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Chapter 13

Exploration and Geology, 1962 to 2002, at the Goldstrike Property, Carlin Trend, Nevada

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Abstract

The Goldstrike property, located in the Carlin Trend in Nevada, contains a diverse group of Carlin deposits, including some of the largest and highest grade examples known. The largest deposit, Betze-Post, has a gold endowment of approximately 1,250 metric tons (t) Au, and the Meikle deposit, which contains 220 t Au, has a grade of 24.7 g/t Au. Goldstrike is part of the larger Blue Star-Goldstrike subdistrict, which has an areal extent of 58.5 by 2 km and a total gold endowment of 1,970 t. The first discovery of gold at Goldstrike was in 1962. Subsequent exploration culminated in the discovery in 1986 of large high-grade orebodies beneath smaller, lower grade orebodies. Exploration over a 40-yr period has relied on the evolution in understanding of geology and ore controls, supported by the application of geochemical and geophysical exploration techniques.

The Goldstrike property is located close to the rifted margin of the North American craton, along an inferred deep crustal structure. Stratigraphy at Goldstrike consists of lower Paleozoic sedimentary rocks, including an autochthonous, miogeoclinal carbonate sequence and an allochthonous eugeoclinal siliciclastic sequence, separated by the early Mississippian Roberts Mountains thrust. Multiple periods of deformation are evident, dominated by contraction in the upper Paleozoic to Mesozoic, followed by extension beginning in the Eocene. This has resulted in a complex structural architecture that is a major control on the location, geometry, and size of the orebodies. Intrusive rocks at Goldstrike include a Late Jurassic calc-alkaline suite of diorite, rhyodacite, and lamprophyre and late Eocene calc-alkaline dacite dikes. These dikes, dated at approximately 39 Ma, are coeval with the Carlin gold mineralization and the onset of regional extension.

Gold in unoxidized ore is mainly found within arsenian pyrite and is associated with Hg, Sb, and Tl. The ore fluids were low salinity (<10 wt % NaCl equiv), had homogenization temperatures of 200° to 225°C, and are of meteoric origin. Alteration varies considerably between deposits and includes decarbonatization, argillization, and silicification. Dissolution of carbonate has produced collapse breccias, which often host high-grade ore. Supergene alteration has produced oxide ores, at depths up to 200 m. Mineralization at Goldstrike occurs in a variety of settings, reflecting an interplay of both structural and lithological controls. Structural controls include folds, low- and high-angle faults, particularly where faults intersect, and zones of fracturing and brecciation. Fracturing is enhanced in areas of rheological contrast, such as the contact of the Jurassic dioritic Goldstrike intrusion, which is the first-order control of the large Betze-Post deposit. The north-northwest–striking Post fault system is associated with the highest grade orebodies, such as the Meikle deposit and the Deep Post subdeposit. The majority of economic gold mineralization is hosted by the autochthonous rocks, mainly the limy to dolomitic mudstones of the Devonian Popovich Formation and brecciated limestones and dolomites of the Silurian-Devonian Bootstrap limestone. Lesser amounts are hosted in other autochthonous units and intrusive rocks. Characteristics of the host rocks that are believed to enhance their favorability to gold deposition are the presence of reactive carbonate, porosity, permeability, and the presence of iron, which can be sulfidized to form auriferous pyrite.

Introduction

THE OBJECTIVE of this paper is to provide an overview of the geology and mineralization at the Goldstrike property and provide information on the exploration process, as it evolved over the last 40 yr. Many geologists have contributed to the large body of geologic work conducted at Goldstrike. This paper attempts to summarize their efforts and hopefully will lead to resolution of the many remaining unanswered questions.

The Goldstrike property is located in northeastern Nevada, United States, in the Carlin Trend, a 60-km-long north-northwest alignment of sedimentary rock-hosted gold deposits (Fig. 1). These gold deposits are commonly known as Carlin deposits after the Carlin orebody, which is located 7 km southeast of Goldstrike. The Goldstrike property, owned and operated by Barrick Goldstrike Mines, covers most of the northern part of the Blue Star-Goldstrike subdistrict of the Carlin Trend, as indicated in Figure 2. Newmont Mining is the owner and operator of some of the northern part (Deep Post) and all of the southern part of the subdistrict. The Blue Star-Goldstrike subdistrict is a sin-

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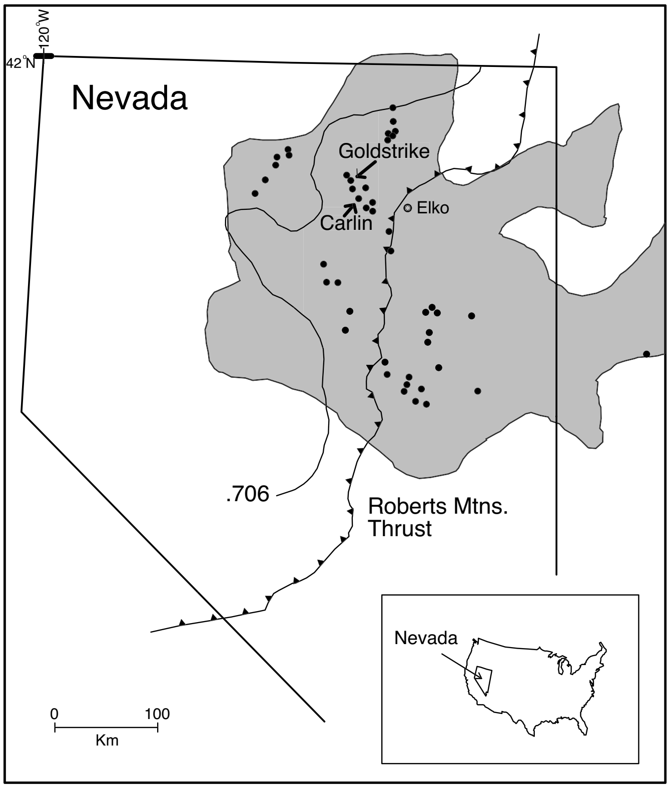

FIG. 1. Map showing location of Carlin gold deposits (black dots). The Carlin Trend is the cluster of deposits, which includes Goldstrike and Carlin. Also shown is their relationship to the Sr_i 0.706 line, Roberts Mountains thrust, and the late Eocene igneous province (shaded). Adapted from Hofstra and Cline (2000) and Ressel et al. (2000b).

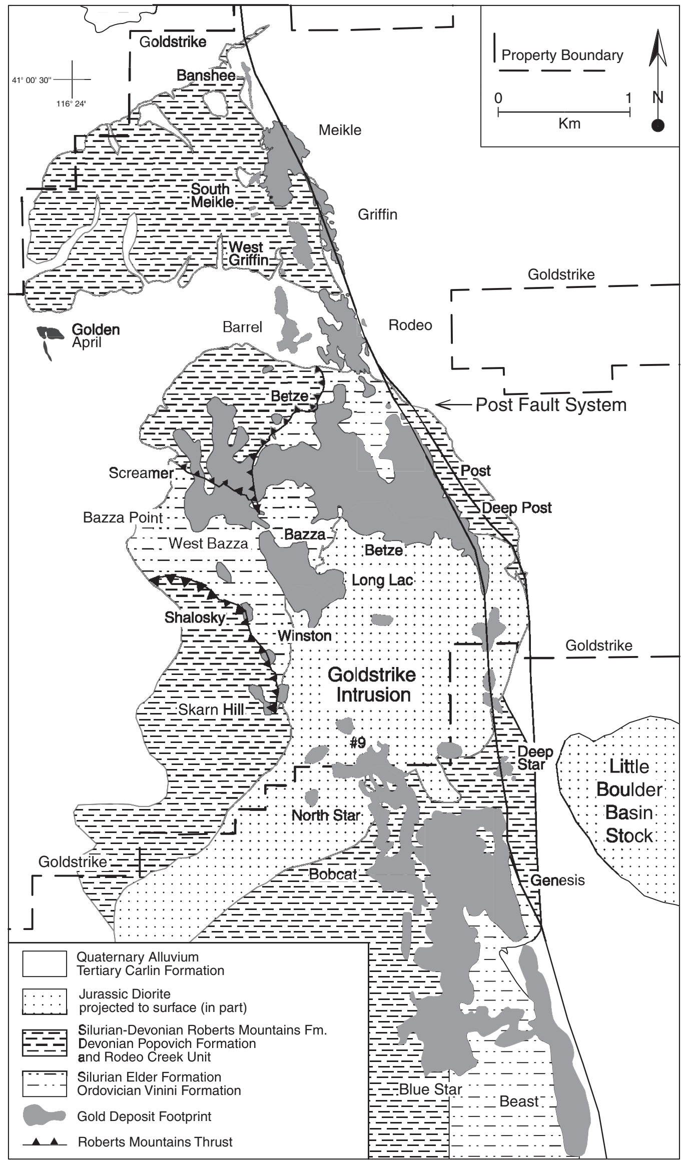

FIG. 2. Gold deposits and subdeposits of the Blue Star-Goldstrike subdistrict of the Carlin Trend, Nevada. The gold deposits and intrusions are projected to surface. The Goldstrike property boundary shows surface ownership only, not mineral ownership, which in the Post and Deep Post areas is dependent on mining method. Modified from Teal and Jackson (1997).

gle contiguous mineralized system and therefore will be described as such in this paper. Betze-Post, the largest gold deposit in the subdistrict and the Carlin Trend, is subdivided into three subdeposits, which are from east to west, Deep Post, Betze, and Screamer. In addition, the previously mined Post deposit (or Post oxide) was located above the Deep Post subdeposit and is therefore part of the overall Betze-Post mineralized system. The orebodies shown in Figure 2, south of the Goldstrike property, are oxidized and were mined from open pits at a low cutoff grade. Therefore, their footprint is exaggerated relative to the refractory and/or underground mineable orebodies to the north.

Total gold endowment in the Blue Star-Goldstrike subdistrict (production, reserves, resources) is approximately 1,970 metric tons (t), with approximately 90 percent of this total located in the northern part of the subdistrict. This places the Blue Star-Goldstrike subdistrict among the largest concentrations of gold on earth. The subdistrict is also notable for its high gold grades, particularly the Meikle and Deep Star deposits and the Deep Post subdeposit (Table 1). Areal extent of the Blue Star-Goldstrike mineralized system, as presently known, is 8.5 by 2 km. Major deposits and approximate gold endowments are Betze-Post, 1,250 t Au; Meikle, 220 t Au; Genesis (including satellite deposits), 155 t Au; Rodeo, 125 t Au; Post, 110 t Au; and Deep Star, 50 t Au (Table 1). Of these, Genesis and Deep Star are owned by Newmont Mining. At December 31, 2000, total production from the Goldstrike property was 592.5 t Au, reserves were 760.5 t Au, and resources were 225.5 t Au, or a total of 1,578.5 t Au. The Goldstrike property comprises approximately half of the total gold endowment in the Carlin Trend. Reserves at the Goldstrike property are subdivided between three operating mines, the Betze-Post open pit, plus the Meikle and Rodeo underground mines. At the end of 2000, reserves at Betze-Post were 105,640,750 t at 5.31 g/t Au, for 559.9 t Au and reserves at Meikle (including Rodeo) were

TABLE 1. Summary of Gold Deposits in the Blue Star-Goldstrike Subdistrict

Deposits and subdeposits	Premining resource Au (t)	Average grade Au (g/t)	Mining and processing	Description
Deep Post	190	20.0	Underground and open pit, autoclave–carbon-in-leach	Large, high-grade orebody in brecciated and highly altered Popovich Formation footwall to the Post fault; proximal to Goldstrike intrusion
Betze	900	7.5	Open pit, autoclave–carbon-in-leach, roaster–carbon-in-leach	Large orebody in fractured-brecciated Popovich Formation, with variable alteration; located along the northern contact of Goldstrike intrusion
Screamer	160	5.0	Open pit, roaster–carbon-in-leach	Western extension of Betze in the Wispy Member of the Popovich Formation; most of the orebody has weak alteration and moderate structural preparation
Post	110	1.7	Open pit, carbon-in-leach, heap leach	Oxidized orebody overlying Deep Post, footwall to Post fault in Post anticline; low-grade ore in fractured-brecciated Rodeo Creek unit
Long Lac, Winston, Bazza deposits, Shalosky, Skarn Hill	12	2.0	Open pit, heap leach	Small oxidized orebodies overlying or to the south of Betze-Post, proximal to the Goldstrike intrusion; low-grade ore is associated with faults in the Rodeo Creek unit
Meikle, South Meikle	220	24.7	Underground autoclave–carbon-in-leach, roaster–carbon-in-leach	Large, high-grade orebody in footwall of Post fault, mainly in silicified, brecciated Bootstrap limestone; South Meikle deposit (~20 t Au) in lamprophyre and Upper Mud Member of the Popovich Formation
Rodeo	125	13.4	Underground roaster–carbon-in-leach	High-grade orebody close to Post fault; upper and lower zones in the Upper Mud and Wispy Member units of the Popovich Formation, respectively; association with lamprophyre dikes, high- and low-angle faults
Griffin, West Griffin, Barrel, Banshee	45	15.0	Underground roaster–carbon-in-leach, Autoclave–carbon-in-leach	Small, high-grade orebodies located in the Meikle-Rodeo corridor in the Rodeo Creek unit and the Popovich Formation; associated with lamprophyres, low- and high-angle faults
Goldstrike stock, Number 9	3	1.4	Open pit, heap leach carbon-in-leach, Autoclave–carbon-in-leach	Small, low grade, oxidized orebodies in low- and high-angle faults in the Goldstrike intrusion (generally just below its upper contact)
Genesis, Blue Star, Beast, Bobcat, Northstar	155	1.0	Open pit, carbon-in-leach, heap leach	Diverse group of oxidized orebodies located to the south of the Goldstrike intrusion; in Popovich Formation and Rodeo Creek unit, which are metamorphosed in part
Deep Star	50	30.0	Underground autoclave–carbon-in-leach	High-grade orebody in tectonic breccias in the Post fault system; in calc-silicate hornfels and diorite of the Goldstrike intrusion

Notes: Deposits are owned by Barrick Goldstrike Mines Inc., with the exception of the Genesis, Blue Star, Beast, Bobcat, Northstar, and Deep Star deposits and parts of the Deep Post and Post orebodies; the premining resources and average grades quoted are approximate and should be used only for relative comparisons of the deposits listed; the estimates are as of December 31, 2000; in general, the estimates are based on cutoff grades related to historical and future mining and processing costs, plus the price of gold; typical cutoff grades are the following: Open pit oxide = 0.3 to 0.5 g/t Au, open-pit refractory = 1.7 to 2.2 g/t Au; and underground refractory = 6.9 to 9.3 g/t Au; the division of the Betze-Post deposit into three subdeposits (Deep Post, Betze, and Screamer) is shown in Figure 8

12,791,304 t at 15.7 g/t Au, for 200.6 t Au. Current annual production is greater than 60 t of gold.

Exploration and Mining History

Prediscovery 1946 to 1961

The earliest gold mining activity in the northern part of the Carlin Trend occurred at the Bootstrap and Blue Star mines prior to the discovery of gold at Goldstrike and indeed earlier than the discovery in 1961 of gold at the Carlin mine, which is located approximately 10 km to the southeast. At Bootstrap, located approximately 5 km northwest of Goldstrike, antimony was discovered in 1918, followed by gold in 1946. Approximately 325 kg of gold was produced in 1957 to 1960. At Blue Star, immediately south of Goldstrike, gold was identified in 1957 in areas that had been mined for turquoise. In 1961, 25 kg of gold was produced until problems with slimes in the ore led to shutdown of the 200-t/d cyanide mill (Coope, 1991; Paul et al., 1993). At Goldstrike, the only evidence of early mining activity is small workings for mercury of unknown age, located along the Post fault zone, south of the Meikle deposit.

Discovery and neglect 1962 to 1974

The first discovery of gold in the Goldstrike property was in 1962 by Harry Ranspot of Atlas Minerals (Bettles, 1989). Soil samples assayed for arsenic identified extensive anomalous areas over many of the later discoveries. Seventeen holes were drilled in 1963, many of which intersected sporadic gold mineralization up to 10.6 g/t Au in siliciclastic rocks. One of these drill holes discovered the Bazza deposit and two others cut mineralization very close to the Number 9 and Winston deposits. Trenching and drilling by Newmont Mining in 1966 discovered low-grade gold in fault zones cutting a diorite intrusion (Goldstrike intrusion). Although this early exploration by both companies had identified significant gold grades, further work was not conducted due to the low gold price. See Table 2 for details of discoveries at Goldstrike.

Rediscovery 1975 to 1977

The increase in the price of gold in 1973 to 1974 led the Nevada Syndicate (funded by Lac Minerals) to reevaluate areas identified by Atlas Minerals. Mapping, rock and soil sampling, and VLF-EM surveys were conducted in several areas in 1975 to 1977, followed by four drill holes. One drill hole intersected the edge of the Skarn Hill deposit and the gold and arsenic soil geochemistry outlined an area of shallow mineralization in the Long Lac and Winston areas. The use of grid soil geochemistry, combined with mapping and sampling of silicified outcrops (jasperoids), proved to be an effective exploration technique for discovering outcropping to shallow gold mineralization hosted in the siliciclastic rocks of the Devonian Rodeo Creek unit. At the same time, using shallow rotary percussion drilling, Polar Resources in 1975, followed by Pancana Minerals in 1976 to 1977, had delineated the Number 9 deposit and several low-grade orebodies within the Goldstrike intrusion to the east of the Nevada Syndicate property. Small-scale production from these deposits was begun by Polar and Pancana, utilizing the new low cost technology of heap leaching. Approximately 100 kg of Au was produced from 1975 to 1977.

Consolidation, exploration, production 1978 to 1986

In 1978, Western States Minerals Corporation entered into a 50/50 joint venture with Pancana Minerals, who had consolidated the various claims and leases in the Goldstrike area. From 1978 to 1986, 7.3 t of Au was produced by the joint venture from 14 separate deposits. During this period the optimization of heap-leach processing led to dramatic reductions in the grade of ore that could be mined. The bulk of the production was from oxidized orebodies in the Rodeo Creek unit, chiefly from the Long Lac, Bazza, and West Bazza deposits, plus some production from deposits within the Goldstrike intrusion.

Exploration was conducted throughout the property, leading to the discovery of small oxide orebodies in the Rodeo Creek unit (West Bazza, Bazza Point, Shalosky) and the Goldstrike intrusion. The large, low-grade, oxidized Post deposit was discovered in 1982 (Morrow and Bettles, 1982; Knutsen et al., 1986). The Post deposit, which occurred partially on the adjacent Newmont property, is the largest deposit in the Rodeo Creek unit, at approximately 110 t of Au. In 1984, Newmont Mining also discovered the large Genesis deposit adjacent to the Blue Star deposit. Exploration at this time was guided by mapping of ore-controlling structures, often outlined by zones of surface silicification. These jasperoids were generally anomalous in gold, arsenic, antimony, and mercury. Soil geochemical grids were expanded but in some cases were completed after discovery of mineralization in the area by drilling. The recognition that distal low-grade gold mineralization occurred along favorable stratigraphy and structure, led to the use of drill hole grade-thickness maps to vector to ore. It was also apparent that mineralization was preferentially located adjacent to the Goldstrike intrusion, often trapped beneath sills, which in some areas extended for several hundred meters from the main intrusive body. An aeromagnetic survey of the northern Carlin Trend delineated the large subsurface areal extent of the Goldstrike intrusion and was useful for district-scale exploration.

Improvements in drilling techniques and equipment allowed cost-effective delineation of orebodies. Nearly all drilling through this period was by conventional rotary or reverse circulation. At this time the stratigraphy at Goldstrike was not well understood. Rocks at surface and in drill holes were believed to be the allochthonous Ordovician Vinini Formation and, hence, depths to the autochthonous lower plate carbonates were speculative. However, in 1986 a 300-m-deep drill hole at the Post deposit had penetrated 60 m of unmineralized limestone, which was recognized as the autochthonous Devonian Popovich Formation. This is the same formation overlying the large, high-grade Carlin deposit, located 10 km to the southeast. Based on this observation, a deep core hole was drilled at Post and the Deep Post deposit was discovered in 1986. This hole intersected 119 m of 6.6 g/t Au from 355 to 474 m. Included within this intercept were two high-grade zones: 7.3 m of 29 g/t Au and 9.1 m of 19 g/t Au. This drill hole was targeted based on the above-mentioned stratigraphic relationships and the presence of a large zone of fractured and mineralized rocks footwall to a large feeder fault, the Post fault (Bettles 1989).

Prior to this discovery, drilling at Goldstrike and Nevada in general had been limited to depths less than about 250 m. This was due to a belief that the size and grades typical of Carlin deposits would preclude open-pit mining to any great depth and the fractured and altered rock mass would limit underground mining. The refractory gold-bearing sulfide mineralization, which had been intersected at depth was an additional factor, as it was known that flotation of the gold-bearing pyrite was not feasible. Therefore high-cost roasting or autoclaving would be required to liberate the gold prior

TABLE 2. Summary of the Discovery of the Gold Deposits in the Blue Star-Goldstrike Subdistrict

Deposit	Year of discovery	Depth (m) below surface	Host rock	Discovery method in addition to geology and drilling
Blue Star	1957	0	Drc, Dp	Sampling for Au in Turquoise mine
Bazza	1963	2	Drc	Soil geochemistry
Goldstrike Stock	1966-83	0-20	Jd	Trenching, soil geochemistry?
Winston	1976	10	Drc, Jd	Soil and/or rock geochemistry
Long Lac	1976	10	Drc	Soil and/or rock geochemistry
Number 9	1977	0	Jd, Dp	Soil geochemistry?
Skarn Hill	1977	50	Drc	Soil and/or rock geochemistry
West Bazza	1981	30	Drc	Jasperoid outcrop, rock and/or soil geochemistry
Bazza Point 1 & 2	1981	0	Drc, Tc	Trenching
Shalosky	1981	0	Drc	Rock geochemistry
Post	1982	90	Drc	Jasperoid outcrop, rock geochemistry
Genesis	1984	0	Dp, Drc	Rock geochemistry
Deep Post	1986	350	Dp, DSrm	Conceptual target beneath Post deposit
Betze	1987	245	Dp, Jd	IP, prior shallow drilling, rock and soil geochemistry
Screamer	1987	280	Dp	IP, prior shallow drilling
Rodeo (Goldbug)	1988	280	Dp, Jl	IP, adjacent soil geochemistry
Griffin	1988	335	Drc, Jl	IP
Deep Star	1988	330	Dp, Jd	IP, jasperoid outcrop, prior shallow drilling
South Meikle	1988	255	Dp, Jl	Jasperoid outcrop, air photo lineament
Meikle	1988	250	DSb, Dp, Jl	Jasperoid outcrop, soil geochemistry, ground mag
Banshee	1990	375	Dp, Jl	Structure, dike outcrop
Barrel	1992	215	Dp, Drc	Structure
West Griffin	1993	220	Drc	Structure, jasperoid

Notes: Deep Post, Betze, and Screamer are subdeposits of the Betze-Post deposit; the Goldstrike stock includes 10 small deposits, hosted by the Goldstrike intrusion; host rocks: Dp = Devonian Popovich Formation, Drc = Devonian Rodeo Creek unit, DSb = Silurian-Devonian Bootstrap limestone, DSrm = Silurian-Devonian Roberts Mountains Formation, Jd = Jurassic diorite, Jl = Jurassic lamprophyre, Tc = Tertiary Carlin Formation; host rocks at Deep Star, Number 9, and part of the Genesis deposit have been metamorphosed to calc-silicate hornfels and minor skarn; rock geochemistry is mostly from silicified outcrops (jasperoids); rock and soil samples were generally assayed for Au, As, Sb, Hg, with the exception of the 1960s (As and Cu) and the 1970s (Au and As); induced polarization (IP) anomalies are believed to be largely due to carbon and barren pyrite above the gold mineralization; the Rodeo, Griffin, Meikle, and Barrel deposits are completely or largely covered at surface by the postmineral Tertiary Carlin Formation

to cyanidation. However, the grades in the first drill hole at Deep Post were sufficient to significantly reduce skepticism and raise enthusiasm.

Deep exploration, production acceleration 1987 to 1995

In January 1987, American Barrick Resources acquired the Goldstrike property from the Western States-Pancana joint venture for a total cost of $62M. Reserves at the Post deposit at this time were 10,314,000 t of oxide ore at a grade of 1.9 g/t Au, totaling 19.5 t of Au. An aggressive deep drilling program outlined the large, high-grade Deep Post orebody, which was subsequently found to continue onto the adjacent property owned by Newmont Mining. Exploration drilling in 1987 to 1988 led to the discovery of a number of other deposits similar to Deep Post hosted in the Popovich Formation. These included Betze and Screamer, which together with Deep Post, comprise the Betze-Post orebody. Other discoveries in 1987 to 1988 included Deep Star, Rodeo, Meikle (previously named Purple Vein), South Meikle, and Griffin. All these deposits were located at 245 to 335 m below the surface (Table 2). Exploration and drill targeting relied on a number of techniques: geologic mapping (including pit mapping), presence of jasperoids, results from prior shallow drilling, and soil and rock geochemistry. The property was surveyed with pole-dipole induced polarization (IP)-resistivity and the IP (chargeability) anomalies detected were an important component of the drill hole targeting process.

Through 1987 to 1988, a drilling campaign of 196 drill holes (110,000 m) expanded reserves at Betze-Post to 473 t of Au, leading to a production decision in late 1988. This rapid delineation program was accomplished mainly with reverse circulation drilling, at depths greater than previously attempted with this drilling method. Early recognition that the orebody was located immediately outboard of the calc-silicate hornfels zone of the Goldstrike intrusion also facilitated the delineation program. Although most of these reserves were greater than 250 m below the surface, the size, grade, and tabular geometry of the Betze-Post orebody, plus the overlying relatively shallow oxidized Post deposit, allowed economic development by open pit.

Exploration continued, with emphasis shifting to reserve development at the Meikle deposit, following a drill hole into the heart of the orebody in 1989, which intersected 135 m of 16.1 g/t Au from 413 to 548 m. This drill hole was targeted in an area of surface silicification, weak arsenic anomalies in soils, and a structural intersection defined by mapping and ground magnetics. By 1991, reserves at Meikle of 150 t of Au, at a grade of 21.6 g/t Au, resulted in a decision to develop a 2,000 t/d underground mine. At Meikle, core drilling was used through the mineralized section, due to the prevalent silicification and to obtain a better sample for assay and geology. This also led to an appreciation of the importance of breccias as ore hosts. Following delineation drilling at Meikle, expansion of reserves continued at Betze-Post, with the addition of the West Betze and Screamer zones. The Banshee deposit was also discovered by Newmont Gold and the West Griffin and Barrel deposits by Barrick Goldstrike Mines.

Production of gold rose rapidly at Goldstrike from 1987, reaching 60 t in 1994, mined from the Betze-Post pit. Initial production from the Betze-Post pit was oxide ore from the Post deposit, which was processed by heap leach (36 t Au total production) and a 6,000-t/d carbon-in-leach mill (20 t Au total production). From 1990 to 1993, as the oxide reserves were depleted, six autoclaves, with a total capacity of 17,000 t/d, were brought on line to oxidize the refractory sulfide ore, prior to cyanidation through an expanded carbon-in-leach circuit. Also during this time period, a large dewatering program was initiated, which eventually lowered the water table in the Goldstrike area by 520 m. By the end of 1993, one billion dollars had been invested in the development of the Goldstrike property.

Underground exploration, production 1996 to 2002

Drilling from surface continued to replace open-pit reserves in the Screamer area of the Betze-Post deposit, to outline underground mineable resources at the Rodeo deposit, and to explore the Goldstrike property. With completion of shaft access at Meikle in 1995 and Rodeo in 1998, underground drilling focused on exploration and reserve development in the Meikle, Rodeo, and Griffin areas. Improved understanding of the autochthonous stratigraphy, combined with detailed structural interpretations, were emphasized in this period. Downhole multielement geochemistry and various geophysical techniques also became more important for the development of exploration targets.

In 1999, a land exchange with Newmont Mining further consolidated the Goldstrike property under Barrick Goldstrike Mines ownership. Production continued from the Betze-Post and Meikle deposits at about 60 to 70 t Au/yr. In 2,000, a 12,000-t/d fluid bed roaster was commissioned to process carbonaceous refractory ore, which will be mined mainly from the western part of the Betze-Post pit and the Rodeo underground mine. By the end of 2,000, a total of $133M had been invested in exploration and reserve development by Barrick Goldstrike Mines at the Goldstrike property.

Geology

Previous geologic work

There are numerous publications on various aspects of the geology of the Goldstrike property. As the emphasis in this paper is on the exploration process and recent geologic information, the reader is referred to the papers cited for additional details of the geology and mineralization. External to Goldstrike, papers on the geology of the Carlin Trend include Christensen (1995), Teal and Jackson (1997), Peters (2000), and Moore (2001). Additional papers on the geology of the Genesis and Deep Star deposits include Drews-Armitage et al. (1996), Williams (1997), and Clode et al. (1997).

Regional geologic setting

The Goldstrike property is located at the northern end of the Carlin Trend, inboard of the inferred western margin of the Precambrian North American craton, as defined by the Sri 0.706 isopleth for Mesozoic and Tertiary granitic rocks (Farmer and DePaolo, 1983; Fig. 1). This margin was established by rifting in the Late Proterozoic (Stewart, 1980). A westward-thickening passive margin sequence was deposited, consisting of Upper Proterozoic to Cambrian terriginous clastics followed by Upper Cambrian to lower Mississippian miogeoclinal carbonates to the east and eugeoclinal siliciclastics of equivalent age to the west. The carbonate sequence was floored by Precambrian continental crust that was cut by normal faults as it was thinned during rifting (Wooden et al., 1998; Tosdal et al., 2000). Lead and strontium isotope studies indicate that the Carlin Trend lies at a significant crustal boundary, suggestive of a major crustal fault or suture, with transitional thinned and underplated continental crust to the west and little modified continental crust to the east. The presence of a deep crustal structure associated with the Carlin Trend is supported by magnetotelluric data (Rodriquez, 1998) and to some extent by regional gravity (Grauch et al., 1995; Hildenbrand et al., 2000). This major crustal fault established during Late Proterozoic continental breakup has an enigmatic expression at surface but has influenced Phanerozoic sedimentation, tectonics, and several episodes of igneous and hydrothermal activity (Hofstra and Cline, 2000).

Contraction during the Early Mississippian Antler orogeny thrust the western euogeoclinal Paleozoic siliciclastic sedimentary rocks over the eastern miogeoclinal carbonate rocks, along the Roberts Mountains thrust. A foredeep basin (overlap sequence) developed east of the Antler highland, though these upper Paleozoic sediments are not seen in the Goldstrike area. Several periods of contraction followed in the late Paleozoic and Mesozoic (Fig. 3). Deformation related to some of these events is observed in the Carlin Trend. Three periods of intrusive activity occur along the Carlin Trend, Late Jurassic, Cretaceous, and late Eocene (Ressel et al., 2000b). At Goldstrike the Late Jurassic intrusions are key elements in the localization of ore and the late Eocene intrusions, though smaller, are believed to be coeval with gold mineralization (Emsbo et al., 1996; Ressel et al., 2000a). Intrusive rocks of Cretaceous age have not been documented at Goldstrike.

In the late Eocene, the preexisting contractional regime changed to an east-west or west-northwest, east-southeast extension. Also in the late Eocene to early Oligocene, an extensive belt of calc-alkaline magmatism swept southwesterly through Nevada. This magmatic and tectonic activity may have been influenced by the hot buoyant Yellowstone mantle plume, which was overridden by the westerly migrating, convergent margin of the North American plate

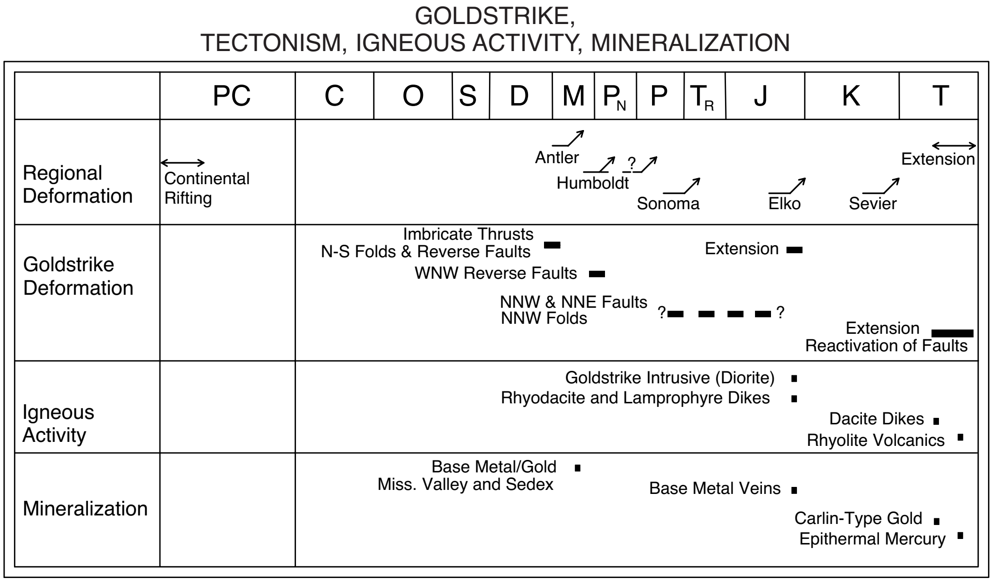

FIG. 3. Summary of tectonism, igneous activity, and mineralization at the Goldstrike property, in the context of regional tectonics. Adapted from Sampson (1993), Orobona (1996), and Hofstra and Cline (2000).

(Oppliger et al., 1997; Murphy et al., 1998). A spatial and temporal association between late Eocene intrusive and/or volcanic rocks, onset of extension, and formation of Carlin gold deposits in northeast Nevada was documented by Seedorf (1991). Extensive age determinations of Eocene intrusive rocks and their relationships to gold mineralization has reinforced this association (Henry and Boden, 1998; Hofstra et al., 1999; Henry and Ressel, 2000). Regional extension continued in the Miocene, accompanied by bimodal magmatism. Many of the gold deposits in the Carlin Trend, including the upper levels of the orebodies at Goldstrike, were sufficiently eroded by the late Miocene to undergo supergene oxidation.

Age of mineralization

The age of gold mineralization at Goldstrike has been a subject of controversy, with dates from Jurassic to Eocene being proposed. Direct dating of the mineralization is difficult, as there are few dateable minerals cogenetic with the gold and because gold mineralization is often superimposed on rocks altered by older hydrothermal events (Hofstra and Cline, 2000). However, dating of galkhaite, a complex Hg-Tl-Cs sulfosalt, associated with gold mineralization at the Rodeo deposit yielded an Rb-Sr isochron age of 39.8 ± 0.6 Ma (D. Tretbar, oral. commun. 2001).

Biotite from a porphyritic dacite dike (BFP dike) at the Deep Post deposit yielded a late Eocene age of 38.8 ± 0.4 Ma by $^{40}Ar/^{39}Ar$ (Arehart et al., 1993a). Detailed mineralogical, geochemical, and isotopic studies identified that the dike locally contains gold values of 0.9 to 4.1 g/t Au and has been subjected to the same mineralizing event that produced the orebodies at Goldstrike, thereby constraining the maximum age of mineralization (Emsbo et al., 1996, 1999). Similar dacite dikes occur along the Post fault zone at the Rodeo, Griffin, and Meikle deposits. At Griffin, the dike yielded a biotite $^{40}Ar/^{39}Ar$ age of 39.21 ± 0.12 Ma (Ressel et al., 2000a) and a zircon U/Pb age of 38.1 ± 0.8 Ma (Mortensen et al., 2000). The dikes at Griffin and Meikle are altered and variably mineralized up to 9 g/t Au. Dating of illite from the gold-bearing dacites yielded $^{40}Ar/^{39}Ar$ ages of 40 to 46 Ma, slightly older than the age of the dike, which probably indicates that alteration and mineralization are Eocene in age (Ressel et al., 2000a). A similar age has been proposed for the Beast deposit, located at the southern limit of the Blue Star-Goldstrike subdistrict (approx 3 km from Goldstrike), where approximately 50 percent of the low-grade gold ore (7.3 Mt at 0.7 g/t) was hosted in a 37.3 Ma rhyolite dike (Ressel et al., 2000b).

Although the age of economic gold mineralization at Goldstrike is coeval with the late Eocene dikes at approximately 39 Ma, there is also evidence for earlier gold and base metal mineralization. Volumetrically minor polymetallic auriferous veins are associated with the Late Jurassic Goldstrike intrusion (Emsbo, 1999; Emsbo et al., 2000). Also identified at Goldstrike is stratiform gold and base metal mineralization, which is inferred to be synsedimentary (Devonian), based on the absence of associated alteration and overprinting by compaction and diagenetic features (Emsbo et al., 1999; Emsbo, 2000).

Stratigraphy

The autochthonous rocks at the Goldstrike property consist of Ordovician to Early Upper Devonian carbonate rocks and Upper Devonian siliciclastic rocks. The sequence is subdivided into the Hanson Creek Formation, Roberts Mountains Formation, and the informally named Popovich Formation, Bootstrap limestone, and Rodeo Creek unit (Fig. 4). Of these, only the siliciclastic Rodeo Creek unit crops out at the surface. These rocks were deposited in an outer shelf, slope to basin environment (Armstrong et al.,

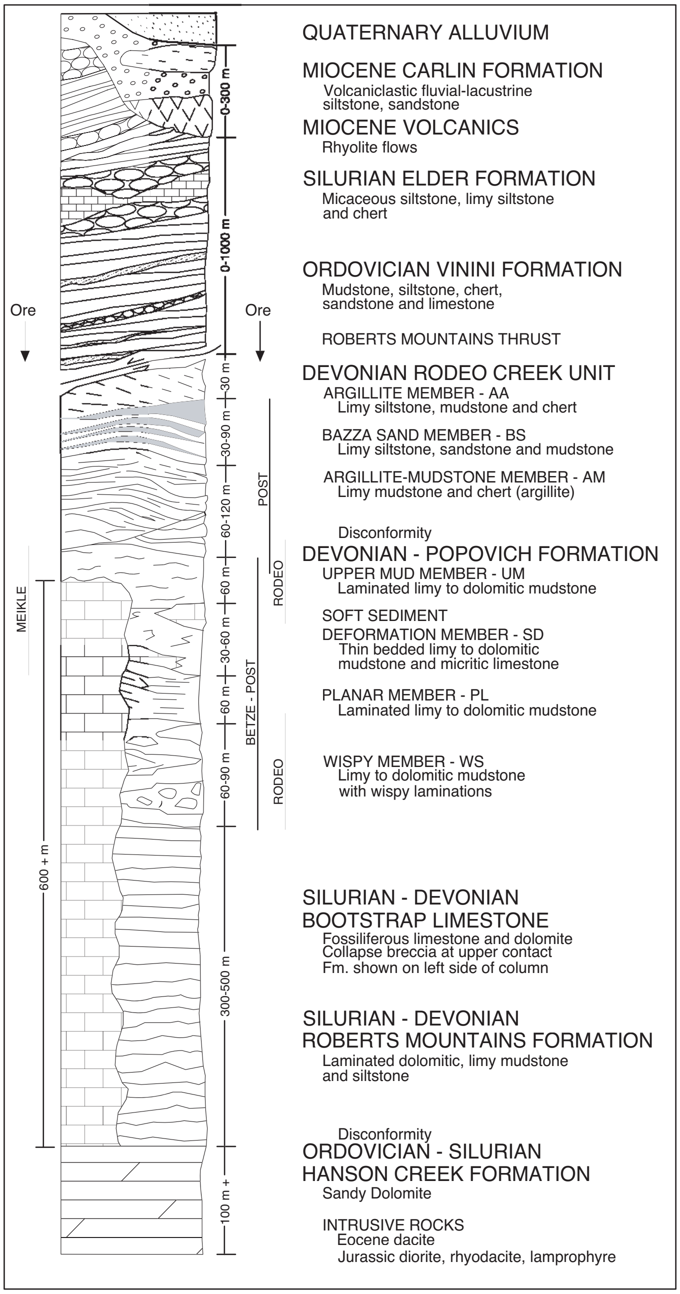

FIG. 4. Stratigraphic column of the Goldstrike property, showing relationship of major orebodies and stratigraphic units. Modified from Bettles and Lauha (1991) and Volk et al. (2001).

1998). Allochthonous siliciclastic rocks of the Ordovician Vinini Formation and the Silurian Elder Creek Formation occur above the Roberts Mountains thrust. Miocene rhyolite and the Miocene Carlin Formation rest unconformably on the Paleozoic rocks.

The following descriptions will emphasize the autochthonous sequence, as it is the primary host for gold mineralization. Detailed drill hole logging and stratigraphic correlation by Barrick Goldstrike Mines geologists (Volk and Zimmerman, 1991; Griffin, 2000), plus petrographic work and facies analyses (Armstrong et al., 1998; Furley, 2001), have vastly improved the understanding of the carbonate rocks at Goldstrike. In the past, the autochthonous carbonates at Goldstrike have been described as limestones or various limy clastic rocks. However, the sequence is partially dolomitic. Much of the dolomite is diagenetic, but some may be caused by circulating, hot basinal brines after burial and compaction. The Roberts Mountains Formation, Popovich Formation, and Rodeo Creek unit are carbonaceous and also contain diagenetic pyrite. The carbon is derived from thermally altered hydrocarbons (Armstrong et al., 1998), with the highest concentrations being in the Popovich Formation, particularly the uppermost member.

At Goldstrike only the upper part of the Ordovician to Lower Silurian Hanson Creek Formation has been observed in deep drill holes. It is an arenaceous dolostone deposited in a shallow-water, shoal environment. Following a 3- to 5-m.y. depositional hiatus (Matti and McKee, 1977), the Silurian-Devonian Roberts Mountains Formation was deposited on the eroded Hanson Creek surface. It is a laminated dolomitic lime mudstone to siltstone, deposited as a turbiditic anoxic basinal facies.

In the northern part of the Goldstrike property, a sequence of fossiliferous limestones and dolomites were deposited on a shelf as a shoal and reef facies (Armstrong et al., 1998). This sequence of shelf carbonates ranges in age from the Lower Silurian to Lower Devonian (Lower Emsian; Armstrong et al., 1998). It is the lateral time equivalent to the basinal facies of the Roberts Mountains Formation. The shelf margin has an approximate N 50° W strike with the basinal facies deposited to the south. Limited drill hole information indicates a thickness of 640 m of the massive shelf carbonates near the Meikle deposit. An appropriate name for this sequence presents problems. Previously at Goldstrike, it has been named the fossiliferous massive limestone of the Roberts Mountains Formation. Generally in the Carlin Trend it is named the Bootstrap limestone, although the 275-m-thick sequence at the type locality (Bootstrap mine) is restricted to the Lower Devonian (Evans and Mullens, 1976; A. Harris, writ. commun., 2001) and is an apron facies of the shoal and reef facies. The author proposes that the informal name Bootstrap limestone be used for this sequence of Silurian-Devonian shoal and reef carbonates observed in drill holes in the Carlin Trend, although it is the equivalent of the Lone Mountain Dolomite, which is recognized as the lateral reef facies of the Roberts Mountains Formation (Coates, 1987). The Bootstrap limestone was at times emergent, resulting in dolomitization, cementation, and karstification. At the contact with overlying units of the Popovich Formation, there is commonly a zone of dissolution and collapse breccia of hydrothermal origin, which may follow earlier areas of karst formation.

The Lower to Early Upper Devonian Popovich Formation is also mainly time equivalent to the Bootstrap limestone, as the lower three of its four members laterally pinch out onto the Bootstrap limestone or its apron facies (Griffin, 2000). In general, the Popovich Formation is composed of carbonaceous, calcareous, and dolomitic mudstone, with the carbonate component varying from 15 to 40 vol percent of the rock. Much of it was deposited as distal turbidity currents in a progressively deepening slope to basin environment adjacent to the Bootstrap carbonate shelf. The members of the Popovich Formation at Goldstrike from the base upward are described below.

The Wispy Member is a laminated limy to dolomitic mudstone that has distinctive wispy laminations, due to bioturbation by burrowing organisms. They indicate that deposition occurred in a shallow oxygenated environment. Descriptions of this member have previously included sedimentary breccias (debris flows) with clasts from the adjacent Bootstrap shelf sequence. Recent work by Furley (2001) has included the debris flows in a separate apron facies, which is described briefly below. It should be noted that the lowermost unit of the Popovich Formation (Wispy Member) is assigned to the Upper Roberts Mountains Formation by Newmont Mining. This has caused some confusion, as this unit is generally the best host rock for gold mineralization throughout much of the Carlin Trend, including the Carlin deposit.

The Planar Member is a laminar limy to dolomitic mudstone. The lack of bioturbation indicates a deeper anoxic environment of deposition than the Wispy Member, following the onset of transgression. Just below the contact with the overlying unit a graptolite zone (*monograptus hercynicus sp.*) represents a zone of very slow to nondeposition, related to a maximum flooding surface.

The Soft-Sediment Deformation Member is composed of thin- to thick-bedded limy to dolomitic mudstone and micritic limestone. The deformed bedding and occasional debris flows indicate slumping of carbonate muds that were deposited rapidly on the slope of the Bootstrap shelf.

The Upper Mud is a laminated limy to dolomitic mudstone. The upper part contains thin concordant laminations of pyrite (pinstripe pyrite) and minor sphalerite, chalcopyrite, and tetrahedrite, enclosed in unaltered sedimentary rocks. Emsbo et al. (1999) documents that these sulfides are auriferous at the Rodeo deposit. The Upper Mud is the only member of the Popovich Formation that extensively covers the Bootstrap limestone, indicating drowning of the shelf environment (Griffin, 1999, 2000).

Recent work by Furley (2001), using a sequence stratigraphic framework, distinguishes an apron facies deposited at the base of slope of the Bootstrap carbonate shelf. It is time equivalent to the lower three members of the Popovich and at least the upper part of the Roberts Mountains Formation. The apron facies is composed of interbeds of the basinal facies, bioturbated facies (Wispy Member), and debris flows with clasts of Bootstrap shelf material. These debris flows had well-developed primary porosity, which made them permeable to later hydrothermal fluids.

Following a depositional hiatus of up to 6 m.y. (G. Griffin, oral commun., 2001), the Upper Devonian Rodeo Creek unit was deposited in the Popovich Formation. It is a siliciclastic unit composed of argillite (siliceous mudstone) with interbedded limy to dolomitic siltstone, fine-grained sandstone, and minor limestone. At Goldstrike it can be divided into three subunits. A lower argillite-mudstone, a middle siltstone-sandstone with mudstone-argillite (Bazza sand), and an upper siltstone-mudstone with argillite and minor limestone. The sequence is variably calcareous to dolomitic and was deposited in an anoxic basinal environment.

The allochthonous rocks above the Roberts Mountains thrust at Goldstrike include cherts, siltstone, mudstone, sandstone, argillite, and minor limestone. These rocks have previously been described as the Ordovician Vinini Formation, but graptolite and radiolarian dates indicate that imbricate slices of the Silurian Elder Formation are included in the allochthon. The Miocene Carlin Formation, consisting of lacustrine and fluvial tuffaceous sediments and airfall tuffs, was deposited in pull-apart basins (Theodore et al., 1998). To the west of the mine area the Carlin Formation is underlain by rhyolite that is also believed to be of Miocene age (Theodore et al., 1998).

Intrusive rocks

The oldest intrusive rocks in the Goldstrike area are represented by a calc-alkaline suite, which was emplaced over a relatively short time interval in the Late Jurassic, from about 158 to 157 Ma (Arehart et al., 1993a; Emsbo, 1999; Mortensen et al., 2000; Ressel et al., 2000a). They consist of the dioritic Goldstrike intrusion, highly altered rhyodacite, and lamprophyre dikes. Crosscutting relationships generally indicate they were emplaced in the order listed above. All of these intrusive rocks host ore. The Goldstrike intrusion crops out to the south of the Betze-Post deposit. In the subsurface, it extends approximately 4 km to the southwest. Extending a similar distance to the southeast are two intrusions of similar composition and age, the Little Boulder basin stock shown in Figure 2 and the Vivian stock, located farther east. The Goldstrike intrusion is a massive sill-like body that thickens to greater than 600 m as it dips to the southwest. To the northeast it rises updip, as sills along formational contacts, above part of the Betze-Post deposit. A thermal metamorphic aureole of diopside hornfels (after carbonate rocks) and quartz hornfels (after siliciclastic rocks) extends up to 200 m and marble extends up to 500 m from the intrusion. There is a limited zone of metasomatic exoskarn in the carbonates and endoskarn in the intrusion (Walck, 1989). The metamorphic aureole is more extensive to the south of the Goldstrike intrusion in the Genesis area.

The rhyodacite dikes occur along many faults, including the Post fault zone as far north as the Meikle area, where they were previously described as monzonites. They are generally highly altered to sericite and quartz. Lamprophyre dikes are found throughout the northern part of the Carlin Trend. At Goldstrike, they generally follow north-northwest–striking high-angle faults or occur as sills along bedding and formational contacts. They generally have phenocrysts of hornblende (vogesite) or phlogopite (minette) and are usually highly altered (Emsbo, 1999). The lamprophyre dikes indicate the presence of deep structures that penetrated to the mantle, in the Late Jurassic.

Late Eocene calc-alkaline dacite to rhyolite dikes dated at 40.1 to 37.3 Ma (Ressel et al., 2000a) occur throughout the northern part of the Carlin Trend, though they are much less abundant than Jurassic intrusive rocks. They are most common in the southern part of the Blue Star-Goldstrike subdistrict, closer to a large positive aeromagnetic anomaly located south of the Carlin mine. Textures in the dikes and elevations of Eocene volcanic rocks to the south are consistent with shallow emplacement (Ressel et al., 2000b). At Goldstrike, porphyritic dacite dikes (biotite feldspar porphyry), which are coeval with the gold mineralization, are found along the Post fault zone from Betze-Post to Meikle.

Structural geology

Structures on the Goldstrike property record a complex history of multiple periods of contractional and extensional deformation. Reactivation of preexisting faults makes it difficult to establish a structural paragenesis, although Jurassic and Eocene intrusions and the Miocene Carlin Formation do provide some key constraints (Volk et al., 2001). As described below, Paleozoic through Mesozoic deformation is characterized by contraction, with periods of relaxation and extension. This is followed by extension beginning in the Eocene (Fig. 3). For detailed descriptions of the structural geology of Goldstrike the reader is referred to Volk et al. (2001).

At Goldstrike, early faults have been reactivated during successive periods of deformation and as most faults were formed prior to mineralization, structural ore controls are diverse and complex. Fault geometries have been influenced by rheological boundaries, such as the contact of the Goldstrike intrusion and the margin of the Bootstrap limestone. High-angle faults generally strike from N 70° W to N 30° E and usually have apparent normal displacement or in some cases apparent reverse displacement. Low-angle faults strike N 70° W to N 30° E and usually show evidence of reverse displacement. Oblique movement, due to accommodation of extension on preexisting faults, is observed on fault surfaces. Map-scale folds strike north-northwest to west-northwest. At the east end of the Betze-Post deposit, the east limb of the north-northwest–trending Post anticline is steepened and truncated by the north-northwest–striking Post fault system (Fig. 5). The west limb is stepped down to the west by a series of north-northwest–striking normal faults of moderate to small displacement. The east-dipping Post fault system has an apparent normal displacement of 800 to 1,600 m, part of this displacement being prior to emplacement of the Late Jurassic Goldstrike intrusion.

Structural fabrics established during rifting and development of the Late Proterozoic continental margin have influenced geometries of depositional basins in the Paleozoic, as indicated by the N 50° W-trending margin of the shelf carbonates of the Bootstrap limestone. The margin of these massive shelf carbonates appears to influence subsequent deformation in the Goldstrike area. The presence of Devonian base metal mineralization in the Rodeo and Meikle areas also suggests early development of synsedimentary faults that were conduits for mineralizing fluids (Emsbo et al., 1999; Griffin, 2000). Structures related to the Antler orogeny at Goldstrike are the Roberts Mountains thrust and related imbricate thrusts and mesoscopic folds in its upper and lower plates. The presence of thrust faults within the lower plate raise the possibility that the lower plate sequence may be parautochthonous. Reverse faults striking north to northeast, dipping 25° to 45° W are also believed to be related to the Antler east-southeast–directed contraction.

Folds and faults that formed subsequent to Antler contraction and prior to the emplacement of the Late Jurassic Goldstrike intrusion appear to be due to several different events, the relative timing of which is somewhat uncertain. Reverse faults striking west-northwest and dipping northeast at 25° to 50° (e.g., Dillon fault zone) and folds of similar orientation may have formed during the south-southwest–directed contraction of the Late Paleozoic Humboldt orogeny. Theodore et al. (1998) documents the Coyote thrust, located 10 km to the north of Goldstrike, as part of this event and cites evidence of south-directed contraction in the Late Paleozoic throughout northeastern Nevada, including the Carlin Trend. North-northwest–trending map-scale folds, such as the Post anticline and north-northwest steep to moderate dipping reverse faults, have formed during a contractional event of uncertain age. North-northwest–striking, steep- to moderate-dipping faults, with apparent normal displacement, may have originally formed as reverse faults during this contraction, as indicated by drag folding (Sampson, 1993). These folds and faults may be as old as the Late Permian-Early Triassic Sonoma orogeny or as young as the Late Jurassic Nevadan or Elko orogenies. The presence of Late Jurassic dikes along these faults indicates that they are of Mesozoic age or older. Irrespective of their age, the north-northwest–striking faults and folds are important ore controls. North-northeast–striking, northwest-dipping faults are also important ore controls and may also have formed in the Mesozoic.

Fault kinematic analysis indicates two periods of extension prior to the emplacement of the Late Jurassic Goldstrike intrusion (Miller 1995). The presence of Late Jurassic lamprophyres preferentially along north-northwest–striking structures indicates a deep-seated west-southwest, east-northeast extension following the emplacement of the Goldstrike intrusion. However, low-angle reverse faults, which cut the Goldstrike intrusion in the Genesis area, are also intruded by Late Jurassic lamprophyres, indicating contraction shortly after emplacement of the intrusion (Orobona, 1996).

In the late Eocene east-west extension reactivated preexisting structures. The age of this extension is constrained by late Eocene dikes in fault zones at Goldstrike and the extension direction is indicated by fault kinematic analysis (Miller, 1995). These relationships are compatible with regional studies (Seedorff, 1991; Henry et al., 2001). Most of this extension has been accommodated by normal to oblique slip on preexisting structures. Extension of similar orientation continued through the Miocene, although it should be noted that the lack of extensive tilting indicates

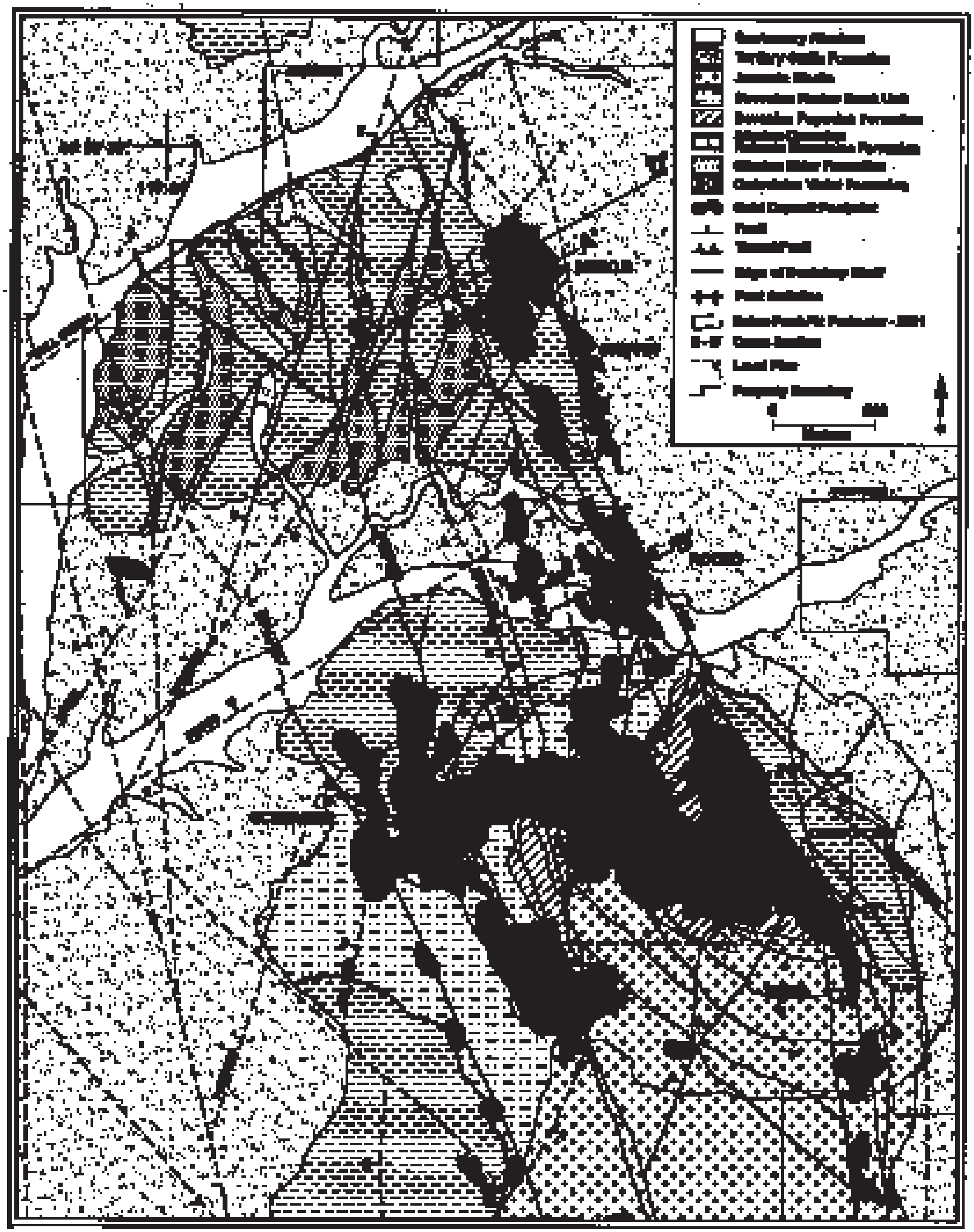

FIG. 5. Simplified geologic map of the Goldstrike property. Geology inside the Betze-Post pit is from pit exposures. Gold deposit footprints and the edge of the Bootstrap shelf carbonate rocks are projected to surface. The Goldstrike property boundary shows surface ownership only. The locations of cross sections and level plans are indicated.

the total amount of extension has been modest in the vicinity of the Carlin Trend (Henry et al., 2001).

Breccias

Breccias are often associated with gold mineralization at Goldstrike and in general are the host to the highest grade orebodies. They are the dominant ore host at the Meikle deposit, the Deep Post and Betze subdeposits, the lower zone of the Rodeo deposit, and at the Deep Star deposit, in the southern part of the subdistrict. Hydrothermal dissolution of carbonate (decarbonatization), both pre- and postore, has produced extensive collapse breccias, which in some cases overprint sedimentary debris-flow breccias. Fault breccias occur in all deposits and are conduits for hydrothermal fluids into brecciated, fractured, or otherwise permeable host rocks.

At the eastern part of the Betze-Post deposit (Deep Post) Williams (1992) noted the coincidence of high-grade ore with a thick package of interbedded debris flows, collapse breccias, and fault breccias. It is inferred that fracturing from this collapse extended into the rocks of the overlying Rodeo Creek unit, producing fracture-controlled access for fluids and the development of the large tonnage, low-grade Post deposit. Alternatively, fracturing in the Post area can also be attributed to preore folding and thrusting. At the adjacent Betze subdeposit similar sedimentary, collapse, and tectonic breccias, as well as polygenetic and hydrothermal breccias, are described by Peters et al. (1997). At the Meikle deposit, Evans (2000) recognizes five stages of brecciation (Fig. 6) that include minor preore breccia related to karst formation, collapse breccia associated with main-stage gold mineralization, and three phases of postore collapse breccia. Bedded, laminated cavity-filling sediments, containing ore-stage pyrite also occur within the postore breccias. Emsbo (1999) suggests that the extreme dissolution and removal of carbonate, both pre- and postore, is one of the factors that has enhanced the grade of the Meikle deposit. In contrast to Betze-Post and Meikle, the high-grade breccias at the Deep Star deposit are tectonic breccias developed in a transtensional dilatant zone within the Post fault system (Altamirano-Morales, 1999; Dunbar, 2001).

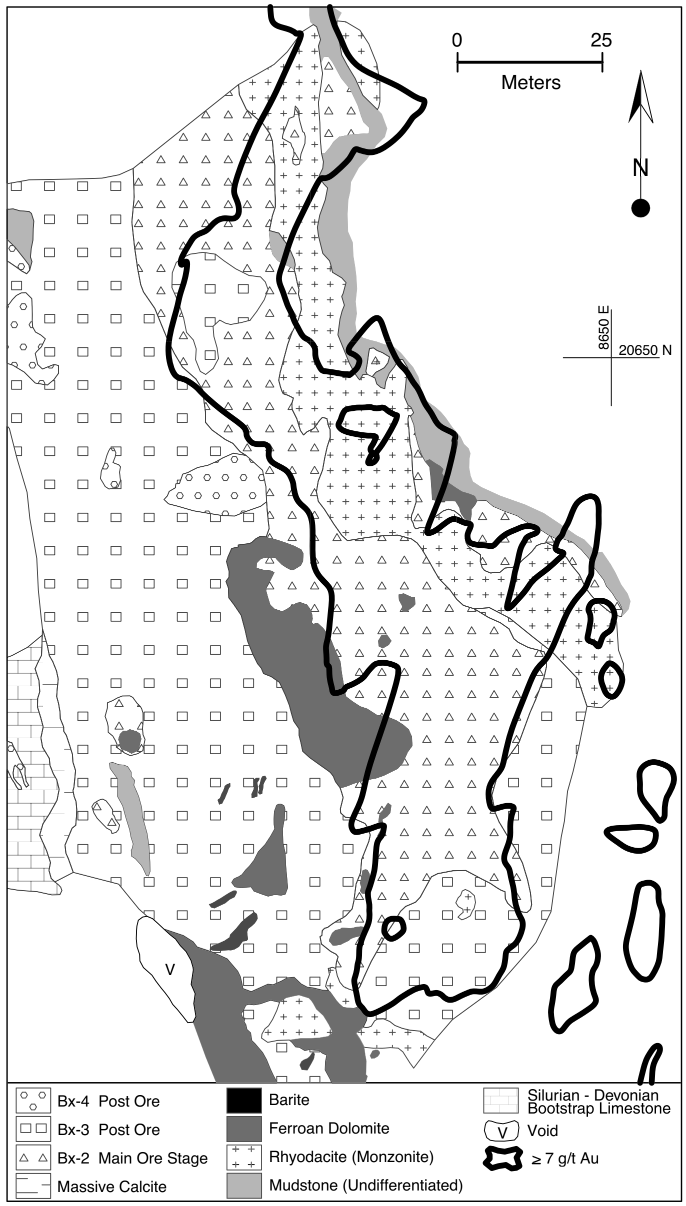

FIG. 6. Plan map of part of the 1375 level (1,294 m) elevation at the Meikle deposit, showing the orebody and the occurrence of breccia types, intrusions, dolomite alteration, and primary lithologies. Location of the level plan is shown in Figure 5. From Evans (2000).

Mineralogy, alteration, and paragenesis

The majority of gold at Goldstrike is located in arsenian pyrite overgrowths on preore pyrite (Arehart et al., 1993c, Ye, 2001). At the Deep Post subdeposit these overgrowth rims are zoned, the innermost layers being the richest in gold and arsenic. The dominant iron-bearing sulfide mineral is pyrite, though marcasite and arsenopyrite are present. The total volume of these sulfide minerals in refractory orebodies averages about 5 percent. The formation of auriferous pyrite by sulfidation of iron in lamprophyre dikes and dolomitized Bootstrap limestone at Meikle has been documented by Emsbo (1999). However, the 2.5 wt percent iron content in the dolomite at Meikle is considerably higher than average iron contents of 0.5 to 1.0 wt percent (excluding iron in diagenetic pyrite) found in partially dolomitized rocks of the Popovich Formation, distal to gold mineralization. Fortuna et al. (2001) has demonstrated that in mineralized samples from the Popovich Formation at the Screamer deposit this iron has been completely sulfidized. However, at Screamer, samples with greater than 10 g/t Au have average iron concentrations of 1.95 wt percent, which infers that additional iron was added during the gold mineralization event. Numerical geochemical modeling of alteration and gold deposition by Woitsekhowskaya and Peters et al. (1998) focused on interactions between a cooling ore fluid and the host rocks. They conclude that sulfidation of iron in the host rocks was the primary gold deposition mechanism but do not exclude the possibility that fluid mixing occurred. It should be noted that the iron contents of the host rocks, which they use for their modeling, are higher than typical for Popovich Formation rocks.

Alteration and gangue mineralogy seen at Goldstrike are a combination of preore, ore-stage, postore, and supergene events, which are influenced by a complex interaction of lithology, structure, and evolution of hydrothermal fluids. Preore events include dolomitization followed by migration and maturation of hydrocarbons. Also, as previously noted, there is evidence for preore base metal mineralization of Devonian and Jurassic age, which is auriferous in some areas. Jurassic intrusive rocks are extensively sericitized, which may be due to retrograde metasomatic alteration. However, several K-Ar dates of sericite from dikes at Goldstrike indicate ages of 117 to 100 Ma (Arehart et al., 1993a), suggesting a Cretaceous hydrothermal event. The abundance of carbon within orebodies is highly variable. In general, carbon occurs in orebodies hosted by rocks of the carbonaceous Popovich Formation, with the major exception of the east to central parts of the Betze-Post deposit, presumably due to destruction or removal of carbon during contact metamorphism by the adjacent Goldstrike intrusion.

Within the Betze-Post deposit there is considerable variation in the type of alteration. From east to west the Deep Post area is characterized by argillic alteration, the Betze area by decarbonatization (upper zone) and silicification (lower zone), and the Screamer area is notable for weak decarbonatization and silicification. In the Betze area, decarbonatization preceded the main gold event and produced extensive zones of collapse breccias, enhancing permeability for ore-stage hydrothermal fluids. Ore-stage alteration was accompanied by deposition of illite and quartz, followed by late quartz and kaolinite (Ferdock et al., 1997). Late-stage mineralization is characterized by stibnite and barite in silicified zones and realgar, orpiment, calcite, and rare fluorite in argillized zones. Other late-stage minerals include pyrite, marcasite, gypsum, apatite, siderite, dolomite, sphalerite, and millerite. Variations in alteration and mineralization at Betze and their relationship to structure are described in detail by Peters (1995), Leonardson and Rahn (1996), and Peters et al. (1998).

At the Meikle deposit a Paleozoic base metal hydrothermal event altered the Bootstrap limestones to ferroan dolomite (Emsbo, 1999). Barite, sphalerite, boulangerite, pyrite, galena, tetrahedrite, chalcopyrite, and minor gold are part of this event. Emsbo (1999) suggests that it is contemporaneous with the auriferous pyrite and base metals found in the Upper Mudstone Member of the Popovich Formation at Rodeo and elsewhere at Goldstrike. Evans (2000) subdivides this alteration and base metal mineralization into two events, dolomitization followed by barite veining, with sphalerite being the dominant base metal sulfide chiefly found replacing the dolomite (Fig. 7). Evans (2000) notes that the alteration, mineral assemblages, and salinities of 9 to 20 wt percent Na Cl equiv in fluid inclusions in sphalerite (Lamb 1995) show similarities to Mississippi Valley-type deposits.

Similar to Betze-Post, at Meikle the decarbonatization and development of collapse breccias precede the main-stage gold event, which was associated with silicification and sulfidation of the iron in the dolomite. Late-stage alteration included further dissolution and collapse along the flanks of the orebody, plus silicification associated with deposition of stibnite and weakly auriferous pyrite (Emsbo, 1999; Evans, 2000). The majority of the quartz at Meikle was deposited during this late ore stage. Deposition of calcite and minor barite, chiefly as breccia matrix and cavity filling, has continued to the present. In contrast to Betze-Post, argillic alteration is restricted to dikes and realgar-orpiment is rare at the Meikle deposit. Emsbo (1999) notes that geochemical and isotopic signatures as well as fluid inclusion data are essentially the same for Betze-Post and Meikle, indicating a common hydrothermal system. Rodeo, the third largest orebody at Goldstrike, has alteration similar to Betze-Post with decarbonatization in the upper zone and silicification in the lower zone.

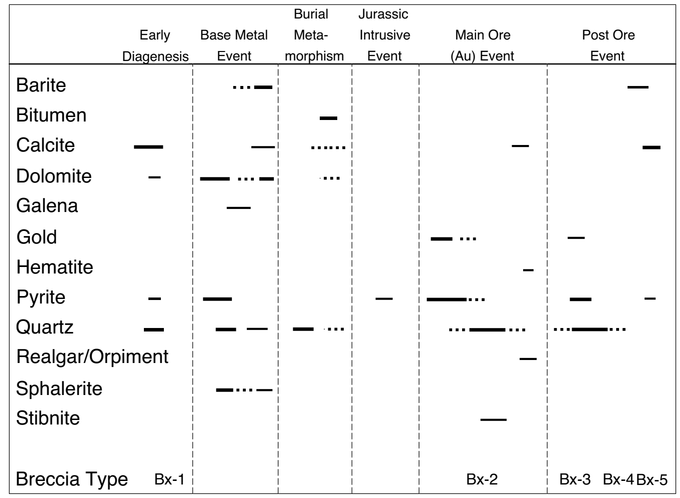

FIG. 7. Mineral paragenesis at the Meikle deposit. From Evans (2000).

Supergene alteration at Goldstrike extends to depths up to 200 m and has resulted in the destruction of pyrite, liberation of gold, and the formation of oxide and sulfate minerals such as goethite, hematite, jarosite, scorodite, alunite, and gypsum. Supergene alteration is deepest in the Post area, probably due to the extensive fracturing and relatively high pyrite content. This deep oxidation had important economic implications, as ore with grades as low as 0.27 g/t Au were mined and processed by heap leaching. The supergene alteration is at least as old as Miocene, based on K-Ar dates on supergene alunite from the Post area, which range from 9.5 to 8.5 Ma (Arehart et al., 1992).

Geochemistry

The Eocene Carlin gold mineralization overprints earlier base metal mineralization, resulting in complex geochemical zoning. Elements always associated with the Carlin gold mineralization at Goldstrike are As, Hg, Sb, Tl, and S. At Meikle, minor occurrences of silver and tellurium are also associated with gold, in part as late-stage mercury, silver, and gold tellurides. Laser ablation ICP-MS data show enrichment of As, Sb, Hg, Ag, Tl, Te, and W within ore-stage pyrite at Meikle (Emsbo, 1999). At Betze-Post and Deep Star, tungsten is also associated with gold. In these deposits values of tungsten are considerably higher than at Meikle, probably due to remobilization of tungsten from scheelite mineralization related to the Goldstrike intrusion or the intrusion itself (T. Collins, writ. commun., 1999). Table 3 shows average elemental abundances at several gold deposits at Goldstrike. Sulfur, which was not analyzed in these specific samples, averages 2 to 3 percent for the deposits listed in Table 3. Further detailed geochemical data from the Betze subdeposit can be found in Berry (1992) and Merino-Marquez (2000).

TABLE 3. Average Geochemical Values for Mineralized Zones with Gold Assays >1 ppm

Element	Betze	Screamer	Meikle	Rodeo
Au	5.0	4.9	20.7	6.3
Ag	1.8	.7	32.6	1.5
As	1,183	685	1,205	398
Hg		4.7	36.2	34.6
Sb		65	476	45
Tl		3.2	24.8	5.9
Cu		37.7	96.9	46.2
Pb		8.1	58	34.9
Zn		212	936	656
Cd	3.1	1.8	10.5	7.3
Mo	25.0	11.7	68.6	41.7
Te		0.11	1.21	0.19
Ba	1,298	830	11,980	1,532
W		33.6	3.4	4.5
Bi		0.18	0.13	0.16
Sn		50	100	67
Ni		50.5	51.7	102.6
Cr		59	108	160
Se		1.21	3.71	10.1
Cs		2.1	2.7	2.9
U		8.61	6.92	10.99
V		146	141	656
P	1,181	602	1,621	1,494
Ca	22,280	100,870	22,044	55,000
Mg	7,078	40,400	2,547	28,642
Na		235	379	354
K	9,329	6,983	7,442	11,194
Fe	21,166	26,435	37,184	19,135
No. of samples	76	23	43	156

Notes: All assays in ppm, by ICP-MS and neutron activation (Activation Labs); individual samples are 12-m drill hole composites

Stable isotope and fluid inclusion studies

Sulfur isotope analyses of ore-stage pyrite have been conducted at Betze-Post and Meikle. Sensitive high-resolution ion microprobe analyses (SHRIMP) of gold-rich arsenian pyrite deposited along fractures in preore pyrite from the eastern part of the Betze-Post deposit have $\delta^{34}S$ values near 20 per mil (Arehart et al., 1993b). They suggest that barite or other sedimentary sulfate minerals from the Paleozoic section may have been the major source of sulfur in gold-transporting solutions. Arsenian pyrite overgrowths without gold enrichment have very low $\delta^{34}S$ values of approximately –25 per mil. Arehart et al. (1993b) suggests that this may be due to oxidation of late ore fluids by boiling or mixing with a second iron-rich fluid with a distinct isotopic character. In contrast, sensitive ion microprobe (SIMS) analyses of gold-rich arsenian pyrite from the western part of the Betze-Post deposit (Screamer) indicate $\delta^{34}S$ values near 0 per mil (Fortuna et al., 2001). They suggest that these values may be due to mixing of a basinal fluid with low $\delta^{34}S$ values from the Screamer area, with fluids from the east with high $\delta^{34}S$ values. Ore-stage pyrite from Meikle has a mean $\delta^{34}S$ value of 9 per mil (Emsbo 1999) or 8.6 per mil (Evans, 2000). Late ore-stage pyrite, which has low to moderate gold values, has a mean $\delta^{34}S$ value of –14 per mil, which suggests a different hydrothermal fluid than the main ore stage (Evans, 2000), possibly due to slight oxidation of the ore fluid by acidic ground waters entrained in the collapsing hydrothermal system (Emsbo, 1999). Calculated values for ore-stage fluids at Meikle and Betze-Post give a mean value of –4.2 per mil for $\delta^{18}O$ and values of about –135 per mil for δD_{H_2O}, which are consistent with a meteoric origin (Emsbo, 1999).

At the Meikle deposit aqueous fluid inclusions in ore-stage quartz have homogenization temperatures of 200° to 225°C and salinites of ±10 wt percent NaCl equiv (Lamb, 1995). Assuming lithostatic conditions, this indicates a minimum depth of formation of 3 km (Lamb and Cline, 1997), although this conflicts with the shallow emplacement of mineralized Eocene dikes in the Carlin Trend (Ressel et al., 2000b). Limited fluid inclusion data by Lamb (1995) from quartz of the Betze-Post deposit (Deep Post) gave a wide range of homogenization temperatures from 140° to 275°C, with modes at 150° to 180° and 200° to 210°C. The inclusions varied from aqueous to CO_2 rich and salinites ranged from 0 to 8 wt percent NaCl equiv. The data suggest mixing of two fluids, although it is possible that some of the inclusions may be related to the preore Goldstrike intrusion. Fluid inclusions in late ore-stage orpiment from Betze-Post have a bimodal distribution of homogenization temperatures at 170° to 210° and 120° to 140°C and salinites of 4 to 6 and 2 to 5 wt percent NaCl equiv, respectively (J. Groff, writ. commun., 1994), which may reflect mixing of two thermally distinct fluids. In support of this Groff cites N_2-Ar-He plots derived from bulk analyses of inclusion fluids from the same orpiment samples that mainly lie along a mixing line between meteoric water and a helium-rich end member, which indicates a mantle source for volatiles (Groff, 1996).

Gold deposits and ore controls

Mineralization at Goldstrike covers an extensive area and there are numerous orebodies that have been localized by a diverse and complex interplay of structural and lithological factors. The unifying large-scale features that localize ore within the Blue Star-Goldstrike subdistrict are the autochthonous Lower Paleozoic sequence, the Jurassic Goldstrike intrusion, and the north-northwest–striking Post fault system (Fig 5). Only brief descriptions are given below of the gold deposits. For details the reader is referred to previous publications and Table 1.

The largest gold deposit, Betze-Post, has an east-west strike length of 2,300 m outboard of the northern contact of the Jurassic Goldstrike intrusion and an extension of its metamorphic aureole to the west. This relationship is the first-order ore control at Betze-Post and is due to the intrusive rocks and calc-silicate hornfels acting as a rigid body during deformation, with increased fracturing and brecciation in the flanking sedimentary rocks (Bettles and Lauha 1991). In addition, loss of volume in areas of calc-silicate hornfels may have developed fracturing that facilitated later movement of hydrothermal fluids. The majority of the ore is within 300 m of this contact with extensions at a greater distance along structural zones. Most of the ore is located in the rocks of the Popovich Formation, especially the Wispy Member, with lesser amounts in the Rodeo Creek unit, calc-silicate hornfels, and diorite. The Betze-Post deposit is subdivided into three subdeposits, which are from east to west, Deep Post, Betze, and Screamer (Fig. 8). The highest grades occur in the Deep Post area adjacent to the Post fault system (Table 1).

At the Betze and Deep Post subdeposits, mineralization occurs as stacked ore zones, which attain a 450-m-vertical range adjacent to the Post fault, including extensive low-grade ore hosted in the Rodeo Creek unit (Post deposit). Mineralization is controlled by faults, either as conduits to fluids or as barriers where they contain dikes or argillic alteration (Penick et al., 2000). Thickness and grade of ore tend to increase along fault zones, particularly at fault intersections. Major ore-controlling faults at Betze-Post strike N 10°–30° W and dip both east and west, or strike N 25°–65° E, and dip north. Most of these have apparent normal displacements, often less than 30 m. An important exception is the Dillon fault zone, which strikes N 40°–70° W, dips 45° NE, has reverse movement, and is up to 70 m wide (Fig. 9). The Dillon fault zone and the associated west-northwest–striking Betze anticline are the dominant ore controls in the Betze area. The multiple episodes of deformation in the Betze and Deep Post areas, combined with dissolution of the Popovich Formation carbonate rocks, have produced extensive zones of fracturing and tectonic and collapse breccias. In the Screamer area, development of breccias is restricted to the southern part of the deposit and mineralization is generally confined to the Wispy Member, with enhanced grades at fault intersections. Anticlines, which are locally domal, have also provided structural and permeability traps to hydrothermal fluids (Leonardson and Rahn, 1996). Likewise, ore is often found beneath impermeable diorite sills extending to the northeast from the Goldstrike intrusion.

Located in a corridor along the Post fault system, over a 2,500-m north-south strike length, are the large, high-grade Meikle and Rodeo deposits and several smaller satellite deposits (Table 1). Orebodies in this area are being mined by underground methods, in contrast to Betze-Post, which is being mined mainly by open pit. Structural controls are similar to Betze-Post, with ore localized by both high- and low-angle faults, breccias, and to a lesser extent, folding. The first-order control to mineralization is the Post fault zone orebodies being preferentially located at changes in strike. Ore is hosted in a variety of lithologies, which include the Bootstrap limestone (Meikle), the Popovich

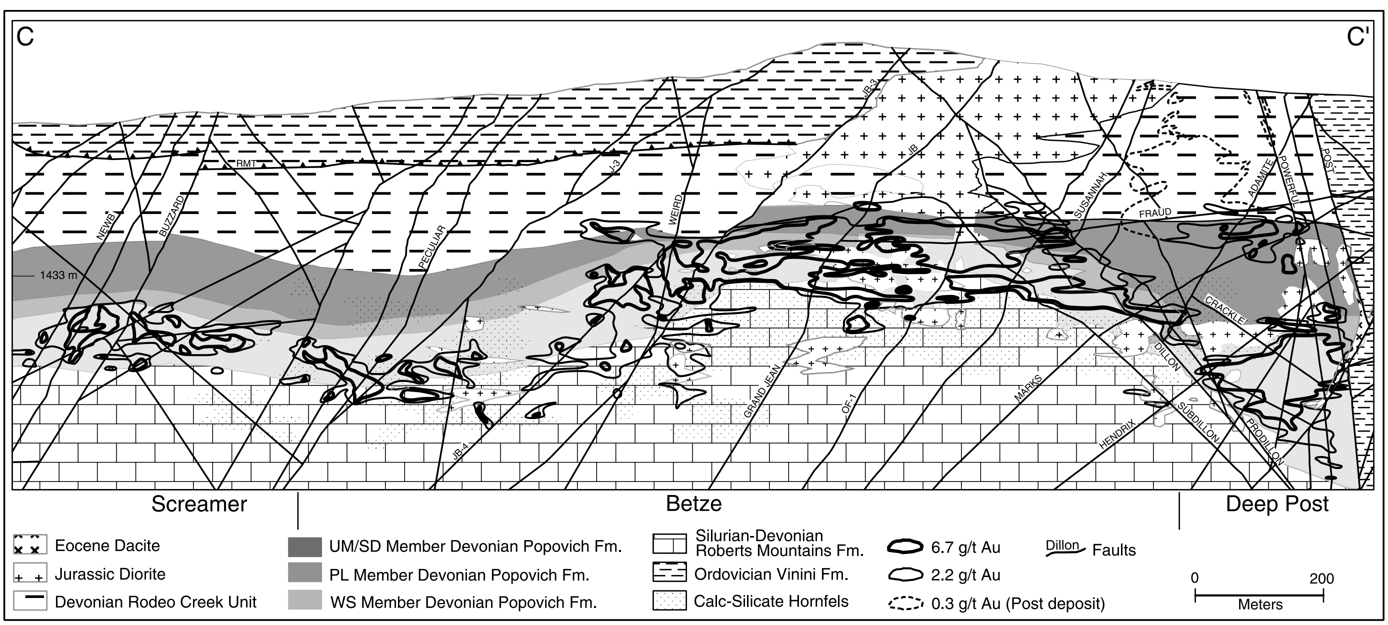

FIG. 8. Simplified east-west long section (C-C′) of the Betze-Post deposit, showing the relationship of the orebodies to stratigraphic units and faults. The low-grade oxidized Post deposit is shown as a dashed outline. All other orebodies are unoxidized and refractory.

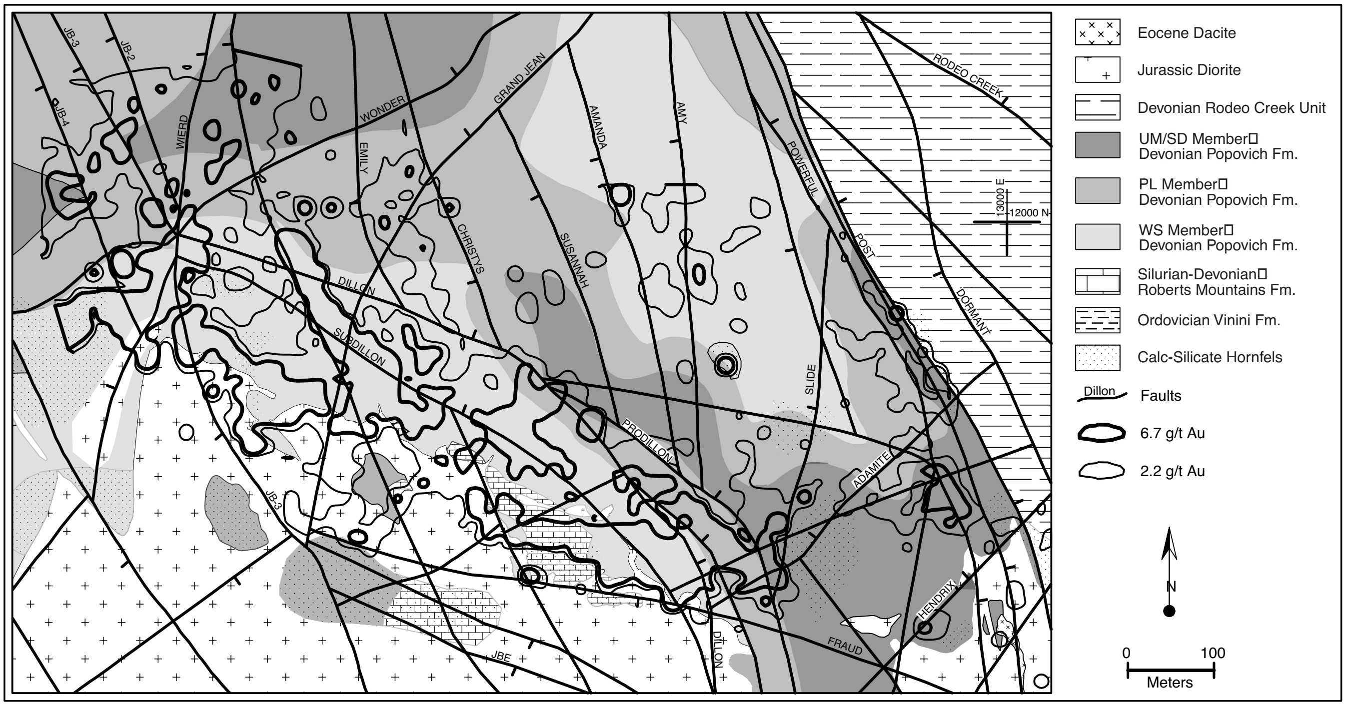

FIG. 9. Level plan at the 4700 level (1,433 m elevation) of the Betze and Deep Post subdeposits of the Betze-Post deposit. Important ore controls shown at this level are the Wispy Member of the Popovich Formation, the Dillon fault zone, and the contact of the Jurassic diorite. Small displacements on faults are not shown. The location of the level plan is shown in Figure 5.

Formation (Rodeo, South Meikle, Barrel, and Banshee), and the Rodeo Creek unit (Griffin and West Griffin). In all areas, Jurassic lamprophyre dikes and sills are a significant host to ore, which is often high grade. At Meikle, lower grade ore is also found in brecciated or fractured Jurassic rhyodacite dikes, located in the hanging wall of the orebody. These dikes, which are relatively impermeable, may have focused fluid flow in the underlying sedimentary rocks. High-grade ore is also found in cavity-filling sediments that were deposited during the mineralization event (Emsbo, 1999).

The Meikle deposit is located close to the intersection of the Post fault with the massive Bootstrap limestone (Fig. 10). Much of the ore at Meikle is in collapse breccias, developed in the Bootstrap limestone, which have a pipelike geometry striking subparallel to the Post fault and dipping 55°–75° E (Volk et al., 2001). At other deposits in the corridor, ore is often localized by specific faults, generally a combination of steeply to moderately dipping and low-angle faults. The steeply to moderately dipping faults strike N-N 30° W or N 40°–80° E and can have either normal or reverse displacement. The low-angle faults, which often strike N 40°–80° W and dip to the northeast are prominent ore controls in the smaller deposits such as South Meikle, West Griffin, Barrel, and peripheral ore zones at Rodeo and Betze (K. Thomson, writ. commun., 1998). As previously noted, gold mineralization overprints earlier base metal mineralization at the Meikle and Rodeo deposits. At Rodeo, this base metal mineralization is auriferous and occurs in the Upper Mud Member of the Popovich Formation, with native gold up to 0.1 mm in size (Fig. 11). This native gold constitutes approximately 10 percent of the gold in the orebody (Baschuk, 2000).

Although structural features and brecciation are of great importance as ore controls at Goldstrike, the location and grade of ore is also strongly influenced by the characteristics of the host rocks. Approximately 95 percent of the ore at Goldstrike, on a contained gold basis, is sedimentary rock hosted, subdivided approximately as follows: Popovich Formation 75 percent, Bootstrap limestone 11 percent, Rodeo Creek unit 7 percent, and Roberts Mountains Formation 2 percent. The host of the remaining 5 percent is divided between lamprophyre, diorite (Betze-Post), and rhyodacite (Meikle). Characteristics that influence the favorability of the host rocks are the presence of reactive carbonate, porosity, permeability (primary or after dissolution of carbonate), and iron, which can be sulfidized to form gold-bearing pyrite. Partial dolomitization of the Popovich Formation has preserved the primary porosity of the rocks, making them accessible to later hydrothermal fluids (Armstrong et al., 1998) and would also enhance permeability due to loss of volume. In addition, the dolomitic rocks have low iron content, which is available for sulfidation. Debris flows within the Popovich Formation, or its apron facies, also provide additional permeable zones. The Bootstrap limestone lacks permeability and is generally a poor host, but at the Meikle

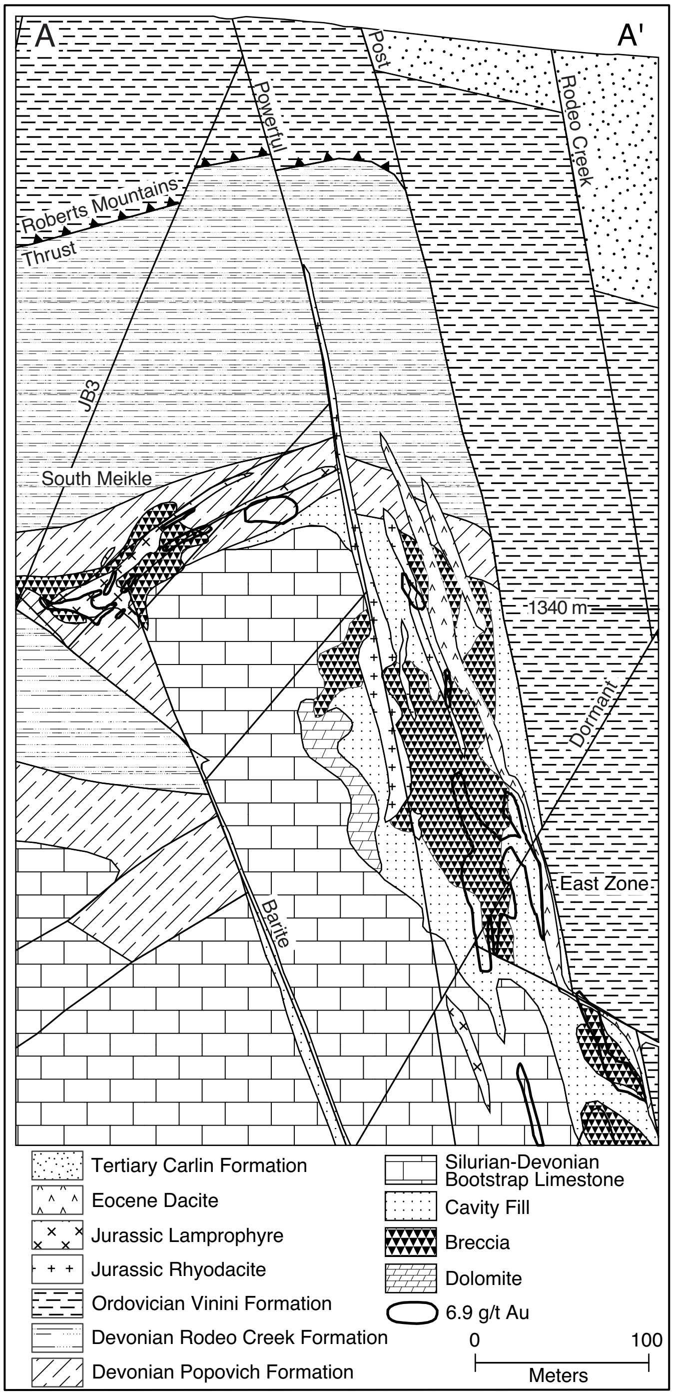

FIG. 10. Simplified cross section (A-A′) of the Meikle and South Meikle deposits, showing the relationship of ore to breccias, intrusions, cavity-fill, and the Post fault zone. The East zone of the Meikle orebody is shown. The previously mined Upper Main zone at Meikle is located to the north of this section, above the East zone. Modified from Volk et al. (2000).

deposit brecciation has provided permeability and iron is present in preore ferroan dolomite alteration. A large part of the low-grade oxide ore hosted by the Rodeo Creek unit was mined at a grade lower than the cutoff grade for refractory ore in other host rocks. Higher grade zones in this unit are located in limy siltstones and sandstones of the Bazza sand subunit or in fault zones.

Jurassic lamprophyres dikes, although volumetrically minor, make an excellent host rock, due to iron contained in hornblende and phlogopite, up to 10 percent calcite in their groundmass, and their common location along faults that are conduits for hydrothermal fluids (Emsbo, 1999). Ore in the diorite of the Goldstrike intrusion at Betze-Post is found along fault zones and in the wall rock, particularly in sills less than 7 m in thickness. Distal to Betze-Post, small, low-grade orebodies are located in flat-lying fault zones cutting the diorite. This mineralization is often associated with quartz veins.

Summary and model

Gold orebodies at the Goldstrike property are the largest and highest grade Carlin deposits known. This is presumably due to a fortuitous combination of many favorable factors, some of which may be included in the following summary or model. The location of Goldstrike, close to the rifted margin of the North American craton, along an inferred deep crustal structure, has influenced subsequent sedimentation, structural development, magmatism, hydrothermal activity, and hence the location of the Carlin Trend. The mineralization at Goldstrike is hosted in a variety of lithologies, with the majority in the Popovich Formation and, to a lesser extent, other units of the autochthonous carbonates. This is believed to be due to their reactivity, porosity, permeability, and also the presence of iron, which is available for sulfidation. Both the porosity and permeability and the iron content have been enhanced in some areas by ferroan dolomite alteration prior to gold mineralization.

Multiple episodes of deformation from the Mississippian to the Eocene developed a complex structural architecture that controls the location, geometry, and size of the orebodies. At a deposit scale, structural controls of mineralization are a combination of folds and both high- and low-angle faults, particularly where the structures intersect. Many of these faults have relatively modest displacements with the notable exception of the subdistrict-scale Post fault system, which is associated with the highest grade orebodies. Ore is preferentially located in anticlines, which provide permeability traps to fluids, the relatively impermeable units often found above ore, being the siliciclastic rocks of the Rodeo Creek unit or the allochthonous sequence. Dissolution of carbonate has produced collapse breccias that often contain high-grade ore. Intrusions of Jurassic age, although considerably older than gold mineralization, are important ore controls by their influence on subsequent deformation and by forming relatively impermeable barriers to hydrothermal fluid flow.

The age of gold mineralization is approximately 39 Ma

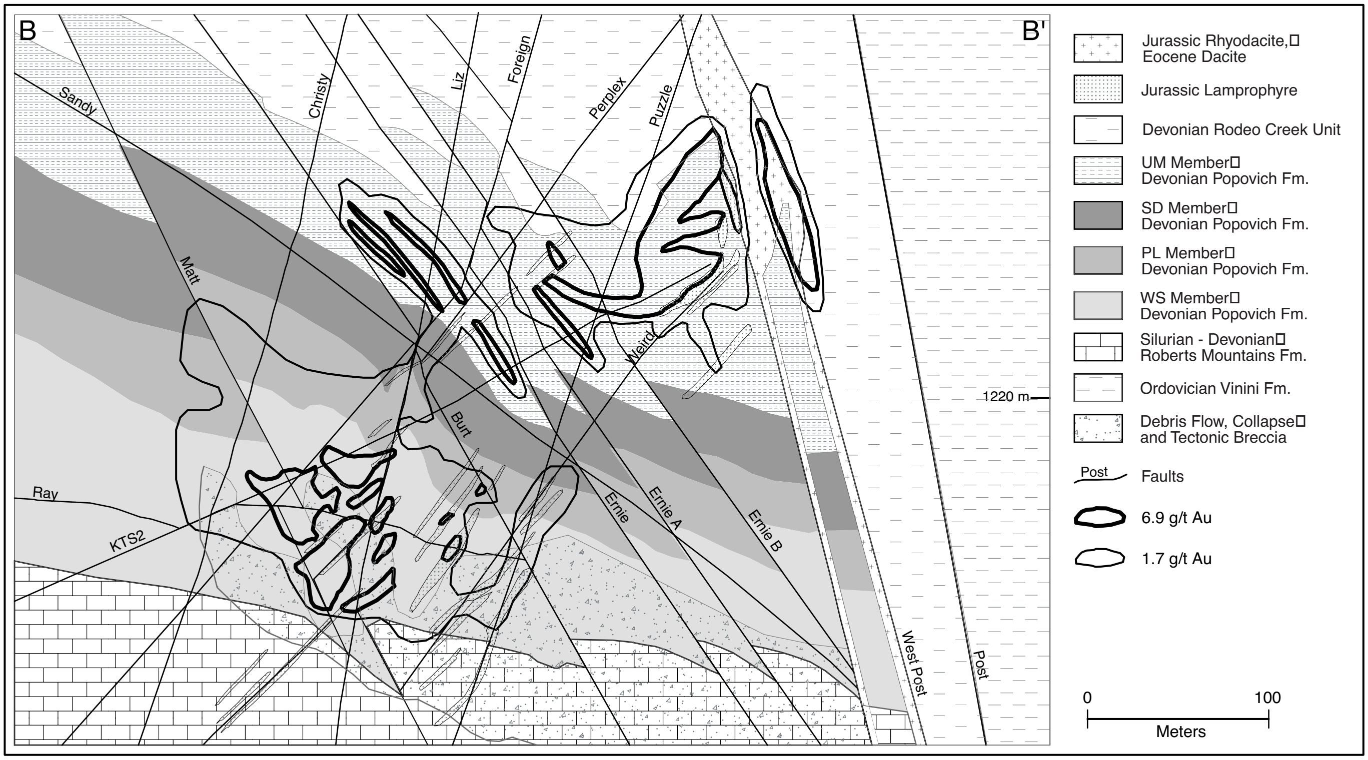

FIG. 11. Cross section of the Rodeo deposit (B-B′), showing the upper and lower ore zones in the Upper Mud and Wispy Members of the Popovich Formation. Structural ore controls include moderate to steep dipping faults that dip both east and west. Ground surface is at the 1,634-m elevation. Modified from Volk et al. (2000).

and has a temporal association with the onset of regional extension and calc-alkaline magmatism. The depth of formation of the gold mineralization and the source of the gold is equivocal. Fluid inclusion studies from the Meikle deposit indicate that ore fluids were low salinity (±10 wt % NaCl equiv), had homogenization temperatures of 200° to 225°C, and were of meteoric origin. Most of the gold is deposited within arsenian pyrite and is associated with Hg, Sb, and Tl. Alteration associated with mineralization varies considerably between deposits and includes decarbonatization, argillization, and silicification. Supergene alteration extends to 200 m below surface in some areas and has resulted in oxidation of gold-bearing pyrite, which has important economic benefits.

Exploration

Introduction

Exploration at the Goldstrike property over a 40-yr period has been based on an evolving understanding of the geologic controls of ore location, supported by the application of geochemical and geophysical exploration techniques. The liberal application of drilling and the interpretation of drill hole data has also been an important element of the exploration process. During the first 24 yr from 1962 to 1986, exploration was targeted at the relatively shallow and small orebodies, hosted in the Rodeo Creek unit and the Goldstrike intrusion. Discoveries were made using a combination of geologic mapping, surface-rock–soil geochemistry, and interpretation of the geology and gold mineralization intersected in drill holes. In 1987, exploration began for larger deposits hosted in the deeper stratigraphic units at depths greater than 250 m. Information from the earlier phase of exploration was utilized with the addition of geophysical data. With time there has been an increasing reliance on geology interpreted from the deep drill holes. Knowledge of the structural controls of mineralization in the Rodeo Creek unit was applied to deeper exploration in the Popovich Formation. Understanding of the subsurface geology was greatly advanced by the change from reverse circulation rotary to core drilling plus detailed mapping of the Betze-Post pit. Table 1 details the discovery method for the various gold deposits at Goldstrike.

The commitment to exploration and delineation of the large and diverse orebodies at Goldstrike has been a major factor in the rapid development of large reserves. By 2000, a total of $133M had been invested in exploration and reserve development. Persistence, despite deep, difficult drilling, and enigmatic geology, has paid off over the lengthy exploration process. Success has been greatly facilitated by continuity of the exploration and mine geology teams at Goldstrike.

Geology

Basic geologic work has been an integral part of exploration at Goldstrike. Geologic mapping has progressed from surface outcrop to road cuts, open pits, and, more recently, underground workings. Detailed logging of drill holes has been emphasized, although subdivision of the stratigraphy has resulted in some relogging of older drill holes. Research by graduate students has contributed greatly to the development of geologic knowledge.

Over 11,500 drill holes have been drilled on the Goldstrike property, including underground delineation drilling and shallow holes from early exploration. Management of the analytical, geological, metallurgical, and survey data for these drill holes has been a challenging task. Currently this data is in a Fox Pro relational database. Interpretation and modeling of subsurface geology has evolved from traditional section and level plan to 3D modeling in Vulcan and Gocad software at a mine and property scale, respectively. In addition, ArcView GIS is used for integration of much of the geological, geophysical, and geochemical data.

Geochemistry

Soil geochemical surveys and sampling of silicified outcrops (jasperoids) were an important contribution to the discovery of many of the gold deposits at Goldstrike. Samples from early surveys were assayed for gold and arsenic, with the addition of antimony and mercury in the period 1978 to 1986. Gold deposits close to the surface and also deeper deposits such as Betze-Post and Meikle have anomalous surface geochemistry (Fig. 12). Assays from jasperoids at surface, 90 m above the Post and Deep Post deposits, averaged 0.3 ppm Au, 794 ppm As, 81 ppm Sb, and 8.2 ppm Hg. In the Meikle and Rodeo areas, where the orebodies are at more than a 250-m depth, both rocks and soils have much lower geochemical values than at Betze-Post. However, anomalous arsenic in soils occurs above the Meikle deposit and was a factor in its discovery. Figure 12 illustrates the variations in gold and arsenic soil geochemistry at Goldstrike. In general, geochemical pathfinder values are higher in soils developed in the Rodeo Creek unit and Goldstrike intrusion (e.g., Betze-Post) compared to soils developed in the upper plate siliciclastic rocks (e.g., Meikle). Other geochemical techniques that have been tried at Goldstrike with some success include biogeochemistry (sagebrush), mercury soil gas detectors (Rehn and Rehn, 2000), and analysis of soil gases (McCarthy et al., 1989).

Much of the Goldstrike property is covered by the post-mineral Carlin Formation and exploration depths are generally greater than 250 m. This presents a challenge to detection of undiscovered orebodies using surface geochemistry. In areas where the Carlin Formation is less than 75 m deep, reverse circulation drill holes have been drilled systematically to the Paleozoic bedrock to obtain a geological and geochemical sample. This has been very useful for mapping geochemical trends and geology in covered areas. Exploration drill holes that penetrate the potential host rocks of the Popovich Formation have been assayed for elements other than gold, utilizing 12-m composites. Modeling of multielement assays within stratigraphic units, such as the Popovich Formation, can indicate areas of alteration and mineralization. As mentioned previously, drill hole grade-thickness maps of gold mineralization were used extensively to vector toward ore.

Geophysics

Various geophysical methods have been used at Goldstrike throughout the exploration process, particularly since 1987. Techniques that have been extensively used include airborne and ground magnetics, gravity, IP, DC resistivity, controlled source audio magnetotellurics, and magnetotellurics. Other techniques that have been tested, or used on a limited basis, are reflection siesmics and electromagnetics. Carlin-type mineralization is generally not amenable to direct detection by geophysical methods (Lide, 1994). However, variations in subsurface physical properties can map lithology, alteration, and structure.

Airborne magnetics at Goldstrike delineates the subsurface location of the large dioritic intrusions and major structures, such as the Post fault system (Fig. 13). The Carlin Formation, which contains detrital magnetite, has a higher magnetic susceptibility than the Paleozoic rocks. These two rock packages are often in fault contact, which is readily discernible in airborne and ground magnetics. Gravity data at Goldstrike shows the large intrusions and their metamorphic aureoles, as well as the massive carbonates of the Bootstrap limestone (Fig. 14). Depth to bedrock below the Carlin Formation and displacement of the Paleozoic section by the Post fault zone has also been modeled from gravity data, with some success.

Electrical geophysical techniques at Goldstrike are challenged by the presence of low-resistivity units, such as the Carlin Formation, Rodeo Creek unit, and parts of the Popovich Formation. In the case of IP surveys, carbonaceous material and diagenetic pyrite in many of the stratigraphic units can give chargeability anomalies unrelated to gold mineralization. Inductive coupling is also a problem, particularly in areas where the Carlin Formation occurs at surface. In 1987, a test IP-resistivity survey across the recently discovered Deep Post deposit detected an IP (chargeability) anomaly, which was believed to be due to the pyritic gold mineralization located at depths of 350 to 475 m below surface. In 1987 to 1988, the Goldstrike property was covered by an IP-resistivity survey using a time domain pole-dipole array with an electrode separation of 600 m (Kornze and Bettles, 1998). Chargeability anomalies were detected in several areas. Exploration drilling of targets determined by a combination of the IP-resistivity data, geology, geochemistry, and mineralization detected in prior shallow drilling resulted in the discovery of the Betze, Screamer, Rodeo, Griffin, and Deep Star deposits. All these deposits are located at depths greater than 240 m and with the exception of Deep Star are overlain by the carbonaceous and pyritic rocks of the Rodeo Creek unit. Therefore, it is most likely that the chargeability response was largely due to the Rodeo Creek unit, rather than the auriferous pyrite within the orebodies. Nevertheless, successful drilling of IP

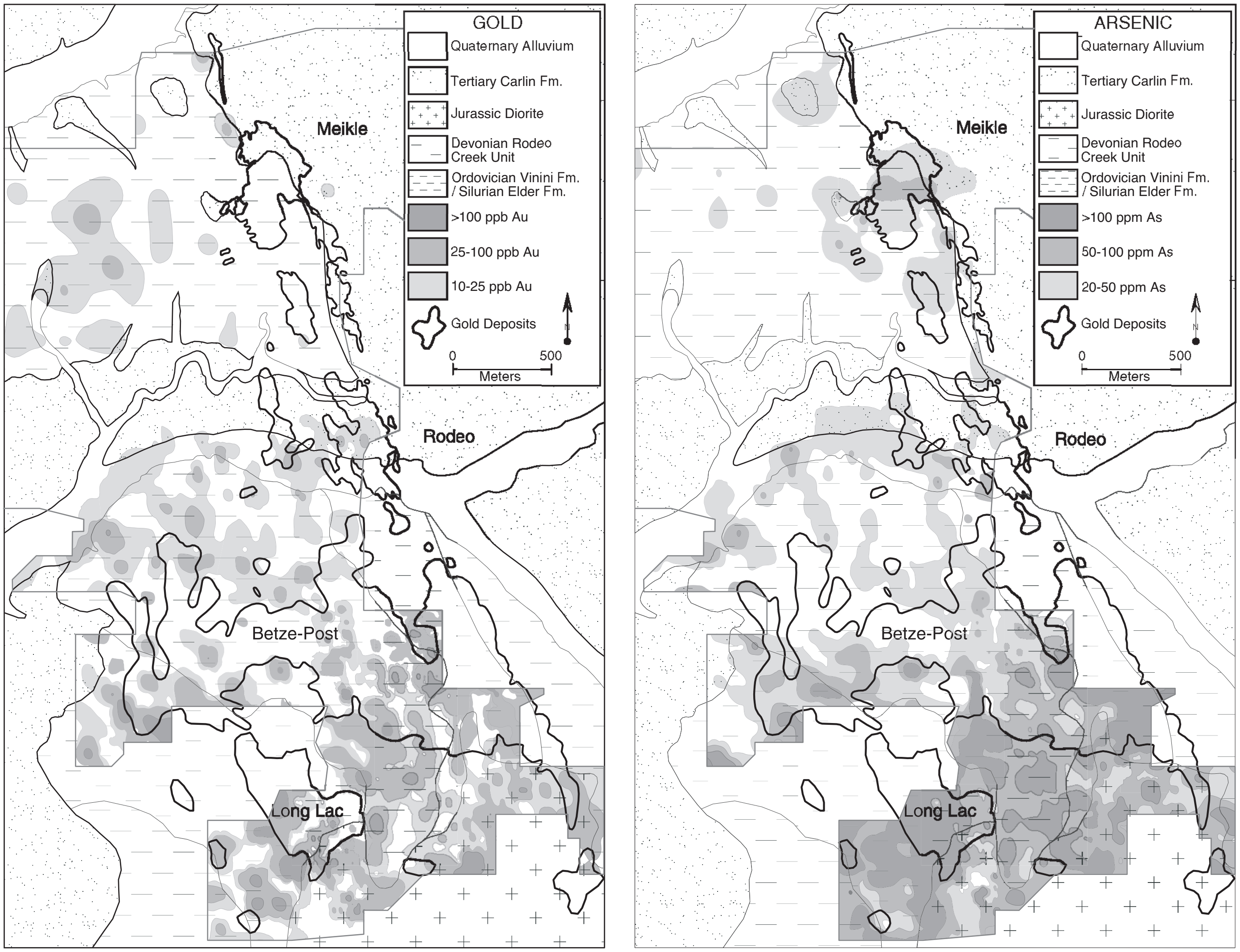

FIG. 12. Gold and arsenic soil geochemistry at Goldstrike, with simplified stratigraphic units, at surface. The outline of gold deposits is a projection to surface of orebodies at depths of 2 to 250 m. Only part of the area in the maps was sampled (boundary is indicated).

anomalies, in combination with other targeting criteria, was important in creating an aggressive, enthusiastic exploration campaign. Resistivity data from the same survey also added to geologic knowledge by mapping the high resistivities of the Goldstrike intrusion and its metamorphic aureole.

In 1989 and 1992, controlled source audio magnetotellurics survey lines were run across the Betze-Post and Meikle deposits, respectively (Fig. 15). These surveys were successful in defining the subsurface expression of the contact of the Goldstrike intrusion, the Post fault zone, and the thickness of the Carlin Formation. Extremely low-resistivity zones, due to carbonaceous material in the Rodeo Creek unit, limited depth penetration in some areas. Supergene oxidation and removal of carbon along fault zones or at gold deposits in the Rodeo Creek unit are seen as zones of higher resistivities within a layer of low-resistivity (Wright and Lide, 1998). Further controlled source audio magnetotellurics surveys at Goldstrike mapped structures of relatively large displacement and high-resistivity units, such as the Bootstrap limestone. Recent geophysical surveys conducted at Goldstrike include a time domain magnetotellurics-IP survey using a distributed array system. The improved signal to noise ratio of this system will allow greater depth penetration and tolerance of electrical interference from mine operations. Interpretation of the data from this survey will be constrained by a 3D geologic model that incorporates physical properties for stratigraphic units, established from electric logging of drill holes and physical testing.

Drilling

Discovery of orebodies and provision of geologic information was made possible by drilling technology capable of

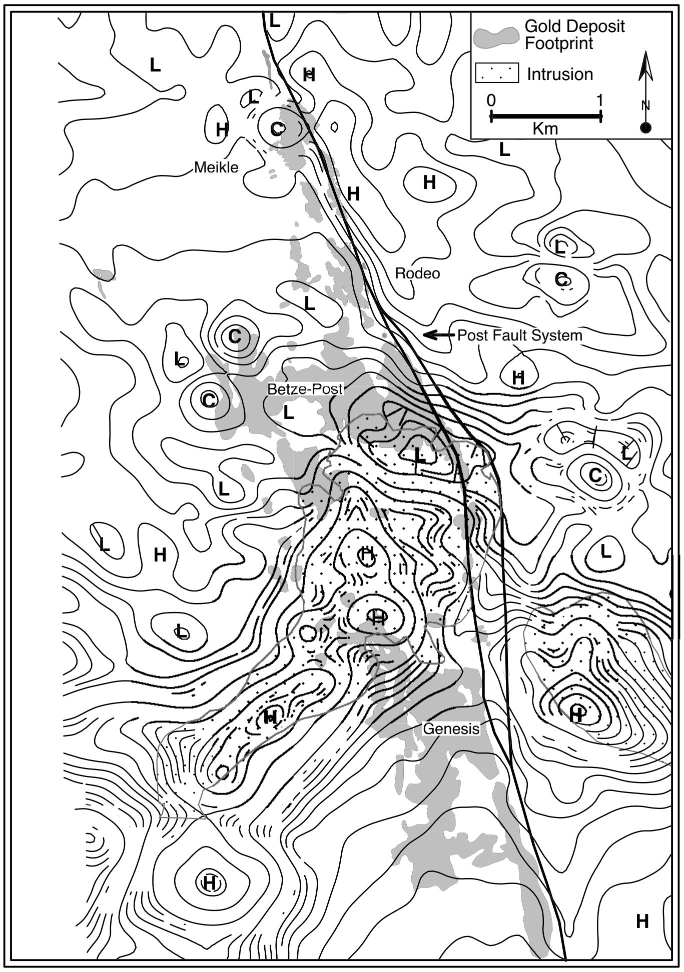

FIG. 13. Total magnetic intensity, reduced to pole for the Blue Star-Goldstrike subdistrict. Contour intervals 10 nt (γ). Magnetic highs (H) and lows (L) are indicated. Magnetic highs due to mining infrastructure are designated by C. Footprints of gold deposits and intrusions are projected to surface. Magnetic contours by Pearson, deRidder and Johnson, Inc.

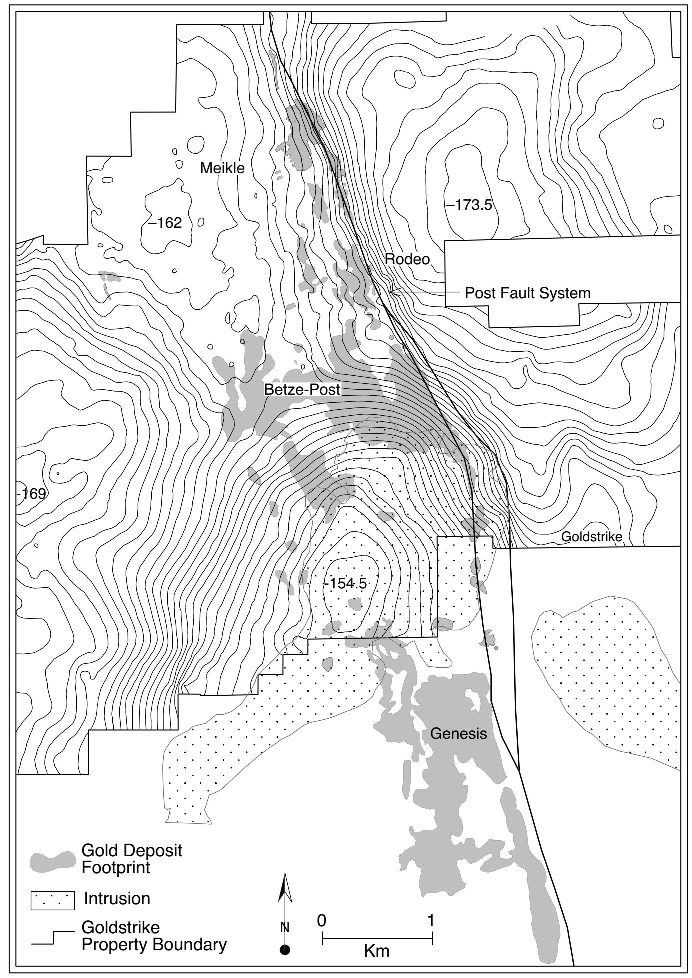

FIG. 14. Complete bouguer gravity for the Blue Star-Goldstrike subdistrict. Contour interval 0.5 mgal. Select highs and lows indicated. Footprints of gold deposits and intrusions are projected to surface. Gravity by Zonge Geosciences, Inc.

retrieving samples from depths greater than 250 m. Exploration and development drilling at Goldstrike and many other Carlin-type deposits is difficult and expensive, due to extensive fracturing, variable alteration, and ground-water conditions. The presence of water in high transmissivity rocks was an impediment to deep reverse circulation rotary drilling and adversely affected sample quality. Conversely, the removal of water by mine dewatering causes problems during core drilling due to loss of drilling fluid. Exploration at Goldstrike was made possible by the solution of these and other problems by contract drillers and exploration staff.

Future exploration and research

Exploration at Goldstrike continues with the current emphasis on collection of new geophysical data and its integration with existing geological and geochemical data as a common earth model. The results of this work will be the basis for future exploration drilling. The extensive area of mineralization and the diverse structural and stratigraphic ore controls at Goldstrike suggest the likelihood of new discoveries and additions to known orebodies. These may be in similar stratigraphic and structural settings, such as the area to the east of the Post fault system where the autochthonous carbonates are located at depth or, alternatively, in settings previously untested.

Although there has been a considerable amount of research conducted at Goldstrike, there are numerous remaining questions. Many of these are currently being addressed. Work is underway to establish property-scale alteration systematics and zoning. The role of sulfidation in the deposition of gold versus other mechanisms is also being evaluated. The depth of formation of the mineralization is still debatable, as is the source of the ore fluids and metals. Further work on the evolution of the complex structural architecture is also ongoing. The extent and signifi-

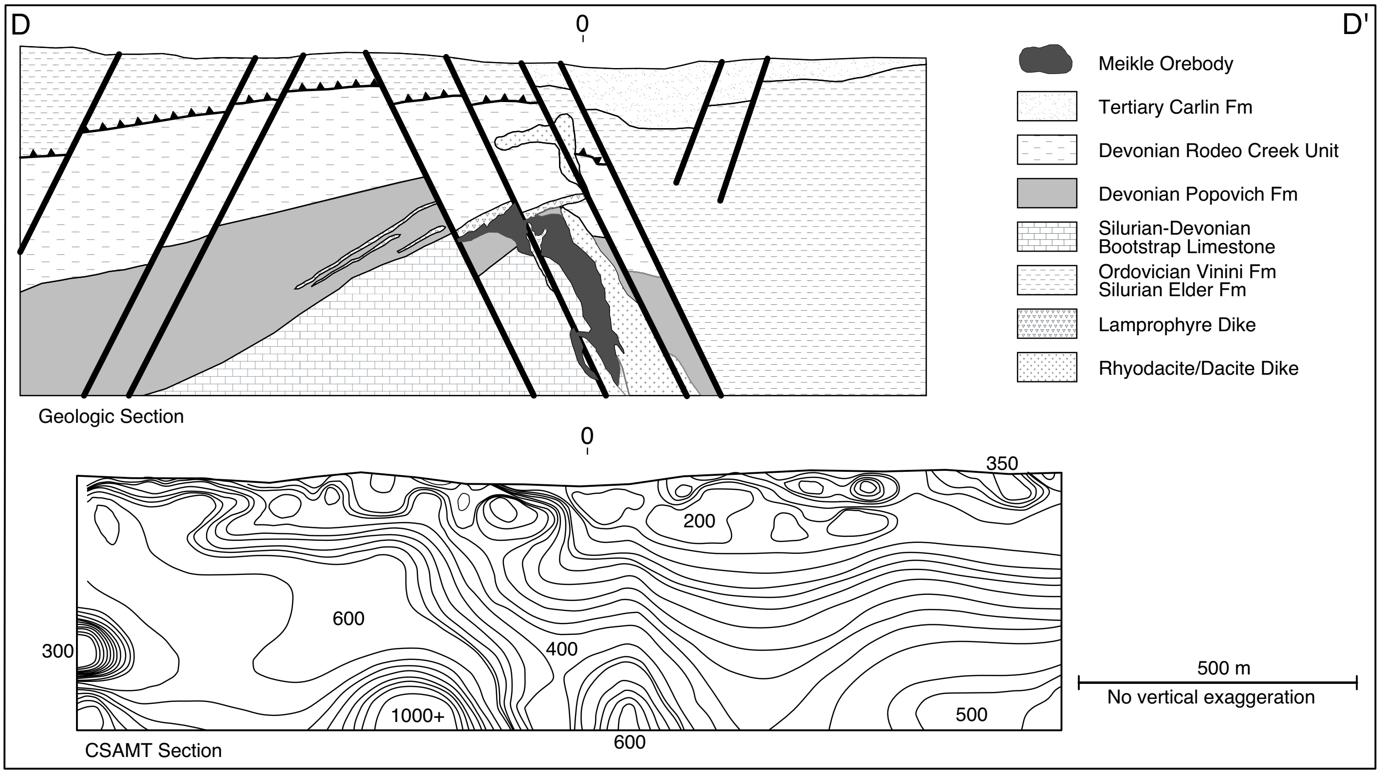

FIG. 15. Cross section D-D′ across the Meikle deposit, showing geology and controlled source audio magnetotellurics (CSAMT) values in ohm-M. High-resistivity values correspond to the massive carbonate rocks of the Bootstrap limestone and low-resistivity values to the Carlin Formation. Geologic interpretation from drill holes prior to mining. Modified from Wright and Lide (1998).

cance of the gold and base metal mineralization in the Upper Mudstone Member of the Popovich Formation at the Rodeo deposit is also under investigation.

Acknowledgments

I would like to thank Barrick Goldstrike Mines for permission to publish this account of the geology and history of Goldstrike. The information in this review is a result of the efforts of all the geologists who have worked at Goldstrike. Thank you all. For help with text and figures, I would like to thank Greg Griffin, Eric Lauha, Al Lander, Mike Penick, Charles Weakly, and Denise Laes. The manuscript benefited from formal reviews by Rich Goldfarb, Steve Garwin, and Poul Emsbo. In addition, reviews by Barrick geologists, François Robert, Jeff Volk, Gary Baschuk, Mike Penick, Paul Dobak, Bob Leonardson, and Charles Sulfrian, were of great assistance. I would like to especially thank Ellen Rochefort for her tireless work on the figures and text. This chronicle is dedicated to my father, Keith Bettles, who also searched for high grade in another time and place.

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