Eocene magmatism: The heat source for Carlin-type gold deposits of northern Nevada

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ABSTRACT

The origin of Carlin-type or sediment-hosted, disseminated gold deposits of the Great Basin, the major source of gold in the United States, is poorly understood. We propose that Eocene magmatism was the heat source that drove the hydrothermal systems that generated these deposits in the Carlin trend and Independence Mountains in northern Nevada. This interpretation is based on a strong spatial and temporal association of Eocene intrusive-volcanic centers with the gold deposits of this region. Our new work and published ^{40}Ar/^{39}Ar dates indicate that magmatism was particularly intense between 39 and 40 Ma throughout northeastern Nevada, especially in and around the area of gold deposits. Carlin-type deposits may have formed preferentially during Eocene magmatism because it was (1) more intense in the area than other magmatic episodes, (2) somehow compositionally distinct, or (3) accompanied by extension that promoted hydrothermal flow. However, large-scale extension does not appear to have been a factor in generating Carlin-type deposits.

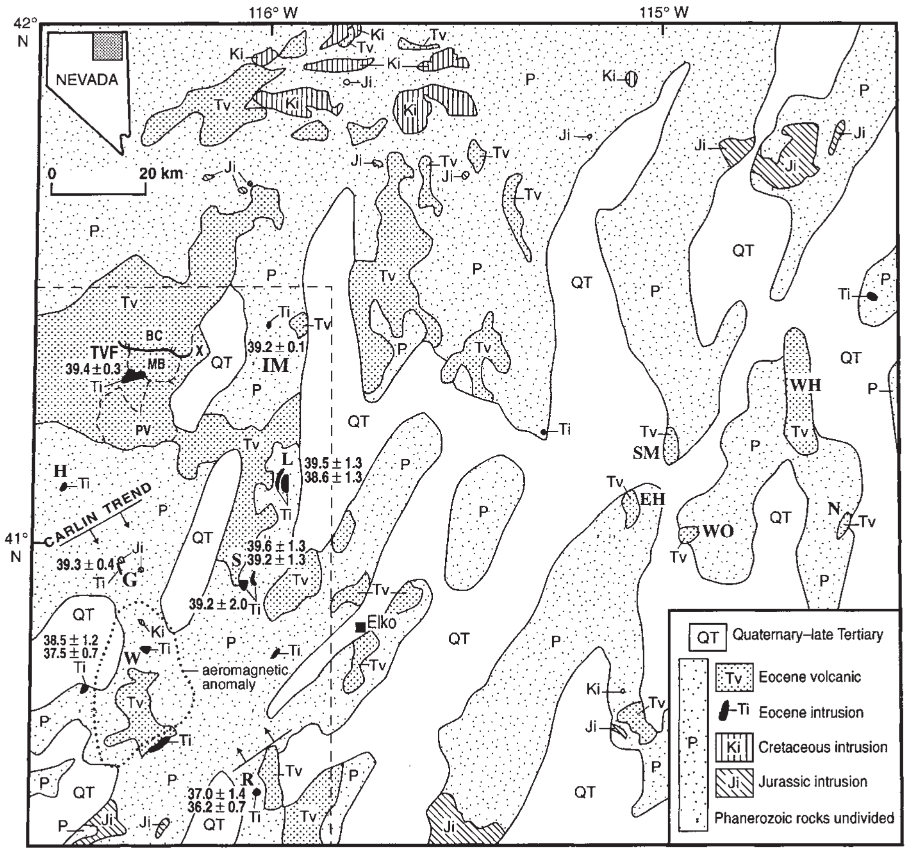

Figure 1. Generalized geologic map of northeastern Nevada showing major gold areas, Carlin trend (G—Goldstrike deposit) and Independence Mountains (IM), in relation to Eocene igneous rocks. Gold deposits are concentrated in area of most intense Eocene magmatism and mostly away from areas of Cretaceous or Jurassic intrusions. Aeromagnetic anomaly (from Hildenbrand and Kucks, 1988) along southwestern edge of Carlin trend indicates large intrusion, probably of Eocene age. Magnetic anomalies are also associated with each of Eocene igneous centers in area but are not shown. TVF—Tuscarora volcanic field (PV, Pleasant Valley volcanic complex; MB, Mount Blitzen volcanic center; BC, Big Cottonwood Canyon caldera; X, Sixmile Canyon lavas); H, Hatter stock; L, Lone Mountain; S, Swales Mountain; W, Welches Canyon; R, Railroad district; EH, East Humboldt Range; SM, Snake Mountains; WO, Wood Hills; WH, Windermere Hills; N, Nanny Creek. Dashed box outlines subarea of Table 2.

Data Repository item 9888 contains additional material related to this article.

INTRODUCTION

Carlin-type deposits in the Great Basin have been intensely studied, yet their origin remains controversial (Sillitoe and Bonham, 1990; Arehart et al., 1993; Kuehn and Rose, 1995; Thorman et al., 1995; Ilchik and Barton, 1997; Oppliger et al., 1997). Controversy centers on the heat source that drove hydrothermal flow and the age of the deposits. Some interpret igneous intrusions to be the heat source (Sillitoe and Bonham, 1990; Arehart et al., 1993; Hofstra, 1995; Thorman et al., 1995; Leonardson and Rahn, 1996; Groff et al., 1997). For example, Sillitoe and Bonham interpret Carlin-type deposits to be distal to porphyry intrusions. Others interpret the heat source to be elevated crustal heat flow related to extension and not to magmatism (Kuehn and Rose, 1995; Ilchik and Barton, 1997); Ilchik and Barton (1997, p. 273) claimed "Carlin-type deposits lack demonstrable time-space links to intrusive centers." Still others consider the heat source to be coupled magmatism and extension (Seedorff, 1991; Oppliger et al., 1997).

The age of Carlin-type deposits is debated because they are difficult to date directly. Host rocks are mostly Paleozoic sedimentary rocks that have undergone multiple episodes of diagenesis, alteration, and metamorphism. The resulting fine-grained alteration minerals are neither easily dated nor clearly tied to gold deposition. Nevertheless, recent work indicates that many formed in the Eocene (Hofstra, 1995; Emsbo et al., 1996; Leonardson and Rahn, 1996; Phinisey et al., 1996; Rota, 1996; Groff et al., 1997). For example, at the giant Goldstrike deposit in the Carlin trend (Fig. 1), a dacitic dike dated as 39.3 ± 0.4 Ma (^{40}Ar/^{39}Ar; biotite) was initially interpreted to be postmineralization (Arehart et al., 1993). Emsbo et al. (1996) found that the dike had locally undergone the same alteration and had the same geochemical enrichment as ore-bearing rocks and concluded that the dike predated ore. Leonardson and Rahn (1996) concluded that this dike was emplaced approximately at the end of mineralization. In the Independence Mountains (Fig. 1), a basaltic dike dated as 40.8 ± 0.1 Ma (^{40}Ar/^{39}Ar; whole rock) is altered and locally contains ore; a weakly propylitized quartz monzonite dike dated as 39.2 ± 0.1 Ma (^{40}Ar/^{39}Ar; hornblende) is outside the main area of alteration and may postdate mineralization (Phinisey et al., 1996). Phinisey and others concluded that ore was deposited contemporaneously with or closely following Eocene magmatism.

What is certain is that the huge Carlin-type deposits require a large-scale process of crustal fluid flow (Christensen, 1996). We argue that this large-scale process was driven by Eocene magmatism, which was widespread in northeastern Nevada, especially in and around the major gold deposits of the Carlin trend and Independence Mountains (Fig. 1), and was the most intense magmatic event of the region. To document the importance of Eocene igneous activity, we briefly describe the geology and geochronology of major igneous centers in the region.

EOCENE MAGMATISM OF NORTHEASTERN NEVADA

That magmatism began in northeastern Nevada about 43 Ma and swept southwestward during the Eocene and Oligocene has long been known (Stewart, 1980). Published $^{40}Ar/^{39}Ar$ and K-Ar ages and our new work in the Tuscarora volcanic field, the largest example of this activity, indicate that magmatism was particularly intense between about 39 and 40 Ma (Fig. 2; Table 1). Although rocks dated by the $^{40}Ar/^{39}Ar$ method are relatively few, every area in which such dating has been performed, including in the Carlin trend and Independence Mountains, indicates that activity was concentrated in this time. Dated rocks are lavas, intrusions, and ash-flow tuffs of intermediate to silicic composition, rock types that erupt or intrude from large, subjacent magma chambers. Sources for the lavas and intrusions must underlie them almost directly. The tuffs may have erupted from more distant sources but are unlikely to have flowed more than ~50 km from source, so eruptive centers were still within northeastern Nevada.

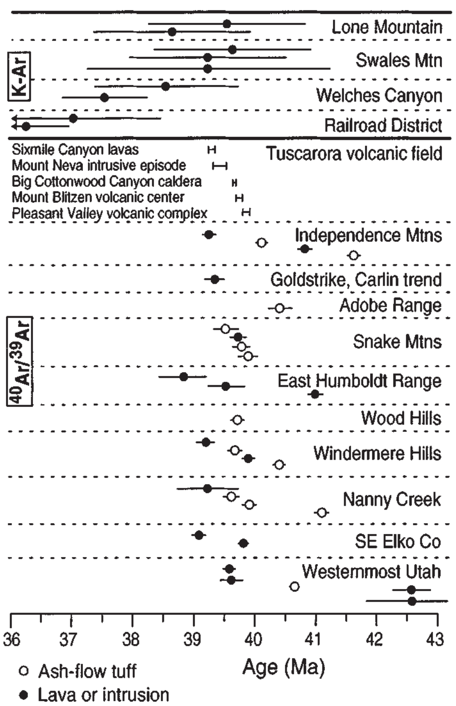

Figure 2. Age plot of Eocene magmatism in northeastern Nevada, including all published $^{40}Ar/^{39}Ar$ ages (Mueller, 1992; Arehart et al., 1993; Hofstra, 1994; Brooks et al., 1995) and K-Ar ages of intrusions near Carlin trend and Independence Mountains. Bars are ±1σ. See Figure 1 for locations. Data for Tuscarora indicate timing of five volcanic centers (Henry and Boden, 1998). Lavas and intrusions have local sources, but ash-flow tuffs may have erupted from sources many tens of kilometers away from dated location.

Tuscarora Volcanic Field

The Tuscarora volcanic field lies just north of the Carlin trend and west of the Independence Mountains (Fig. 1). At least five major igneous centers were active in the southern part of the field during an intense period of magmatism between 39.9 and 39.3 Ma (Figs. 1 and 2;[1] Henry and Boden, 1998). From oldest to youngest, these centers are: (1) an ~16-km-diameter andesitic to dacitic lava pile (39.9–39.7 Ma); (2) a dacitic dome and tuff field that fills an 11 × 6 km basin (39.8–39.7 Ma); (3) a 16-km-diameter rhyolitic ash-flow caldera (39.7 Ma); (4) a three part intrusive episode with early dacite plugs, a granodiorite pluton, and andesitic to rhyolitic dikes (39.5–39.3 Ma); and (5) another andesitic to dacitic lava pile (39.3 Ma).

[1]GSA Data Repository item 9888, $^{40}Ar/^{39}Ar$ data, laser-fusion analyses, and step-heating analyses, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Carlin Trend

Although not prominent in early descriptions of deposits of the Carlin trend, Eocene dikes are abundant there (Arehart et al., 1993; Lauha and Bettles, 1993; Leonardson and Rahn, 1996; Rota, 1996; M. Ressel, 1997, personal commun.). Only the 39.3 Ma dacite dike is confidently dated (Arehart et al., 1993). Other dikes range from andesite to low-silica rhyolite and from unaltered to ore bearing. These dikes are petrographically indistinguishable from dated Eocene dikes at Tuscarora and in Welches Canyon (see following) and unlike older intrusive rocks. Older intrusions in the Carlin trend are the Jurassic (158 Ma; Arehart et al., 1993) Goldstrike diorite, which predated mineralization, and a small (0.26 km^2), Cretaceous granite near Welches Canyon (ca. 108 Ma; Evans, 1980).

Obviously, heat from a few dikes is insufficient to drive major hydrothermal flow. However, silicic to intermediate dikes such as these generally emanate from much larger magma chambers, which are required to generate intermediate to silicic melts by differentiation of parental basalt or melt-

TABLE 1. EOCENE MAGMATISM OF NORTHEASTERN NEVADA

Location, name	Rock types	Age (Ma)*	Reference†
Tuscarora volcanic field		39.9-39.3	1
Sixmile Canyon lavas	Dacite-andesite lava pile	39.3	1
Mount Neva intrusive episode	Dacite, granodiorite, and andesite to rhyolite intrusions	39.5-39.3	1
Big Cottonwood Canyon caldera	Rhyolitic ash-flow caldera	39.7	1
Mount Blitzen volcanic center	Dacite dome and tuff field in 11 x 6 km fault-bound basin	39.8-39.7	1
Pleasant Valley volcanic complex	Dacite-andesite lava pile	39.9-39.7	1
Carlin trend	Andesite to rhyolite dikes	39.3 ± 0.4	2
Independence Mountains	Basalt dike	40.8 ± 0.1	3
	Quartz monzonite dike	39.2 ± 0.1	4
	Rhyolite dikes	?	5
	Andesite tuffs	41.6 ± 0.1 40.1 ± 0.1	2, 3
Areas surrounding Carlin trend			
Hatter stock	Dacite intrusion	Eocene	
Lone Mountain	Quartz monzonite, possible silicic ash-flow tuff and small caldera	*38.6 ± 1.3* *39.5 ± 1.3*	6
Swales Mountain	Porphyritic quartz monzonite and granodiorite	*39.6 ± 1.3* *39.2 ± 1.3* *39.2 ± 2.0*	7
Welches Canyon	Porphyritic dacite and rhyolite; granodiorite	*38.5 ± 1.2* *37.5 ± 0.7*	8
Railroad district	Porphyritic rhyolite, granite, and monzonite	*36.2 ± 0.7* *37.0 ± 1.4*	9, 10

* Regular type: $^{40}Ar/^{39}Ar$ ages. Italicized: K-Ar ages. Tuscarora ages based on 17 $^{40}Ar/^{39}Ar$ ages.

†1, Henry and Boden, 1998; 2, Arehart et al., 1993; 3, Hofstra, 1994; 4, Phinisey et al., 1996; 5, Adams, 1996; 6, Ketner, 1998; 7, Evans and Ketner, 1971; 8, Evans, 1980; 9, Ketner and Smith, 1963; 10, Armstrong, 1970.

ing of crust or both (e.g., Barker, 1981; Anderson, 1990). Therefore, the presence of even a few dacite dikes indicates that a larger intrusion is nearby or below, probably within a few kilometers, a conclusion also reached by Leonardson and Rahn (1996).

Independence Mountains

Both intrusive and extrusive Eocene rocks are present in the Independence Mountains (Figs. 1 and 2; Table 1; Hofstra, 1994; Adams, 1996; Phinisey et al., 1996). Intrusive rocks include the 40.8 Ma basalt dike and 39.2 Ma quartz monzonite dikes discussed here (Phinisey et al., 1996) and undated but mineralized rhyolite dikes (Adams, 1996). Rhyolitic to andesitic ash-flow tuffs have unknown sources; some may have erupted from near Tuscarora.

Igneous Centers Surrounding the Carlin Trend

Eocene igneous centers are particularly abundant around the Carlin trend but few rocks have been dated by the $^{40}Ar/^{39}Ar$ method (Figs. 1 and 2; Table 1). Common porphyritic textures of intrusive rocks and their association with volcanic rocks demonstrate shallow emplacement. Therefore, cooling was rapid and K-Ar ages likely approximate the time of emplacement.

The Hatter stock is a small (2 km^2) porphyritic dacite that cuts Ordovician sedimentary rocks just north of the Carlin trend. No dates are published, but the dacite is petrographically similar to Eocene dacites near Tuscarora and elsewhere.

At Lone Mountain, Paleozoic rocks form a 13 × 8 km dome that is probably underlain by a major intrusion (Ketner, 1998). Exposed intrusions are quartz monzonite dated as about 39 Ma (Fig. 2; Table 1). Porphyritic dacite or low-silica rhyolite containing abundant lithic fragments and possible pumice occupies the core of the dome and may be ash-flow tuff filling a small caldera. Porphyritic dacite and rhyolite dikes are common.

Numerous granodiorite to quartz monzonite stocks and porphyritic dacite dikes intrude and dome Paleozoic rocks over a 20 km^2 area at Swales Mountain (Evans and Ketner, 1971), in a setting much like at Lone Mountain. Three K-Ar dates on larger intrusions are about 39 Ma.

Several 38 Ma granodiorite and quartz latite stocks and numerous dikes crop out in Welches Canyon adjacent to the Carlin trend (Figs. 1 and 2; Evans, 1980). An extensive (~200 km^2), intermediate to silicic volcanic field begins 5 km south of the intrusions; still more intrusions are at the southern end of the field. The volcanic rocks are Eocene (Stewart, 1980) and are likely extrusive equivalents of the Welches Canyon intrusions. A prominent aeromagnetic anomaly coincides with the belt of Eocene intrusive and volcanic rocks (Fig. 1; Hildenbrand and Kucks, 1988). Although Evans (1980) attributed the anomaly to a larger pluton beneath the small Cretaceous intrusion near Welches Canyon, the coincidence of the anomaly with the Eocene rocks suggests that it more likely reflects a large Eocene pluton.

A composite stock (1 km^2), consisting of 36 to 37 Ma granite, monzonite, and rhyolite, and related dikes intrude Mississippian rocks in the Railroad mining district near the south end of the Carlin trend (Ketner and Smith, 1963).

DISCUSSION

In an initial attempt to quantify the intensity of Eocene magmatism, we calculated outcrop areas of Eocene volcanic and intrusive rocks and Cretaceous and Jurassic intrusions for northeastern Nevada and for an area near the Carlin trend and Independence Mountains (Table 2). These data show that Eocene intrusive and volcanic rocks are concentrated near the gold districts where volcanic rocks constitute 31% of exposed bedrock (total area minus Quaternary–late Tertiary alluvium). Although intrusions crop out only locally, magnetic data (Hildenbrand and Kucks, 1988) indicate that they underlie all recognized areas of activity, including those with volcanic rocks and those with dikes such as in the Carlin trend. Exposed intrusions of all ages show major magnetic anomalies. Anomalies around Eocene intrusions are significantly larger than the exposed bodies and total 940 km^2 (22% of bedrock) in the area of gold deposits. Even these data understate the abundance of large intrusions; the 39.7 Ma, 16-km-diameter caldera at Tuscarora has no magnetic expression but must be underlain by an intrusion of similar size (Henry and Boden, 1998). Lack of exposure of large intrusions simply reflects insufficient erosion. Eocene dikes are widespread in the Carlin trend (Arehart et al., 1993; Leonardson and Rahn, 1996; Rota, 1996) and are probably apophyses from Eocene stocks at depth. The dikes could be from a single, large intrusion that underlies the aeromagnetic anomaly shown in Figure 1. Alternatively, other major intrusions underlie the trend but are too deep to be expressed magnetically. Similarly, silicic dikes in the Independence Mountains indicate a large, nearby pluton. In contrast, Cretaceous and Jurassic intrusions are significant away from the gold districts but minor near them (Fig. 1; Table 2).

The data here indicate that large volumes of intermediate to silicic magmas intruded throughout northeastern Nevada in the Eocene (Figs. 1 and 2; see also Brooks et al., 1995). This intense pulse of Eocene magmatism provides an obvious heat source for Carlin-type deposits, i.e., the large-scale process of Christensen (1996). The age data are consistent with either a distinct pulse of activity between 39 and 40 Ma around the Carlin trend and Independence Mountains, or with a southward sweep through this area as is recognized more regionally (Stewart, 1980). These two alternatives offer some interesting implications for the timing of mineralization, whether broadly synchronous or showing a similar age gradient. Given the difficulty in dating mineralization, these alternatives will be difficult to evaluate, but more precise $^{40}Ar/^{39}Ar$ dating of igneous activity in and around the Carlin trend and Independence Mountains is warranted.

Numerous questions remain about Carlin-type deposits. The likelihood that Eocene magmatism was a major heat source does not preclude other episodes of magmatism generating deposits nor does it address the important question of sources of metals and fluids. Nevertheless, no deposits of the Carlin trend and Independence Mountains are demonstrably of any other age, so was Eocene magmatism somehow special?

1. Eocene magmatism appears to have been more intense, both regionally and particularly near gold deposits, than either Jurassic or Cretaceous magmatism (Fig. 1). In the Carlin trend and Independence Mountains, Jurassic and Cretaceous intrusions include only the Goldstrike diorite and the small granite near Welches Canyon (Evans, 1980; Arehart et al., 1993). Intrusions or volcanic centers of all ages are present throughout northeastern Nevada but are not associated with Carlin-type deposits. Oligocene volcanic centers are even more abundant in central Nevada than Eocene centers are in northeastern Nevada (Table 2), but Carlin-type deposits are few. Combined with the obvious concentration of gold deposits in narrow structural belts, these observations indicate that magmatic heat source is not the only factor.

2. Eocene magmatism was geochemically distinct. This would seem important only if magma also provided metals, which is equivocal (Sillitoe and Bonham, 1990; Ilchik and Barton, 1997). No magmatic episode is sufficiently well characterized to evaluate this possibility.

TABLE 2. AREAS OF EOCENE INTRUSIVE AND VOLCANIC ROCKS AND JURASSIC AND CRETACEOUS INTRUSIONS

	Area* of Figure 1			Subarea of Figure 1 near gold districts			Central Nevada 38°-39.5° N, 115.5°-118° W		
Total	37,720	Percentage		7170	Percentage		36,160	Percentage	
QT	18,760	of total	total – QT	2880	of total	total – QT	19,970	of total	total – QT
Ti	65	0.17	0.34	40	0.56	0.93	210	0.58	1.3
Tv	2500	6.6	13.2	1330	18.5	31	9290	25.7	57.4
Ki	278	0.74	1.47	0.26	0	0	290	0.80	1.8
Ji	294	0.78	1.55	28	0.39	0.65	115	0.32	0.71

* All areas in km^2. Ti and Tv in Figure 1 are 43-34 Ma; in central Nevada are 34-17 Ma.

3. Contemporaneous extension facilitated hydrothermal flow (e.g., Seedorff, 1991; Ilchik and Barton, 1997; Oppliger et al., 1997). Extension, locally of high magnitude, is recognized to have begun in northeastern Nevada in the Eocene, approximately contemporaneous with the onset of magmatism (Seedorff, 1991; Brooks et al., 1995). The tectonic setting of Mesozoic magmatism is equivocal but may have been contractional (Arehart et al., 1993). Otherwise, the role of extension in generating Carlin-type deposits is problematic. Although the deposits may have formed during extension, the amount of extension in the Carlin trend contemporaneous with mineralization appears to have been minor. For example, the present-day gentle dip of the Roberts Mountains thrust fault, which formed in the Paleozoic as a regional, subhorizontal fault, indicates negligible total tilting and therefore negligible extension at any time. A significant episode of extension occurred in northeastern Nevada between 35 and 15 Ma (Wallace and John, 1998; Henry et al., 1998). Moderate, post–15 Ma extension is indicated by 20° westward dips of 15 Ma rhyodacitic lavas along the western edge of the Carlin trend (Evans, 1980). However, neither episode can have generated Carlin-type deposits if they formed about 39 Ma. The role of tectonism is a particularly important area for further work.

4. The link between Carlin-type deposits and magmatism may be better elucidated by more detailed comparative studies of sediment-hosted gold deposits in porphyry districts and those that also contain mineralized volcanic rocks. These "Carlin-like" deposits (Seedorff, 1991) may document the bridge between Carlin-type and igneous-related deposits.

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