Ordovician Vinini Formation, which is in the upper plate of the Roberts Mountain Thrust. In the footwall of the fault are Devonian dolomites and locally quartzites that are in the lower plate of the Roberts Mountain Thrust. Within the Permian rocks there is a prominent conglomerate that

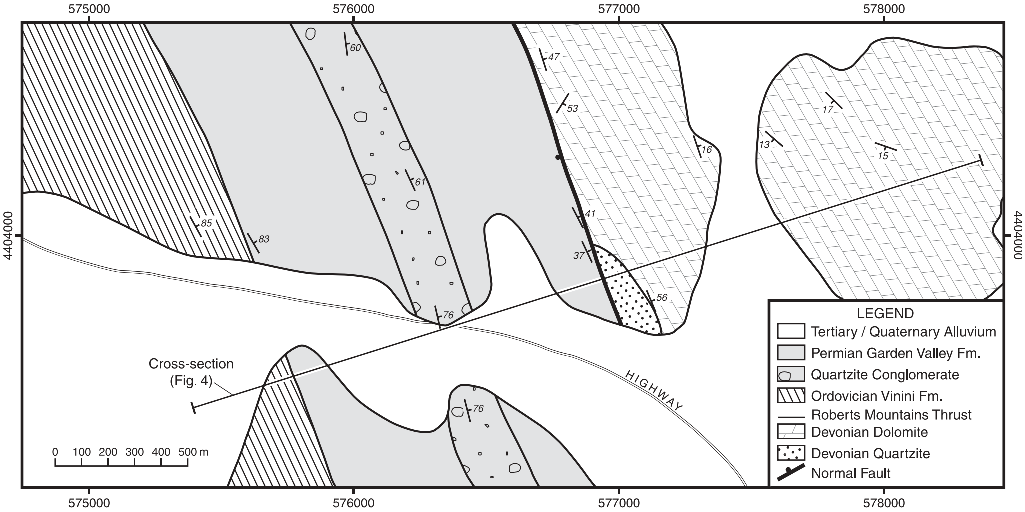

Fig. 3. Map of Garden Pass area completed during this study, showing location of cross-section in Figure 4. Coordinates are UTM metres (NAD 27, Zone 11). (See text for discussion.)

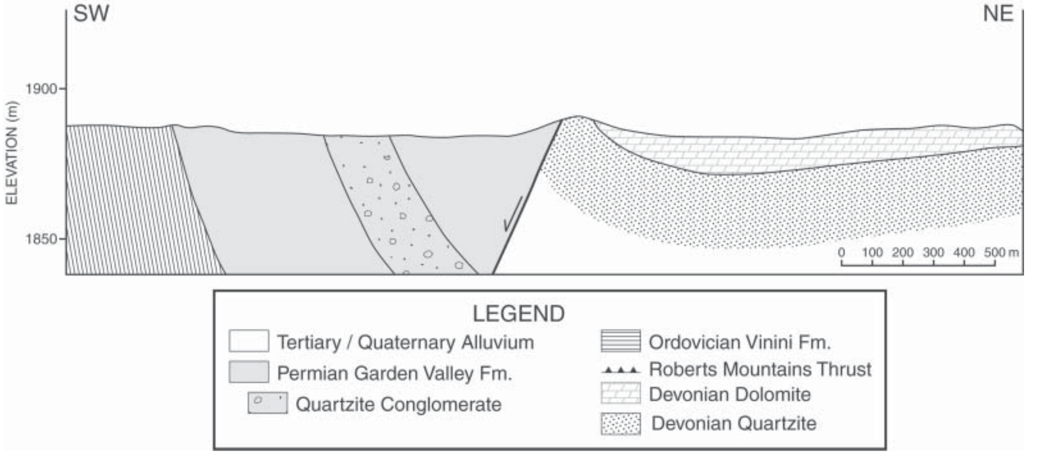

Fig. 4. Cross-section of Garden Pass area looking N15°W.

contains angular, pebble- to cobble-sized clasts of quartzite that appear to be identical to the Devonian quartzite in the footwall, strongly suggesting fault growth during the Permian. The Permian rocks were subsequently folded into a hanging-wall anticline during Mesozoic compression, as interpreted in Figure 5. There are continuations of this fault or similar faults all along the western edge of the ranges, north of Garden Valley Pass (Fig. 1).

Northern Carlin trend

First, evidence for inversion of a buried Palaeozoic (or older) normal fault zone at the scale of the entire Carlin trend (Fig. 1) comes from regional inspection of fold axes. Evans & Theodore (1978) first demonstrated that the Carlin trend corresponds to a zone of anomalously trending fold axes. Outside the Carlin trend fold axes trend mostly NNE, fairly typical

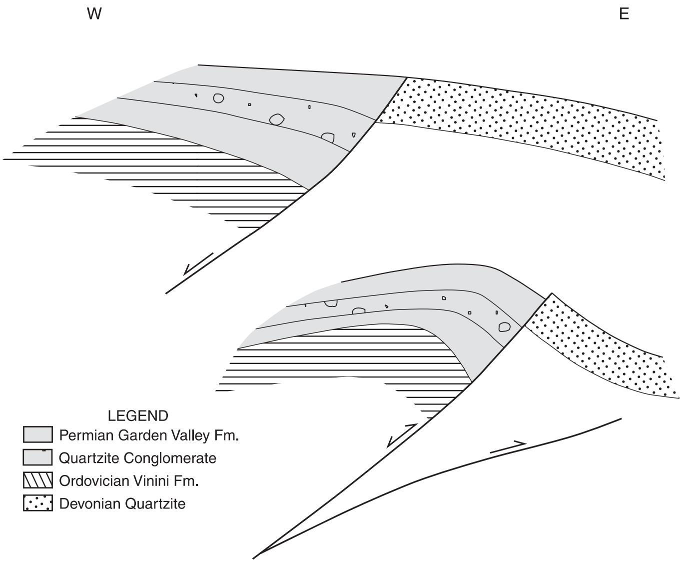

Fig. 5. Schematic cross-section of Garden Pass area, illustrating interpreted development of inversion structures at Garden Pass. Top: partially restored cross-section showing original Permian normal fault. Bottom: development of fault-propagation fold during Mesozoic inversion. See text for discussion.

of folds associated with the Antler Orogeny and subsequent compressional events. However, within the Carlin trend, in a zone <10 km wide, fold axes trend NW, parallel to the alignment of Carlin-type gold deposits.

Ample stratigraphic evidence for Palaeozoic normal faulting exists in the northern Carlin trend (Figs 1 and 6). Northwest of the Post-Betze open pit, Palaeozoic normal faulting is suggested by a rapid facies change over a distance of <800 m across a WNW-trending boundary (Armstrong *et al.* 1998; Griffin 2000; Moore 2001; Bettles 2002). Massive oolitic, fossiliferous limestones of the Devonian Bootstrap Limestone, indicative of shallow high-energy conditions, occur to the NE. To the SW, laminated muddy limestones and debris-flow breccias of the time-equivalent Popovich Formation indicate a transition to deeper water. At the Meikle Mine, a prominent pillar of Bootstrap Limestone in the footwall of the Post Fault is surrounded by carbonate debris-flow breccias (Volk *et al.* 1995). Such relationships are characteristic of reefs forming on the tops of tilted fault blocks (see Enos & Moore 1983). Gold-bearing sedimentary exhalative sulphide occurrences in the Popovich Formation (Emsbo *et al.* 1999) also suggest the presence of synsedimentary faulting.

Examples of fold geometries in the northern Carlin trend, consistent with inversion, are illustrated with cross-sections in Figure 7. At the Rodeo Mine (Fig. 7a), the N30ºW-trending Ernie Anticline is a tight asymmetric west-verging fold in the hanging wall of the parallel Ernie Fault, which is a reverse fault (Baschuk 2000). The vergence is anomalous in that most folds associated with the Antler and subsequent orogenies are east-verging. The Ernie Fault can be interpreted as a footwall shortcut thrust associated with inversion of the Post Fault. The Post Fault was later reactivated in the Tertiary with a significant normal component, resulting in a ‘floating island’ preserved between the Ernie and Post faults. The parallel Post Anticline in the Post-Betze open pit and the Tuscarora Anticline, to the south in the Genesis open pit, are analogous to the Ernie Anticline.

At West Bazza (Fig. 7b), a series of N60–70ºW-trending high- and low-angle south-dipping faults, with a characteristic radiating geometry, has been interpreted as a flower structure, related to strike-slip faulting (Lauha 1998). The geometry is interpreted here as a radiating array of shortcut thrusts. These faults have parallel-trending, asymmetric north-verging anticlines in their hanging walls. Again, as at Rodeo, there are characteristic ‘floating islands’, where reverse motion is preserved in the hanging wall of the lower-angle shortcut thrusts but not in the hanging wall of the original higher-angle normal

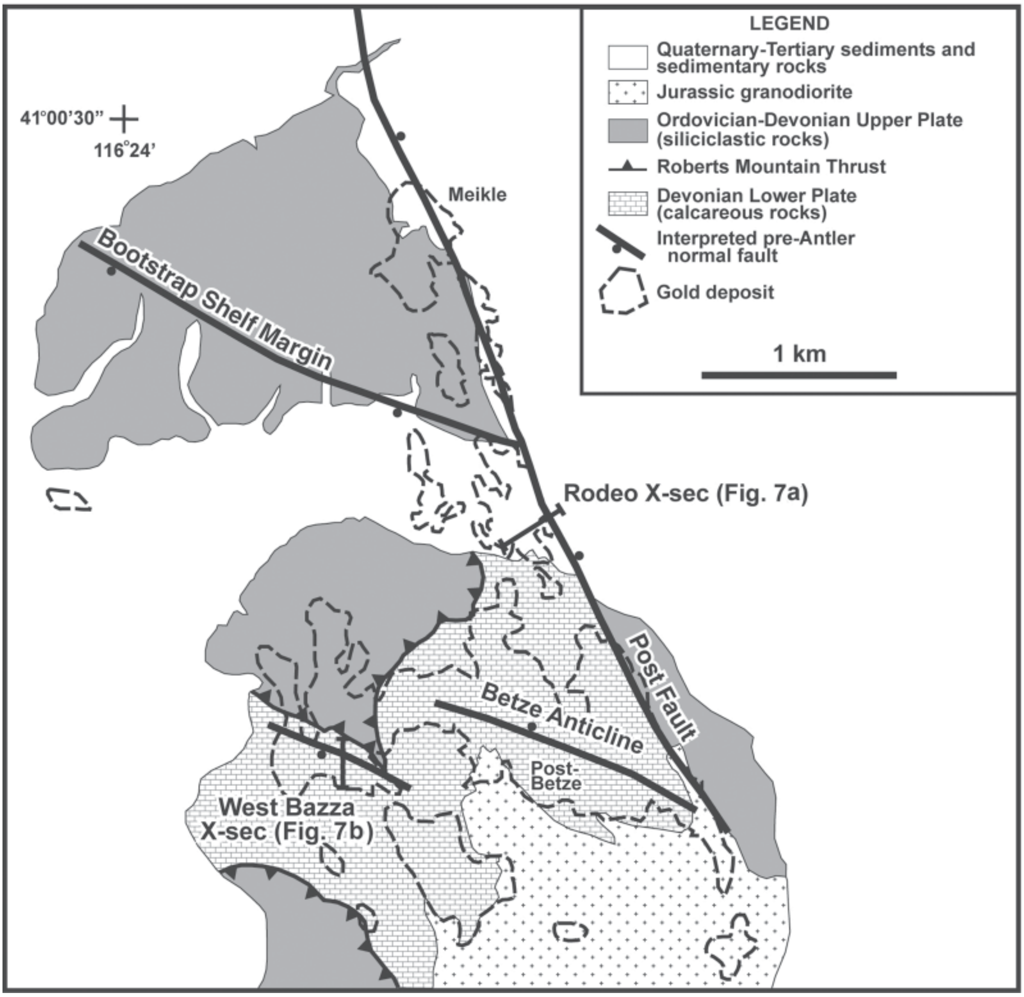

Fig. 6. Map of the northern Carlin trend, modified from Bettles (2002) and Moore (2002), showing the location of interpreted Palaeozoic normal faults and cross-sections (Fig. 7) discussed in text.

fault. The shortcut thrusts are locally intruded by Jurassic dykes, indicating that the structure is at least Jurassic in age (Lauha 1998). The flower structure in the West Bazza Pit is parallel, but with opposite vergence, to the Betze Anticline, a main ore-control in the Post-Betze open pit. The Betze Anticline has been related to the emplacement of the Jurassic Goldstrike Stock (Leonardson & Rahn 1996); however, the folds predate the Goldstrike Stock, as argued by Moore (2001). Both the West Bazza and Betze anticlines are interpreted to be related to reactivation of Palaeozoic WNW-trending faults that developed along the southern boundary of the Bootstrap Limestone shelf.

Getchell

As for the northern Carlin trend, evidence for both NNW- and WNW-trending Palaeozoic normal faults is present in the Getchell district (Figs 1 and 8). A lower sequence of pillow basalt and underlying sedimentary debris-flow breccias of Cambrian–Ordovician age has a sharp N70ºW southern margin that is an important ore control to the Turquoise Ridge deposit (Fig. 8). The margin occurs along the northern limb of a monocline that is interpreted to have formed by syndepositional reactivation of an underlying north-dipping, WNW-trending Palaeozoic normal fault (Placer Dome Exploration, pers.

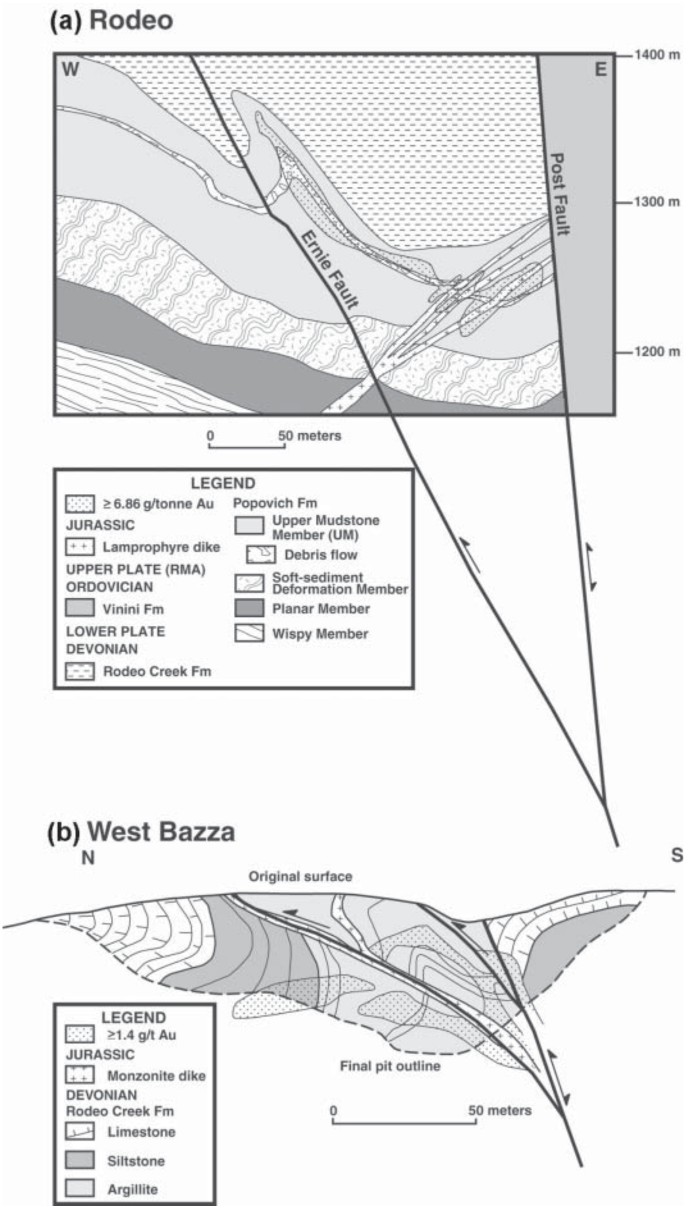

Fig. 7. Examples of inverted Palaeozoic normal faults in the northern Carlin trend. Bold lines are the interpreted inversion-related faults. (**a**) Cross-section of the Rodeo deposit looking N30°W, modified from Baschuk (2000). The Ernie Fault is interpreted to be a shortcut thrust related to inversion of the Post Fault as represented by the interpreted projections of the faults below the box enclosing the cross-section. The reverse separation on the Ernie Fault and the tight asymmetric anticline in its hanging wall should be noted; and that the top of the cross-section is *c*. 250 m below the surface. The section is based on fans of closely spaced underground core holes, which are not shown here, but were shown by Baschuk (2000). (**b**) Cross-section of the West Bazza pit looking east, modified from Lauha (1998). The radiating array of shortcut thrusts (bold lines), which shows net contraction, should be noted. The Palaeozoic normal fault, to the right, shows net extension. All of the faults have hanging wall anticlines.

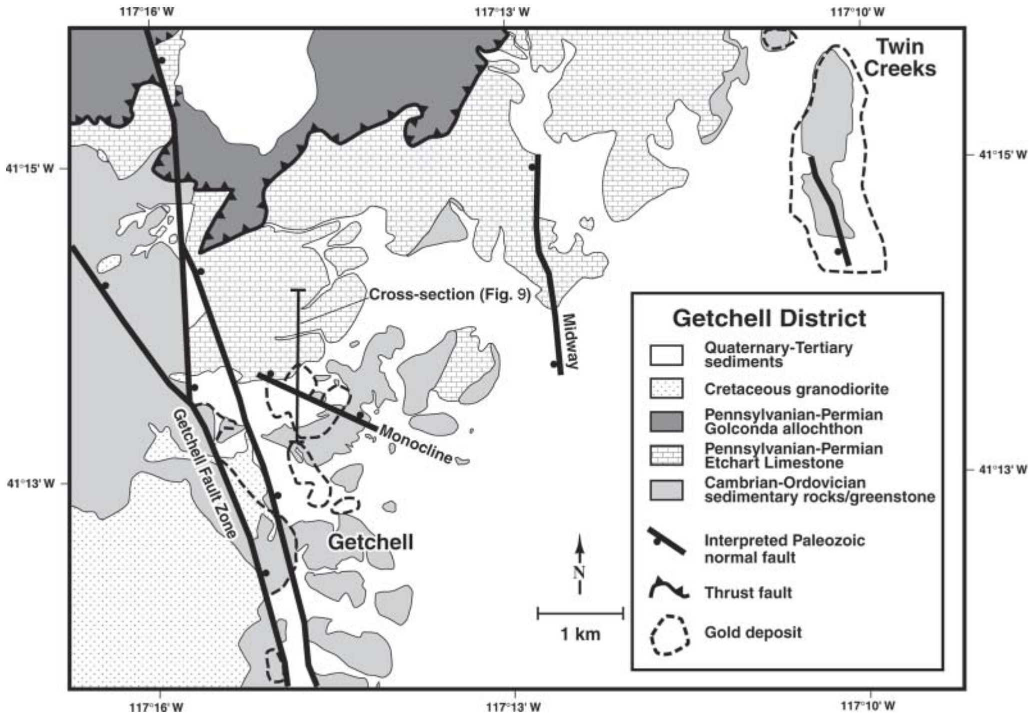

Fig. 8. Geological map of the Getchell–Twin Creeks area, based mostly on mapping by Hotz & Willden (1964) and unpublished mapping by Placer Dome geologists. The map shows location of interpreted Palaeozoic normal faults discussed in the text and the location of the cross-section shown in Figure 9.

comm., 1999; Fig. 9). In addition, folded growth sequences along east-dipping faults with NNW strikes, such as the Getchell Fault, are interpreted from seismic sections. At the Twin Creeks gold deposit, just to the east, the asymmetric NW-trending, east-verging Conelea Anticline, located in the hanging wall of the parallel Lopear Thrust (Bloomstein *et al.* 1991), is a fault-propagation fold, interpreted here to be the result of inversion of a west-dipping NNW-trending normal fault. The Conelea Anticline is truncated by what was interpreted by Breit *et al.* (2005) to be the Roberts Mountain Thrust.

Post-Antler reactivation of the Getchell Fault is evident in the Pennsylvanian–Permian Etchart Limestone. The Etchart Limestone appears to be substantially thicker east of the Getchell Fault and contains abundant interbeds of quartzite pebbles (Fig. 8). The pebbles appear to be derived from Cambrian and Ordovician quartzite located in the footwall of the Getchell Fault, suggesting that there was fault growth during deposition of the Etchart Limestone. The Etchart Limestone was broadly folded (*c.* 2 km wavelengths) along NE-trending axes during the Golconda and/or subsequent Mesozoic orogenies, but inversion is evident in a narrow zone of tight, symmetrical NNW-trending folds in the Etchart Limestone in the hanging wall of the parallel west-dipping Midway Fault (Fig. 8).

Relationship between Palaeozoic normal faults and Carlin-type deposits

Comparisons demonstrate a remarkable similarity between Carlin-type deposits in all districts in Nevada (Cline *et al.* 2005). Although isotopic differences suggest different fluid sources at some deposits, detailed studies show that all districts display broadly similar styles of mineralization and alteration over vertical scales of at least 1 km and up to 20–35 km laterally in individual districts. The large hydrothermal systems responsible for Carlin-type gold deposits are characterized by low-salinity fluids (mostly *c.* 2–3 wt% NaCl equivalent), moderate CO_2 contents (<4 mol%), high Au/Ag ratios, high Au/base metal ratios, a Au–As–Hg–Sb association, moderate temperatures (180 and 240 ºC), a lack

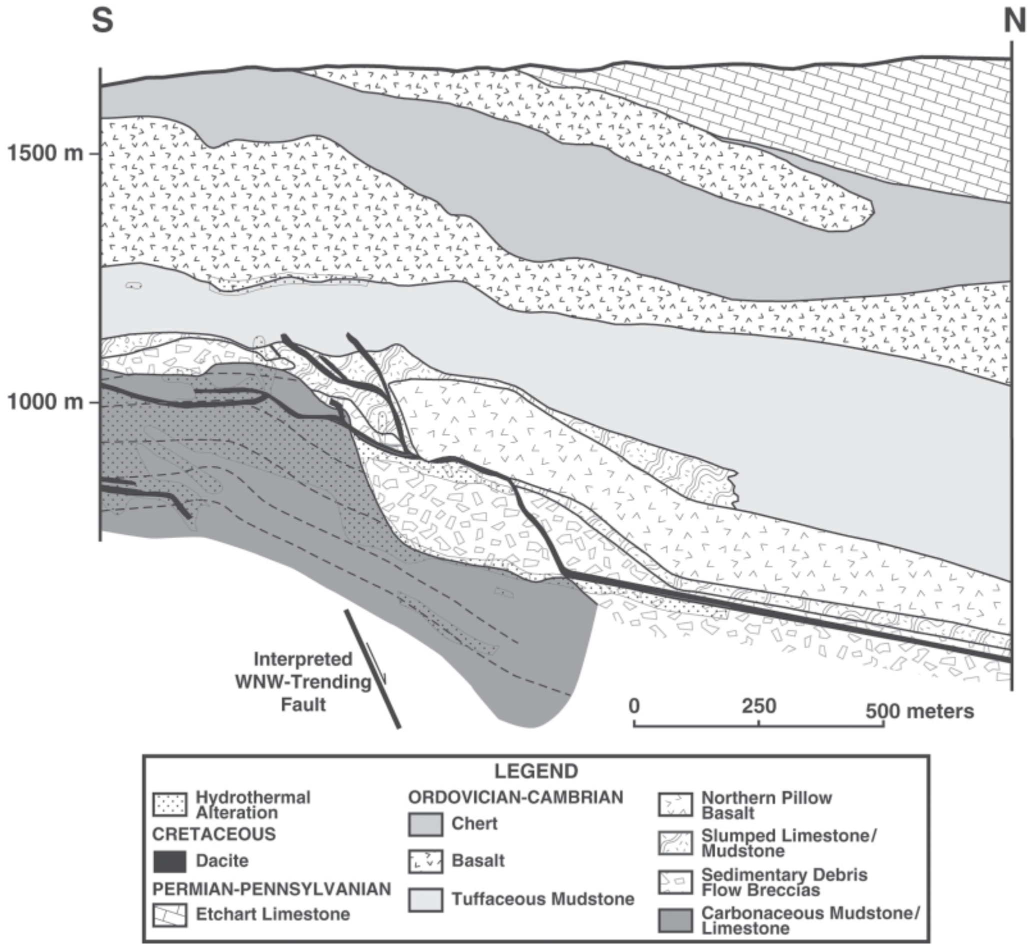

Fig. 9. North–south section (867600E) looking west through the north part of the Turquoise Ridge deposit at Getchell based on work completed during this study, showing WNW-trending monocline. As discussed in the text, the monocline is interpreted to have formed by syndepositional normal reactivation of an underlying normal fault. The monocline formed the margin to a basin that filled initially with carbonate debris-flow breccias and then with pillow basalt. The section is based on surface core holes (not shown) spaced 30 m apart.

of consistent alteration and metal zoning, and a coincidence with regional thermal events (see Hofstra & Cline 2000; Cline *et al.* 2005). These characteristics are broadly consistent with other hydrothermal systems that form other types of large 'gold-only' deposits in the world, such as orogenic gold deposits. As originally pointed out by Phillips & Powell (1993), such deposits form from a uniform ore fluid that required a large and uniform source. They suggested that deep crustal-scale processes could best generate such a fluid. Although most stable isotope data indicate exchanged meteoric waters as the main source of hydrothermal fluids, data from Getchell and the Deep Star deposit in the northern Carlin trend point towards a magmatic or metamorphic fluid source (Cline & Hofstra 2000; Heitt *et al.* 2003). The fluid source may be exchanged meteoric, magmatic or metamorphic, rather than having a local source associated with epizonal stocks and shallow convecting meteoric water, such as a porphyry-related hydrothermal system that would exhibit strong lateral zoning patterns in metals and alteration (i.e. Sillitoe & Bonham 1990). Cline *et al.* (2005) concluded that hydrothermal fluids, responsible for the formation of Carlin-type deposits, had their origins during removal of the Farallon slab below north–central Nevada in the Eocene, which promoted deep crustal melting, prograde metamorphism and devolatilization, thus generating deep, primitive fluids. In the upper crust, ore fluids were then diluted by exchanged meteoric waters, prior to depositing gold within a few kilometres of the surface.

Figure 1 shows a close spatial correlation between the proposed Palaeozoic normal faults and the location of Carlin-type gold deposits. Zones of Palaeozoic normal faults are coincident with the Carlin and Battle Mountain–Eureka trends. There is an inherent bias because this study focused on mine areas where the exposure is better and there is much more information. However, Figure 1 also shows proposed Palaeozoic normal faults well away from known mines. As shown in Figure 1 and described in Table 3, Palaeozoic normal faults that have been identified in this study mostly trend NNW (N0–30°W) and WNW (N50–70°W). Studies of rift strata and dyke swarms in the Rocky Mountains, the Colorado Plateau and the Mid-continent indicate that WNW-trending faults originally formed during a rifting event between 1.1 and 1.3 Ga, and formation of north-trending faults and reactivation of WNW-trending faults occurred between 0.7 and 0.9 Ga (Marshak *et al.* 2000; Timmons *et al.* 2001). Thorman & Ketner (1979) first pointed out evidence for N50–70°W-trending basement faults of probable Proterozoic origin in northeastern Nevada (e.g. Wells Fault) based on offset of regional stratigraphic and structural features.

The coincidence of these Proterozoic features with the Palaeozoic faults identified in this study, strongly suggests that the faults are linked at depth with basement faults, formed during continental rifting of western North America in Proterozoic times and were continually reactivated in the Early Palaeozoic during the formation of the continental margin. Such basement-penetrating, linked high-angle fault systems probably have a greater vertical extent than later faults and served as the main collecting points and conduits for deep, gold-bearing crustal fluids responsible for Carlin-type mineralization in the Eocene. Inversion of these fault systems during the Antler and subsequent orogenies commonly resulted in structural culminations, especially where NNW- and WNN-trending Palaeozoic normal faults intersect. Subsequent erosion of these culminations led to the currently observed windows of lower plate rocks. The superimposition of these structural culminations over Palaeozoic normal faults created an optimal setting for the formation of Carlin-type gold deposits.

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