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Geochemical Exploration for Gold Through Transported Alluvial Cover in Nevada: Examples from the Cortez Mine

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Abstract

Geochemical orientation surveys were completed over covered Carlin-type gold deposits in the Cortez mine area with the expressed aim of identifying and evaluating exploration methods to discover Au ore under transported alluvial cover in Nevada. Orientation tests were designed to assess the utility of geochemical applications at various scales of exploration, both drill targets at the deposit scale and "footprints" associated with deposits at the district scale.

Detailed surveys were completed over the covered Gap deposit, located adjacent to the giant Pipeline deposit. Both Carlin-type gold mineralization and earlier, spatially associated, base metal skarn mineralization at Gap were located by soils, soil gas, and vegetation. Loam soils at 6- to 12-cm depth provided a consistent and uniformly available sample medium. Gold ore under 10 m of cover in the northern portion of the Gap deposit was readily detected by analysis of Au by fire assay and ultra trace aqua regia methods in the -80 mesh fraction of these loam soils. Arsenic anomalies occur over the northern end and over the main ore zone at Gap, where there is 25 to 50 m of alluvial cover. Zinc concentrations in soil show the most coherent spatial relationship with underlying Au ore. Tests of MMI-B and Enzyme Leach selective leaches did not result in significant enhancement of the anomalies relative to aqua regia. CO_2 and O_2 in soil gas indicate faults and underlying mineralized carbonates at Gap, where weathering reactions likely generated CO_2 from acid reaction with carbonate. Elevated Au and As in mixed sagebrush and shadscale occur over most ore zones, with the highest Au concentrations over the main ore zone rather than the shallowly buried northern zone. Like soils, elevated Zn in vegetation shows the most coherent spatial relationship with underlying ore.

Assays from 1,859 drill holes show a 4- to 5-km^2 "footprint" at the basin gravel-bedrock unconformity centered on the Pipeline Carlin-type gold deposit, where samples of basal alluvium provide a large, coherent >50 ppb Au anomaly. Enriched As, Tl, K, and F in alkaline groundwater sampled from monitoring wells surrounding the Pipeline open pit provide a ≥5-km^2 hydrogeochemical footprint. Higher As and Tl concentrations occur down gradient from Pipeline indicating Carlin-type Au mineralization is the source of the enrichment.

The surface metal anomalies are consistent with upward migration of metals through fractured alluvial cover. Likely metal transport mechanisms include barometric pumping of gases or seismic pumping of groundwater. Upward diffusion of metals through the thick vadose zones in northern Nevada is not a viable process. Surface anomalies over Gap and other deposits appear to be mature and may have developed over millions of years. In such mature anomalies, much of the metal that migrated from underlying bedrock is probably hosted in resistant secondary minerals, which are more readily dissolved by aqua regia than by various selective leaches.

Sampling of soil gas and soils is appropriate at the drill target scale. Vegetation should be sampled when consistent soils are not available. Sample spacing should be adjusted according to "real-time" soil gas readings in order to increase sampling density over fracture zones. The patterns of >50 ppb Au for both the top of bedrock and base of alluvium at Pipeline provide useful templates for comparison with other drilling programs through cover. Groundwater is an effective and under-utilized reconnaissance-scale sample medium. Gold is likely to be soluble in neutral to alkaline groundwater in Nevada, and could provide a direct indicator of blind covered ore.

Introduction

Nevada remains one of the premier gold-mining regions in the world, producing 5 Moz of gold in 2009 (Price, 2010). However, since peaking at 8.9 Moz in 1998, production has dropped 10 of the last 11 years. Among other factors, the drop in production reflects a decrease in discoveries over the last decade. Table 1, which summarizes a selection of discoveries over the last 50 years, shows the majority of discoveries since 1986 have been under cover. Many of the large deposits discovered since 1986 have been found under transported alluvial cover, including Twin Creeks, Pipeline, and Cortez Hills. Those three deposits alone have amounted to over 40 Moz of gold in production, reserves, and resources. Spatial analysis of the Nevada state geologic map (Stewart and Carlson, 1978) indicates 49 percent of Nevada is covered by transported, largely unconsolidated, alluvial sediments of Neogene to Quaternary age that fill basins between linear north-south mountain ranges. The decrease in discoveries reflects the difficulty of exploring through this alluvial cover.

Exploration in these alluvial basins has focused mainly along the edges of the ranges, where shelves of shallowly covered pediment surfaces (<~200-m depth) can extend up to a few kilometers away from bedrock exposures. Most companies have generated targets along these shallow pediments by projecting the following features from the bedrock along the range front out to the pediment and underneath cover: (1) geochemical anomalies in rock chips or residual soils, (2) alteration

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TABLE 1. Summary of Selected Nevada Gold Deposit Discoveries

Deposit	Year	Au (Moz)	Description	Discovery methods	References
Carlin	1961	5.0	Outcropping Carlin-type Au deposit	Mapping and rock-chip geochemistry	1, 2
Cortez	1966	1.68	Outcropping Carlin-type Au deposit	Mapping and rock-chip geochemistry	3, 4
Jerritt Canyon (Alchem)	1973	0.16	Outcropping Carlin-type Au deposit	Mapping and rock-chip and residual soil geochemistry	5, 6
Alligator Ridge	1977	0.79	Outcropping Carlin-type Au deposit	Mapping and rock-chip and residual soil geochemistry	7, 8
Gold Quarry	1979	>25	Carlin-type Au deposit covered by 30–150 m of alluvium	Drilling (wildcat hole 180 m from known small resource)	6, 9
Fortitude	1980	2.2	Au skarn deposit covered by >45 m of barren pre-ore rocks	Drilling based on metal zoning patterns around known Cu-Au-Ag deposit centered on a stock and anomalous rock-chip geochemistry along fault that cut the barren cover ("leakage anomaly")	6, 10
Paradise Peak	1983	1.6	Outcropping high-sulfidation epithermal Au-Ag deposit	Field inspection of Hg prospect, rock-chip sampling, followed by drilling	6, 11
Gold Bar	1983	0.36	Carlin-type Au deposit covered by 1–10 m of alluvium, buried horst block located 4 km from range front	Rock-chip geochemistry (float, 20-30 ppb) followed by drilling	12
Sleeper	1984	2.36	Low-sulfidation epithermal Au-Ag deposit covered by 20–50 m of alluvium, located 1 km from range front.	Drilling based on projections of geology and rock-chip geochemistry from the range	6, 11
Marigold (8 South)	1985	0.41	Carlin-type Au deposit /distal-disseminated Au deposit covered by 1–150 m of alluvium	Drilling based on projections of geology from range	13
Twin Creeks (Megapit)	1986	15.6	Carlin-type Au deposit covered by 5-200 m of alluvium	Drilling based on projection of geology and sagebrush anomaly (12–15 ppb Au, 5 m of alluvial cover) that was located 1.5 km south of outcropping Chimney Creek Carlin-type Au deposit	6, 11
Cove	1986	3.3	Outcropping distal disseminated Ag-Au deposit	Stream sediment geochemistry, mapping, and rock-chip and residual soil geochemistry	6, 11
Betze-Post	1986	40.2	Carlin-type Au deposit covered by ~200–300 m of upper plate siliciclastic rocks that contained small, near-surface low-grade oxide orebodies	Drilling to test favorable underlying lower plate carbonates	14
Meikle	1988	7.1	Carlin-type Au deposit covered by up to 150 m of alluvium and 250 m of essentially barren upper plate siliciclastic rocks	Drilling based on old Hg prospect, mapping, and IP anomaly	14
Deep Star	1988	1.7	Carlin-type Au deposit covered by sporadically, weakly mineralized upper plate siliciclastic rocks	Drilling below old open pit, based on IP anomaly	15
Lone Tree	1989	4.5	Distal-disseminated Au deposit covered by 0.5–120 m of alluvium	Drilling based on projections of geology from range	6, 11
Mike	1989	8.6	Carlin-type Au deposit covered 120–240 m of alluvium	Drilling based on NW extension of Good Hope fault from gold quarry	16
Jerritt Canyon (SSX)	1990	1.7	Carlin-type Au deposit covered by 140–300 m of essentially barren upper plate siliciclastic rocks	Drilling based on weakly anomalous rock-chip geochemistry (15 ppb Au) along altered dikes that cut the barren cover ("leakage anomaly")	5, 17
Pipeline	1991	17	Carlin-type Au deposit covered by 25–250 m of alluvium	Condemnation drilling	6, 11
Archimedes	1992	2.83	Carlin-type Au deposit covered by 15–150 m of alluvium	Drilling based on projections of rock-chip geochemistry and geology from range	11, 18
Turquoise Ridge	1993	9.5	Carlin-type Au deposit covered by ~500 m of mainly siliciclastic and basaltic rocks that contained small, near-surface, low-grade oxide orebodies	Drilling to test favorable underlying carbonate rocks, based on projections of geology from nearby Getchell deposit	11, 19
West Leeville	1994	3.2	Carlin-type Au deposit covered by 450–600 m of essentially barren siliciclastic rocks	Drilling based on projected intersection of faults and favorable stratigraphy	20
Cortez Hills	2002	14.1	Carlin-type Au deposit covered by ~100–200 m of alluvium	Drilling based on ore-grade intercepts in widely spaced old drill holes, gravity low interpreted to be result of alteration, and projections of geology from the range	11, 21
South Arturo	2005	1.5	Carlin-type Au deposit covered by ~200–260 m of alluvium	Drilling of an untested area underneath old mine dumps	11, 22

Normal typeface = outcropping deposit; italics = deposit covered by pre-ore bedrock; bold typeface = deposit covered by transported alluvium

Au (Moz) = estimate of mined Au and remaining Au reserve-resource

References: 1 = Jory (2002), 2 = Livermore (1996), 3 = Hays et al. (2007), 4 = Erickson et al. (1966), 5 = Jones (2005), 6 = Sillitoe (1995), 7 = Nutt et al. (2000), 8 = Schull and Sutherland (2005), 9 = Powell (2007), 10 = Kotlyar et al. (1998), 11 = Muntean (2010), 12 = French et al. (1996), 13 = Theodore (2000), 14 = Bettles (2002), 15 = Clode et al. (2002), 16 = Norby and Orobona (2002), 17 = McMillin (2005), 18 = Dilles et al. (1996), 19 = Chevillon et al. (2000), 20 = Jackson et al. (2002), pre-mining resource, 21 = Hays and Thompson (2003), 22 = Cope et al. (2008)

zones, (3) structures (mainly high-angle faults), and (4) favorable host rocks. The covered targets are commonly further refined with geophysics, which help identify high-angle faults and zones of shallow bedrock, and then they are drilled. Such exploration requires intensive drilling to be successful and, thus, is very costly.

Although surface geochemistry is a tried and true method in areas of bedrock and residual soil, explorationists remain skeptical about its application in areas of transported cover. Table 1 shows surface geochemistry was not important, with the possible exception of Twin Creeks, in any of the discoveries under transported cover. Skepticism is rooted in the possibility that upward migrating elements will not create sufficiently strong anomalies that can be distinguished from variations in the background composition of the cover. Nevertheless, companies have continued to try surface geochemistry as new methods are developed and analytical techniques improve. The precision of analyses has increased and detection limits have been driven downward. Larger companies that were particularly active in trying and developing surface geochemical techniques through transported cover in Nevada in the 1990s included BHP, Newmont, and Placer Dome. Much of this work has remained unpublished.

In the 1990s, Placer Dome tested several emerging techniques, including soil gases and various selective leaches on soils, over known covered deposits and applied them on prospects, mainly with poor results. In 2002, it decided to reassess the application of surface geochemistry through cover, based mainly on advances in techniques and positive findings from a Canadian Mining Industry Research Organization (CAMIRO) study, called "Deep-Penetrating Geochemistry," which was undertaken between 1998 and 2002, and was supported by 26 companies, including Placer Dome. Some of the results of the CAMIRO study have been published by Cameron et al. (2004, 2005). Placer Dome charged the authors of this paper with carrying out a series of orientation surveys on its Cortez mine property in late 2002, utilizing a wide variety of techniques over undisturbed gold deposits covered with transported overburden, as well as over prospects that had encouraging drill intercepts.

Several Carlin-type gold deposits of likely Eocene age (Arehart and Donelick, 2006; John et al., 2008) are located on the Cortez property on both sides of Crescent Valley, a large alluvial basin (Fig. 1). The deposits are hosted by variably silty carbonate rocks of Silurian to Devonian age that are exposed in windows through the Roberts Mountain thrust, the upper plate of which consists of Ordovician to Devonian chert, argillite, quartzite, and greenstone. The Gold Acres window on the west side of Crescent Valley hosts the Pipeline and Gold Acres deposits. Gold Acres was the first Carlin-type gold deposit discovered in Nevada, in 1922, and was put into production in 1935. The much larger Pipeline deposit was discovered underneath alluvial cover in 1991 and put into production in 1995. Approximately 20 Moz of gold have been produced and identified as reserves and resources in the Carlin-type gold deposits in the Gold Acres window. On the east side of Crescent Valley, the Cortez window hosts the Cortez and Horse Canyon deposits, and the large, high-grade Cortez Hills deposit, which was discovered underneath alluvial cover in 2002. Barrick Gold Corp. currently operates the Cortez

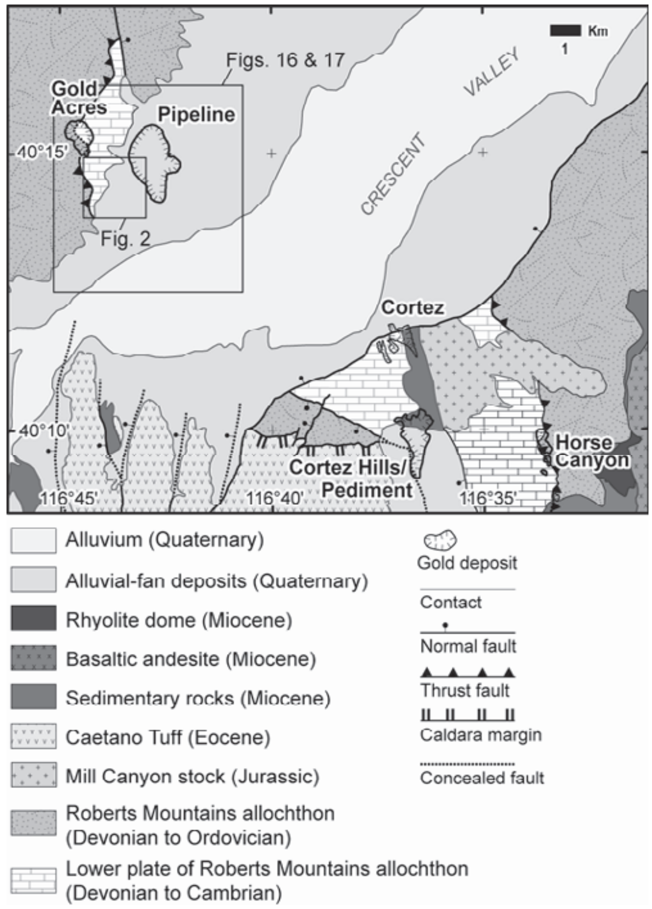

FIG. 1. Geologic map of the Cortez showing locations of Carlin-type gold deposits. Simplified from Plate 1 in John et al. (2008). Based on mapping by Gilluly and Gates (1965), Gilluly and Masursky (1965), and John et al. (2008).

mine, with production coming from the Pipeline and Cortez Hills deposits. The geology of the Carlin-type gold deposits and of the Gold Acres and Cortez windows have been described in many publications, including Gilluly and Gates (1965), Gilluly and Masursky (1965), Wells et al. (1969), Wrucke and Armbrustmacher (1975), Hays and Foo (1991), and Foo et al. (1996a, b). Like other Carlin-type gold deposits in Nevada (cf. Cline et al., 2005), the deposits in the Cortez area are associated with decarbonatization and silicification and elevated concentrations of As, Hg, Tl, and Sb.

This paper presents results of the orientation surveys that were conducted on the west side of Crescent Valley, along the pediment adjacent to the Gold Acres window (Fig. 1). Most of the paper focuses on detailed soil, soil gas, and vegetation surveys over the Gap deposit, a covered deposit that is now part of the Pipeline open pit. In addition, the geochemistry of the top of bedrock and the base of gravel, based on drill hole data, and the hydrogeochemistry of water wells are presented for the greater Pipeline area. Based on the results of these and other surveys we completed, we offer recommendations for geochemical exploration through cover in Nevada.

Orientation Surveys over the Gap Deposit

The Gap deposit and survey area are located just west of Pipeline (Fig. 2). Gold ore, which is mostly weathered and

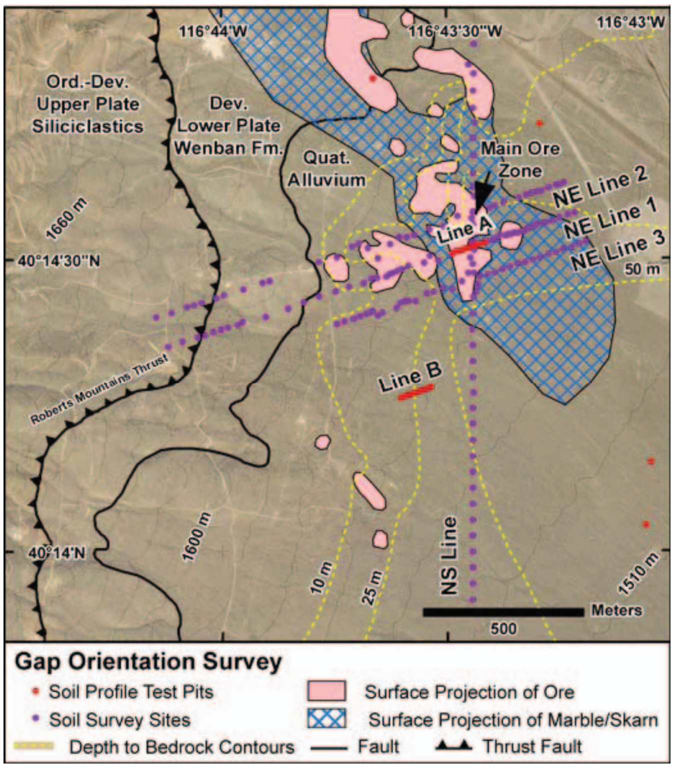

FIG. 2. Aerial photograph of the Gap orientation survey site showing location of soil profile test pits and soil survey sites discussed in the text. Also shows surface projections of covered Au ore and marble that locally contains base metal-bearing skarn. Main geologic contacts are shown as well as contours of thickness of alluvial cover based on several hundred drill holes that are not shown. Faint black lines are topographic contours with an interval of 15 m. Photo was taken in 2002. See Fig. 1 for location

oxidized, occurs in limestone of the Devonian Wenban Formation that has been thermally metamorphosed and recrystallized locally to marble during emplacement of the Cretaceous Gold Acres stock located in the subsurface to the west of Figure 2. Spatially associated with the marble are zones of base metal-rich gossan and skarn. The Au ore crosscuts gossan and skarn and is interpreted to be Eocene in age, as are the other Carlin-type gold deposits on the Cortez property. A north-northwest–trending anticline along with parallel high-angle faults is an important control on the gold ore. The main ore zone shown in Figure 2 is thicker and contains more zones of higher grade ore (>1.7 g/t Au) than other ore zones. The Roberts Mountain thrust and siliciclastic rocks in its hanging wall occur along the west end of the survey area. Apart from isolated areas of limestone outcrop, these siliciclastic rocks dominate the gravel component of soils at Gap. At the time of the survey, the resource at Gap was approximately 500,000 oz of Au in ore grading approximately 1 g/t.

In the Gap survey area, the thickness of the alluvial cover ranges from 0 to 90 m, increasing from northwest to southeast across the deposit (Fig. 2). The north end of the Gap deposit is covered by approximately 5 to 10 m of transported alluvium; however, the thickness of alluvium over the main ore zone is in an area of recessed bedrock that is typically 25 to 50 m below the surface. Gold ore zones occur at depths as shallow as a few meters below the alluvium-bedrock unconformity at the north end of Gap to depths as deep as 175 m below the unconformity in the main ore zone. The marble zones extend to the alluvium-bedrock unconformity but the tops of skarn and gossan are mainly 60 to 190 m below the unconformity.

The climate is arid and vegetation is sparse (Fig. 3A). Annual precipitation averages 23 cm and is dominated by snowfall in the winter and short-duration, high-intensity thunderstorms in the summer. The water table at Gap prior to dewatering at Pipeline was approximately 100 m below the surface. Many of the ore zones straddle the water table. Topography gently slopes downhill, eastward across the Gap survey area, with a total relief of about 100 m. The survey area is transected by dry, low-relief, west-northwest-trending drainages, spaced 200 to 250 m apart. The sampling described below was carried out periodically between late September and early December, 2002, under dry conditions.

Soil profile tests

A necessary first step in completing quality geochemical surveys through cover is to characterize soils in the survey area with an emphasis on understanding variations in soil composition and chemistry. The goal is to identify a suitable soil medium with an appropriate target matrix for selective extraction analyses, with characteristics that are sufficiently consistent so that low-contrast anomalies can be recognized. In order to meet that goal, we carried out vertical profile sampling in 26 pits dug to depths of about 30 to 75 cm at various sites in the Gap area, as well as at various alluvium-covered sites within the Cortez window. The locations of the pits at Gap are shown in Figure 2 and include four isolated pits and two 100-m-long lines, each consisting of 11 pits spaced about 10 m apart. One of the lines was over the main ore zone (line A), whereas the other line (line B) was approximately 300 m from known mineralization.

As in most places in Nevada, soil profiles at Gap and in the Cortez window are immature and can be considered mostly C horizon. The B horizon is weakly developed, and the A horizon is absent. In detail though, soils at Gap have variable thicknesses of various soil horizons over short lateral distances. Underneath a surficial layer of loess and pebbles a few centimeters thick is a gray to locally brown, fine-grained loam with varying amounts of silt and gravel. The loam reacts variably with 5 percent HCl. A brown to red smectitic clay was present in some of the pits at depths of mainly 26 cm below the top of the loam. Pedogenic carbonate, referred to here as caliche, was variably developed in some of the pits below the clay, or below the loam where the clay was absent. Figure 3B shows an example of a soil profile from the Cortez window, showing the loam, clay, and caliche.

The profiles were sampled consistently, at depths of 0 to 6 cm (after the surficial material was scraped off), 6–12 cm, 12–26 cm, and 26 cm to the bottom of the pits. Samples were randomized prior to submittal to ALS Chemex laboratories because samples that are prepared and analyzed in the same sequence that they are collected can lead to contamination or batch errors in preparation and analysis. Such errors can lead to spatially coherent areas of high concentrations that can be misinterpreted as real features. Samples for each of the depth intervals were sieved by ALS Chemex into two size fractions, –80/+200 mesh and –200 mesh, to determine whether soil

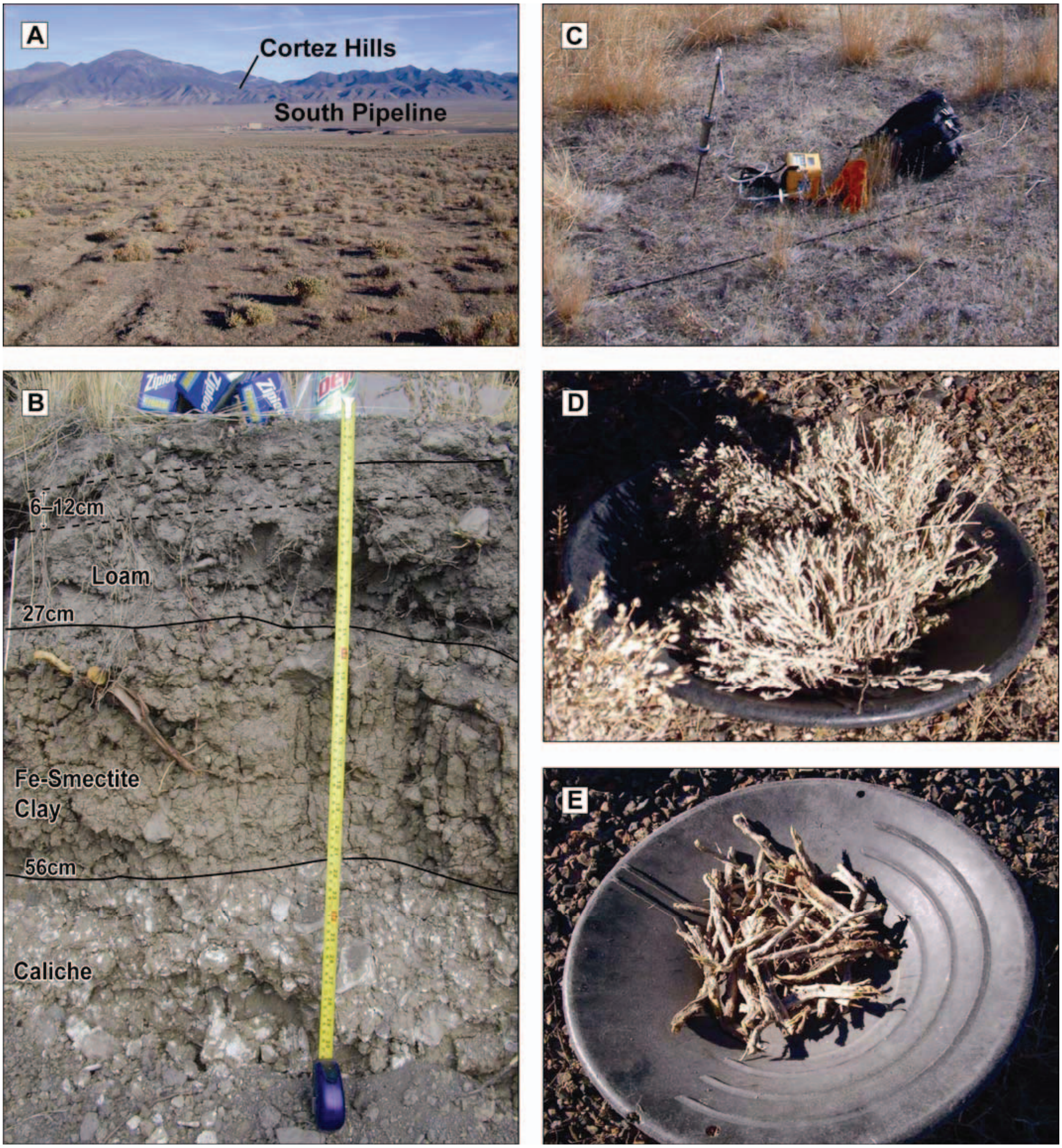

FIG. 3. A. View of Crescent Valley looking southeast from the Gap orientation survey site. Foreground shows the typical nature of the surface overlying Gap. The south part of the Pipeline deposit, where mining was initiated in 2001 as well as the Cortez Hills deposit on the east side of Crescent are pointed out. B. Soil profile test pit from the east side of Crescent Valley showing the typical horizons discussed in the text. Shows the 6- to 12-cm loam that was considered the most consistent sampling medium and the underlying red Fe-bearing smectitic clay and caliche zone. C. Portable analyzer (yellow) used to measure CO_2 and O_2 in soil gas. Sticking out of the ground is the hollow steel sampling tube with slide hammer and attached tubing. D. Example of sampled sagebrush twigs. E. Example of sampled live shadscale bark.

surface area and soil particle size impact soil chemistry. For each of the size fractions for each sample, a fire assay for gold was completed (30 g with ICP-MS finish, 1 ppb detection limit, ALS Chemex assay package Au-MS21) along with analyses for 50 elements by a combination of ICP-MS and ICP-AES using an aqua regia digestion (ALS Chemex analytical package ME-MS41). In addition, pH and conductivity measurements were completed on slurries of the soil samples.

The results for Ca show no difference in the –80/+200 mesh versus the –200 mesh size fractions (Fig. 4A). Gold concentrations appear to be slightly higher in the –200 mesh fraction (Fig. 4B). However, the differences in the concentrations of Au and other elements between the two size fractions were not deemed sufficiently significant to justify the need for very fine soil-size fractions at Gap.

In general, the soil chemistry appears to follow observable features in the soil profile (Fig. 5). Calcium concentration tracks the amount of caliche, and Fe concentration tracks the amount of brown to red smectitic clay. There is a correlation between Au and Ca at all depths, indicating accumulation of Au in precipitated carbonate, and a process whereby soluble Au is being precipitated (Fig. 6A). In contrast, there is no correlation between Au and Fe concentrations, indicating Fe oxides in the soil are not fixing gold (Fig. 6B). Similarly, there is no correlation between Au and Mn concentrations. Accumulation of Au in caliche as a guide to underlying ore has been documented in many arid to semi-arid environments throughout the world, including several areas of Australia (e.g., Lintern, 2001) and Nevada (e.g., Smee, 1998). The accumulation of Au in caliche is likely the result of geomicrobial processes and evapotranspiration (Reith et al., 2009).

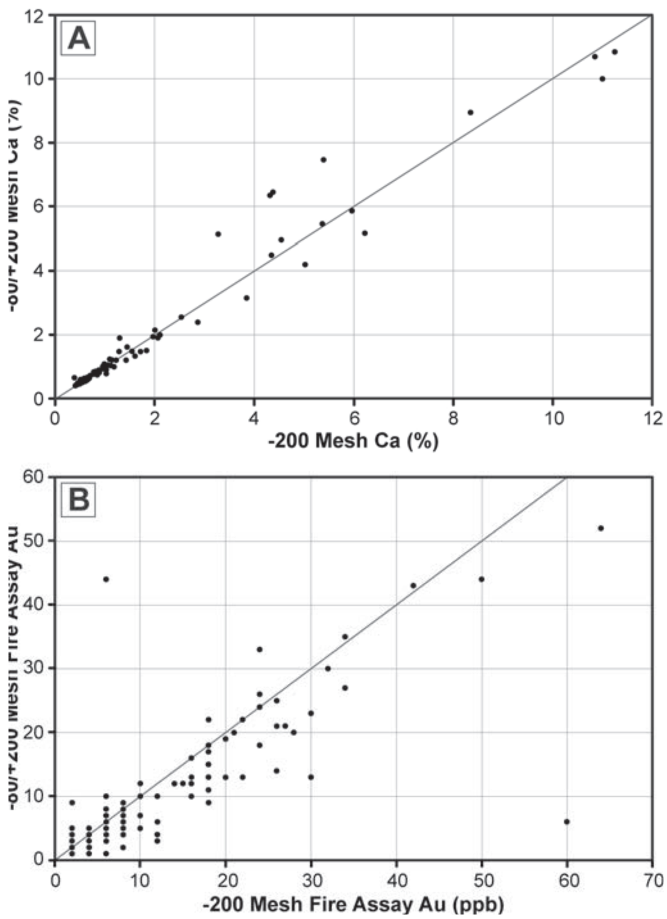

FIG. 4. Graphs comparing soil analyses of the –80 to –200 mesh size fraction with –200 mesh fraction for A. Ca and B. Au. Au was done by fire assay. Ca, As, and Fe analyses were done using an aqua regia digestion.

Trace elements appear to exhibit behavior distinct from Au in the soils at Gap. Arsenic, Sb, Tl, and other elements correlate with Fe at all depths (Fig. 6C), indicating Fe oxides are fixing these elements. Unlike Au, As and Sb do not correlate with Ca (Fig. 6D), indicating they are not accumulating with carbonate precipitation. Mercury shows no correlation with either Fe or Ca, indicating it was likely liberated during oxidation of sulfides and migrated to the surface in the form of Hg° (cf. Klusman, 1993).

Results of pH and conductivity measurements on soil slurries showed that pH ranged from 8.5 to 9.8, and conductivity ranged from 18 to 362 (median of 46). The pH showed no systematic variation with soil horizon or depth. Conductivity increased with depth in most of the test pits.

Selective leach soil analyses

In addition to the Au fire assay and the multielement analyses using an aqua regia digestion, two commercially available selective leaches were tested. During the vertical profile sampling of the pits along lines A and B (Fig. 2), two extra samples, at depths of 6 to 12 cm, were collected for Enzyme Leach and MMI-B. These selective leaches attempt to extract the most mobile fractions of the elements present in soils, such as water-soluble salts, weakly adsorbed ions and colloids, or amorphous secondary minerals, such as Mn oxides (cf. Cameron et al., 2004). The objective of such leaches is to maximize the contrast between anomalies and background.

Enzyme Leach, marketed by Actlabs, claims to be specific for dissolving amorphous Mn-oxide (Clark, 1993). An enzyme is added to sugar water (dextrose), which forms gluconic acid and hydrogen peroxide. The hydrogen peroxide acts as a reductant, preferentially dissolving amorphous Mn oxides, while gluconic acid buffers the pH and complexes the metals. The reaction shuts down when hydrogen peroxide is no longer consumed. The method is best applied to B-horizon soils and reports 61 elements by ICP-MS. Advantages of the method are that it uses a very weak leach and should go after all water soluble phases, amorphous Mn oxides, but little else.

MMI-B (Metal Mobile Ions-Base), currently marketed by SGS Minerals Services, is a proprietary method that claims to extract metals loosely attached to clays, organic matter, iron oxides, and other phases (Mann et al., 1998). The leach uses selected ligands to complex and retain specific metals in solution, rather than selectively dissolving specific phases in the soil. We utilized MMI-B, which at the time of the study was a weak base with ligands optimal for detaching and dissolving Au, Ag, Ni, Co, and Pd.

Figure 7 compares Au analyses by fire assay, MMI-B, and Enzyme Leach for line A. Clearly, the Enzyme Leach analysis was inappropriate for Au in this setting, which is consistent with the lack of correlation between Au and Mn. The fire assays (especially the –200 mesh size fraction) and the MMI-B results were comparable and have similar anomaly contrasts

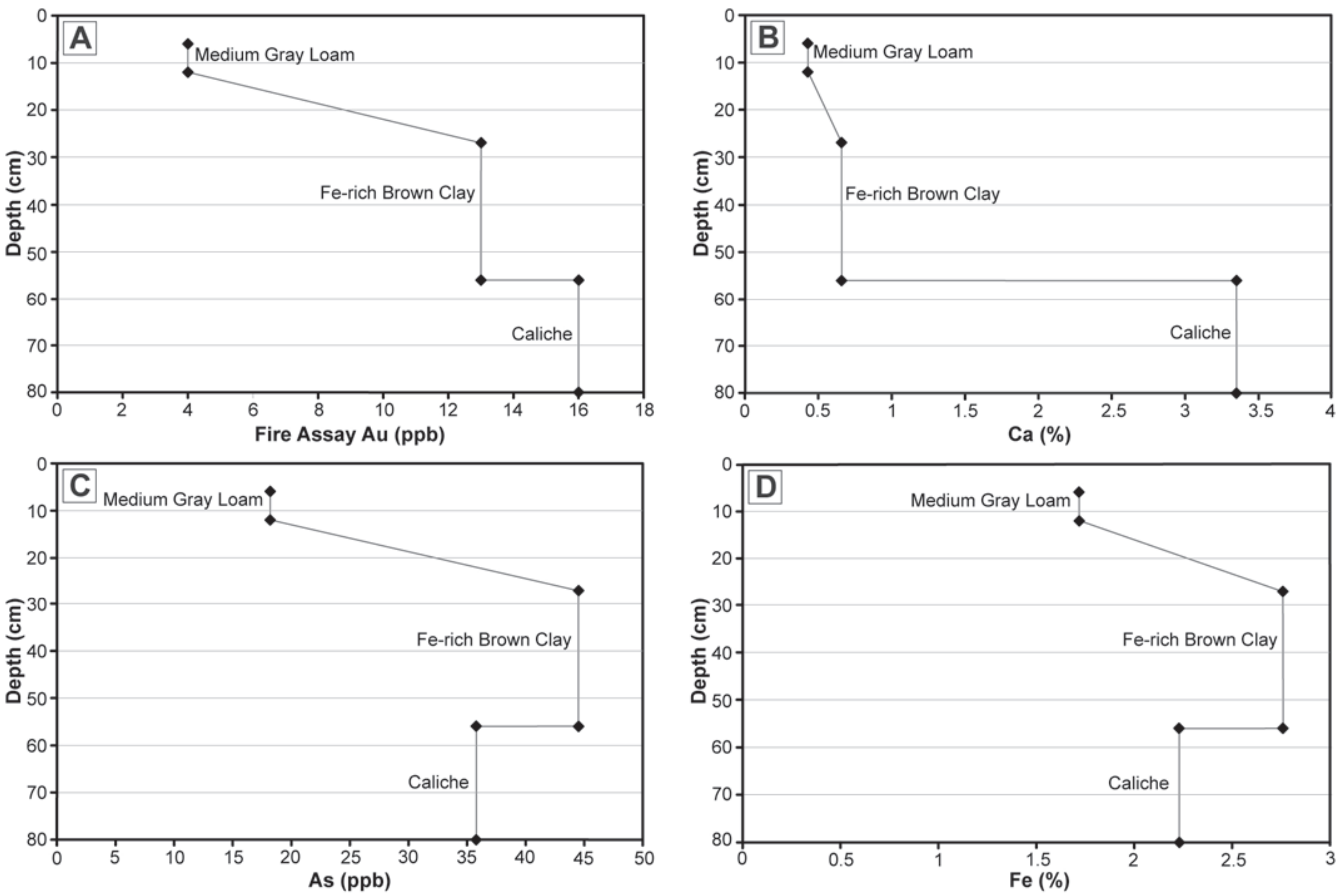

FIG. 5. Graphs showing the concentration of the following: A. Au, B. Ca, C. As, and D. Fe, as a function of depth in soil profile test pit shown in Figure 3B. Shows gold is enriched in the caliche zone, and, to a lesser extent, in the brown smectitic clay, while As is more enriched in the clay relative to the caliche. Au was done by fire assay. Ca, As, and Fe analyses were done using an aqua regia digestion.

for both lines A and B. The mean of the MMI-B Au analyses was 30 percent lower than that the mean of the fire assays.

The Enzyme Leach analyses show coherent anomalies for As and Sb that are slightly offset from the Au anomaly along line A (Fig. 8). The anomaly to background contrast is much stronger for the Enzyme Leach analyses. The Enzyme Leach and aqua regia results for As along line B (not shown) showed similar patterns and contrasts, but the Sb results for line B had different patterns.

Design of Gap soil orientation survey

Based on the vertical profile sampling and the selective leach analyses, a survey that covered a larger area over Gap was designed. A dispersion model is necessary to effectively design a survey, including sample line orientation, line spacing, and sample spacing along the lines. As discussed by Cameron et al. (2004, 2005), element migration to the surface in arid environments with deep water tables, such as at Cortez, likely occurred along bedrock faults and fractures that propagated upward through the overburden. If that is the case, lines of closely spaced samples would be favored over a grid. Using this model for elemental dispersion, we placed three sampling lines across the main ore zone and north-northwest–striking structural fabric at Gap (NE lines 1–3, Fig. 2). These three lines extend up to 570 m away from known underlying ore. In addition, we included a north-south tie line that extended 950 m southward from the main ore zone (NS line, Fig. 2). Much of the eastern parts of NE lines 1 to 3 and much of the northern part of the NS line are underlain by marble and local skarn.

Samples were planned at 50-m spacings along each line. At each site along NE lines 1 to 3, vertical profile line B, and much of the N-S line, the concentration of CO_2 and O_2 in soil gas was measured with a portable meter. If there was a CO_2 anomaly, we backtracked 25 m toward the last sample and took another soil sample and soil gas measurement. If CO_2 was still anomalous, we backtracked an additional 12.5 m and took one more soil sample and soil gas measurement. Therefore, the sampling was biased toward areas of anomalous CO_2, which could be indicators of faults and fracture zones acting as pathways for elements migrating upward from bedrock. The methodology and the results of the soil gas measurements are presented below.

From the soil horizon descriptions and the soil chemistry work presented above, it was apparent that Au was being remobilized at times by precipitation processes related to caliche formation. Similarly, As, Sb, Tl and other elements were fixed by iron oxides in the soil. However, the soil profiles

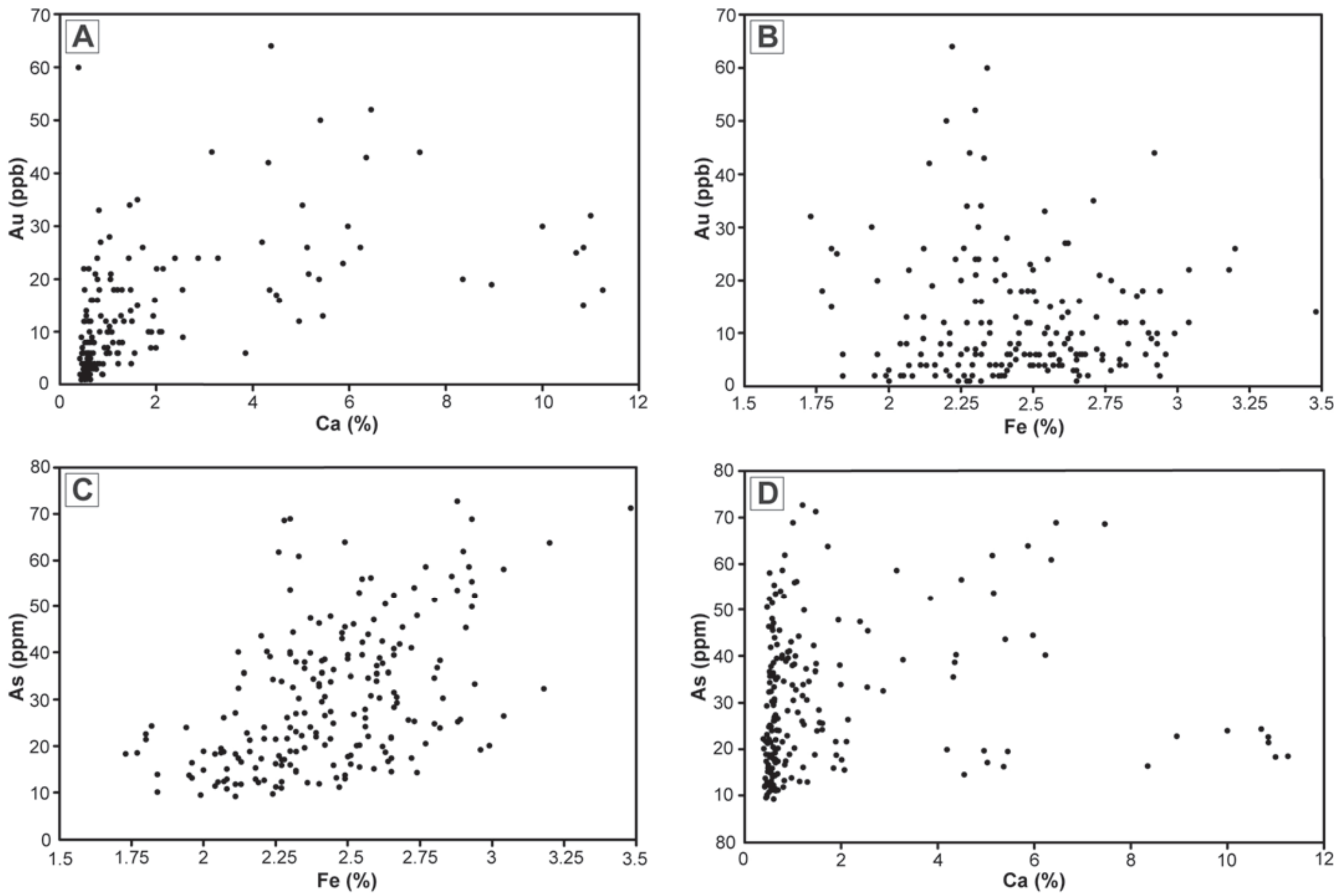

FIG. 6. A. Au versus Ca in Gap soils collected from all depths in profile test pits, including both the –80 to –200 mesh and –200 mesh size fractions. Correlation coefficient of 0.554. B. Au versus Fe. Correlation of –0.026. C. As versus Fe. Correlation coefficient of 0.496. D. As versus Ca. Correlation coefficient of 0.125.

vary greatly at Gap. Neither caliche nor iron oxides were present in all the test pits, and, therefore, do not provide consistent, readily available media for routine sampling. The consistent soil sampling medium identified at Gap, and sites in the Cortez window on east side of Crescent Valley, was the near-surface brown to gray loam layer. The 6- to 12-cm–depth loam horizon provided a sample removed from surface windblown contamination, and material with sufficient Fe (1–3%) and Ca (0.4–2%) to scavenge and accumulate mobile trace elements. As pointed out above, no advantage was seen in collecting –200 mesh soils over –80 mesh soils, and as a practical matter, –80 mesh soils would deliver sufficient sample size for the required analyses. Based on the findings from the vertical profiles, –80 mesh loam from 6- to 12-cm depth was selected as the soil medium of choice for the orientation survey.

Based on the apparent presence of Au in both caliche and its local occurrence in iron oxides and the observation that MMI and Enzyme Leach offered no apparent significant improvement in response, an aqua regia digestion was selected for the orientation survey. Given aqua regia extraction appeared to be sufficient, an ALS Chemex ultratrace-level gold method, called ZARG, was utilized in addition to conventional fire assay. The ZARG analysis, now referred to by ALS Chemex as “super travel level” Au (package Au-ST43), combined an aqua regia digestion with a graphite furnace atomic absorption analysis utilizing a Zeeman analyzer for improved sensitivity. The method determined Au at a detection limit of 0.1 ppb, an enhanced sensitivity compared to fire assays. Comparison of the ZARG Au analyses with conventional Au fire assays is presented below.

Mapped results of Gap soil survey

In total, 175 soil samples were collected by the authors in November 2002 along the 4 lines. The analyses were of composite samples taken from a depth of 6 to 12 cm from three holes dug within a radius of 2 m. Such composite sampling reduces sample variance and permits less distinct anomalies to be recognized, as pointed out by Cameron et al. (2005). Fire assay Au results are shown in Figure 9A. Clear, anomalies of >17 ppb appear at the north end of Gap where bedrock is relatively shallow, typically at depths of less than 10 m. A clustering of elevated Au concentrations (5–14 ppb Au) exists over the more deeply buried, main ore zone at Gap (located where the NE lines intersect the NS lines). Local anomalies, as high as 10 ppb Au, occur along the portions of lines well away from underlying known ore.

Like the fire assays, the ZARG analyses show a strong Au anomaly at the north end of Gap, a cluster of samples with

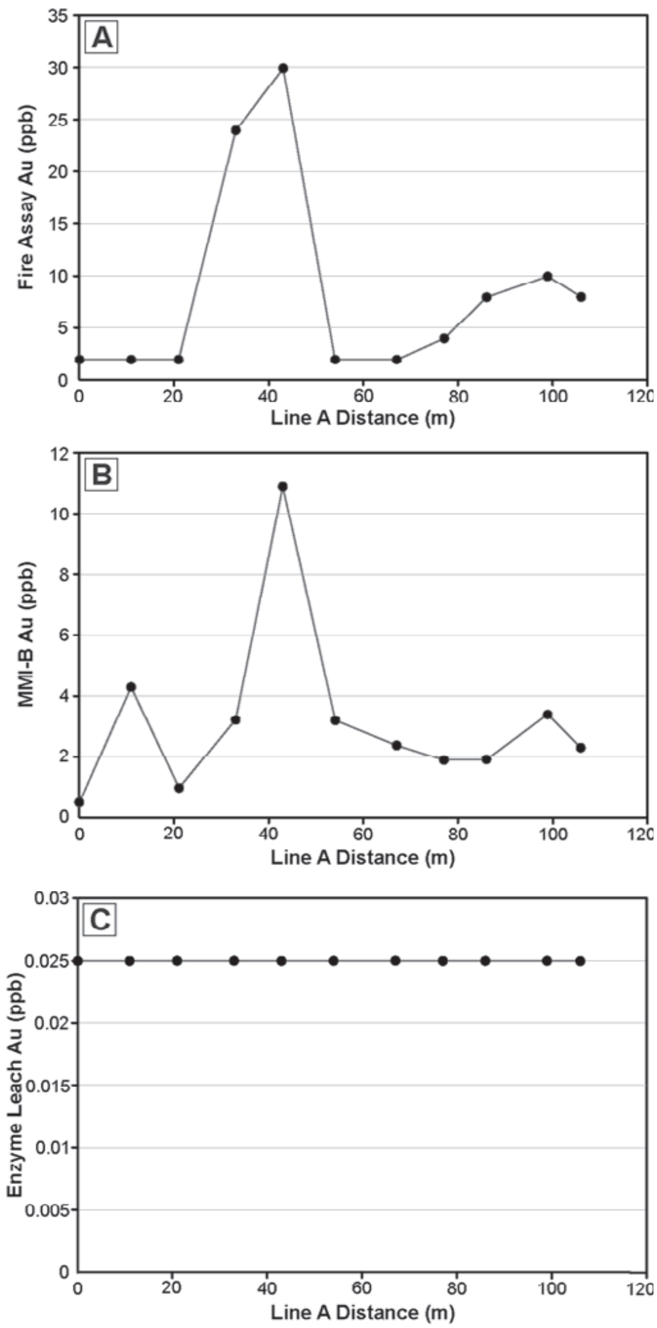

FIG. 7. Comparison of Au analyses by A. Fire Assay, B. MMI-B, and C. Enzyme Leach from soils at Gap collected at 6- to 12-cm depth from the profile test pits along line A in Figure 2.

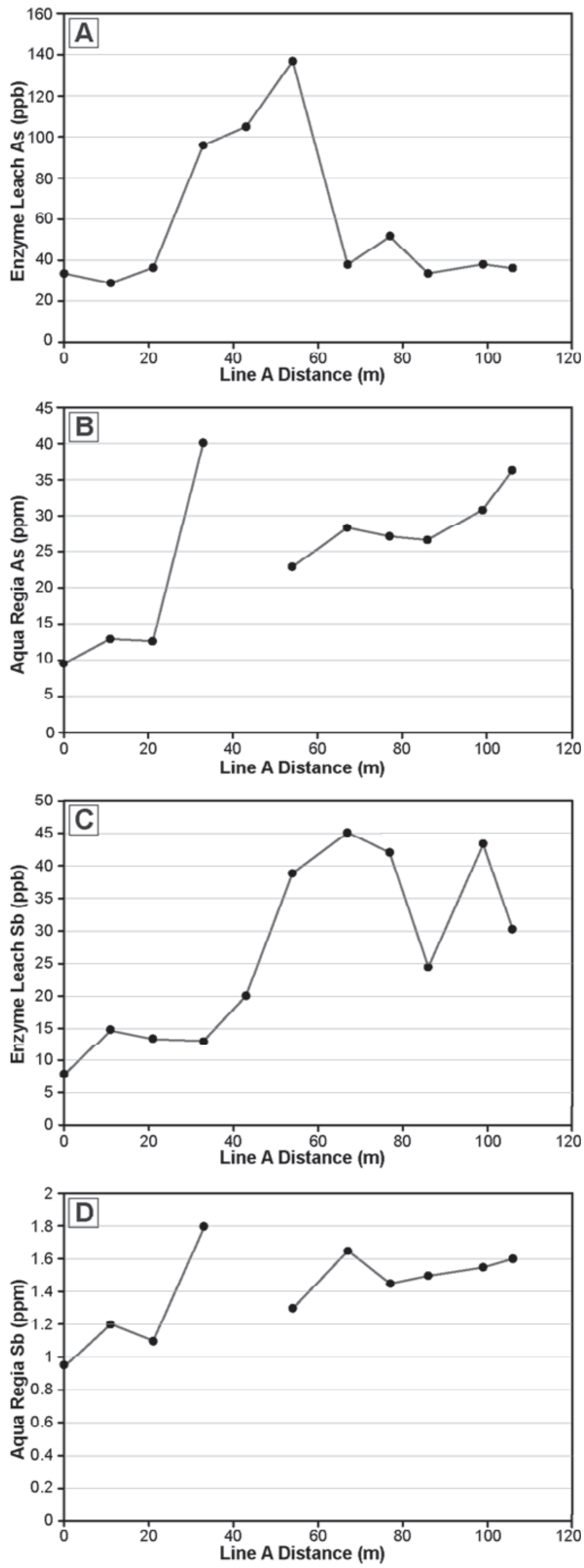

FIG. 8. Comparison of As analyses using A. Enzyme Leach, and B. aqua regia digestion, and comparison of Sb analyses using C. Enzyme Leach, and D. aqua regia digestion from soils at Gap collected at 6- to 12-cm depth from the profile test pits along line A in Figure 2.

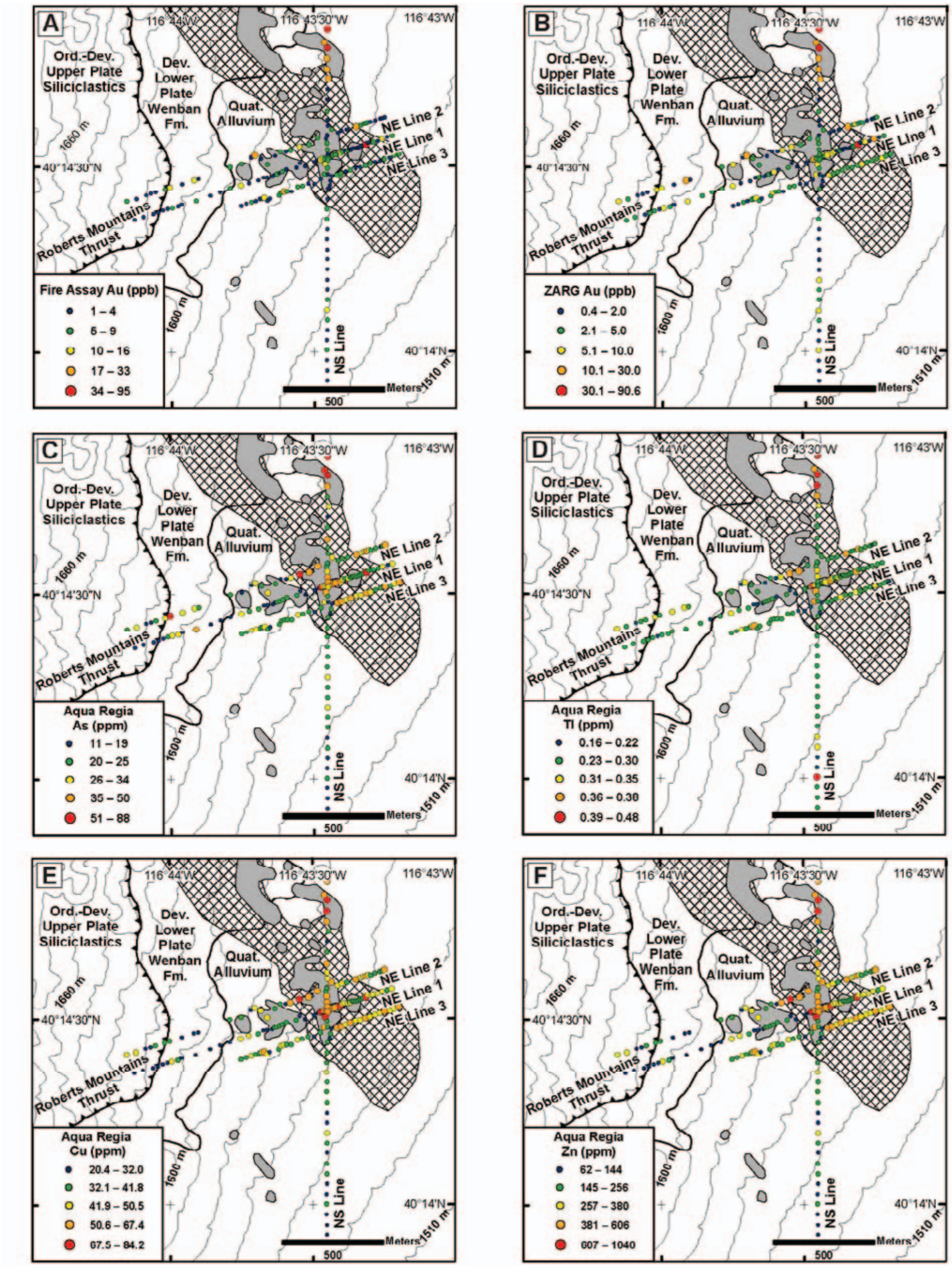

FIG. 9. Results of the soil orientation survey at Gap. A. Au (fire assay), B. Au (ZARG), C. As, D. Tl, E. Cu, and F. Zn. The gray zones are the surface projections of covered Au ore. The cross-hatched zones are the surface projections of marble that locally contains base metal-bearing skarn. Main geologic contacts are shown as well as topographic contours with an interval of 15 m. Except for the fire assays, the other analyses were done after digestion by aqua regia. Maps are of the same area as Figure 2.

elevated Au over the main ore zone, and local spikes in the same positions as the fire assays away from ore (Fig. 9B). In addition, the ZARG results show a more coherent cluster of anomalous values east of the main ore zone at Gap. Figure 10 shows a very good comparison between the fire assay and ZARG results. The fire assays provide a more complete extraction of Au from the soil, as demonstrated by the slightly higher Au concentrations in the fire assays versus the ZARG analyses. However, this feature of fire assays makes it more likely to include stray quartz-encapsulated or refractory Au in the alluvium that is not part of a mobile Au anomaly that formed by upward migration through the overburden.

Several trace elements in the soils at Gap using an aqua regia digestion indicate the presence of buried mineralization. Arsenic exhibits a strong anomaly over the relatively shallow ore at the north end of Gap and over the main ore zone, where a northwest trend of anomalous As is parallel to the underlying zone of marble and skarn (Fig. 9C). Results also indicate a well-expressed Tl anomaly over the shallow ore zone at the north end (Fig. 9D). A clustering of elevated Tl concentrations also occurs over the main ore zone. Antimony and Hg concentrations in the soil show no systematic pattern with respect to buried ore or anything else at Gap. Both Cu and Zn concentrations demonstrate a good spatial association with underlying Au ore, both over the shallow ore at the north end and the deeper main ore zone (Fig. 9E, F). Bismuth and Te also show coherent anomalies over the main ore zone.

Measurements of pH and soil conductivity on slurries of soils collected at 6- to 12-cm depth did not show any pattern with respect to underlying ore at Gap. The pH measurements ranged from 8 to 9.8 with a normal distribution centered on approximately 9. Conductivity ranged from 14 to 1020, with a median of 33.

Mapped results of Gap soil gas survey

Soil gas CO_2 and O_2 geochemistry provide important information in exploring through cover (cf. Klusman, 1993; Highsmith, 2000; Lovell, 2000; Kelley et al., 2006). These gases occur naturally in rocks and soils and move steadily as a flux

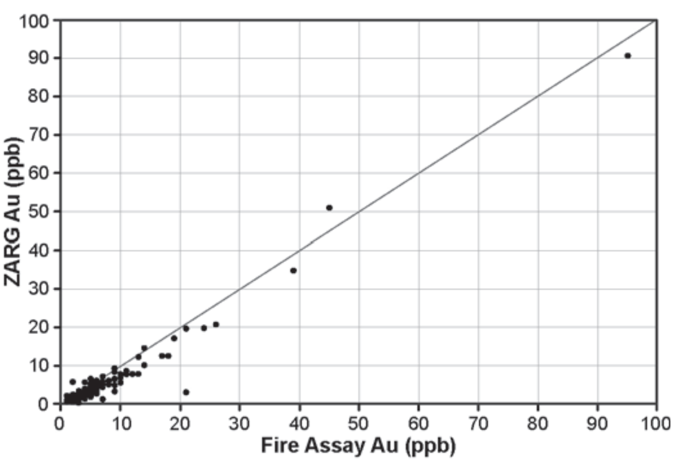

FIG. 10. Comparison of ZARG Au and fire assay gold analyses from soils collected at 6- to12-cm depth as part of the Gap orientation survey shown in Figure 9. Line marks equal concentration between the two methods. As expected, fire assays are up to 50 percent higher than the ZARG analyses.

from depth to the atmosphere. CO_2 is produced naturally from the oxidation of hydrocarbons and other carbonaceous matter. CO_2 is also produced by weathering and oxidation of sulfides and acid reaction with carbonate in rocks or naturally occurring bicarbonate in water. Typically, elevated concentrations of CO_2 in soil gas are accompanied by diminished concentrations of O_2, which is consistent with the consumption of O_2 to produce CO_2. Probably due to increased flux of all gas compounds along fractures, CO_2 and O_2 anomalies in soil gas can be used to locate fault zones propagating through cover (e.g., McCarthy and McGuire, 1998).

In this study, CO_2 and O_2 were measured with a battery-run, portable field analyzer due to the infrared absorption characteristics of CO_2 and the paramagnetic properties of O_2 with electron capture chemical cells. A specially designed hollow steel probe, with a steel nail inserted into the lead opening, was pounded approximately 0.75 to 1 m into the ground with a slide hammer. The probe was connected to the analyzer with tubing. The atmospheric levels of CO_2 and O_2 were first measured, then the probe was lifted slightly to allow the nail to drop. Approximately 4 liters of gas was then pumped from the soil, through the probe and tubing, and into the analyzer. The differences between atmospheric and soil level of gases were recorded and denoted as "Delta CO2" (ΔCO_2) and "Delta O2" (ΔO_2). Atmospheric values of CO_2 averaged 415 ppm with a standard deviation of 85 ppm, whereas O_2 averaged 20.9 percent with a standard deviation of 0.17 percent. Background conditions can change due to temperature and changing atmospheric conditions, but daily measurements taken at a base station showed the soil gas concentrations were stable during the sampling period in November 2002. In addition, soil moisture can strongly affect the results; however, sample localities were dry during the sampling period.

Figure 11 shows the results of the soil gas survey completed by the authors with the assistance of Patrick Highsmith. A total of 168 sites were measured. The ΔCO_2 ranged from 250 to 14,620 ppm with a median of 2,235 ppm, while ΔO_2 ranged from 0 to 2.7 percent with a median of 0.2 percent. The highest CO_2 and lowest O_2 values occur along the east sides of NE lines 1 and 2, across and along the eastern flank of the main ore zone at Gap. These areas are underlain by skarn and marble. Strong CO_2 anomalies, accompanied by low O_2 also occur on the west side of NE lines 1 and 2. These anomalies are spatially associated with the Roberts Mountain thrust.

Mapped results of Gap vegetation survey

A vegetation survey was completed at Gap by the senior author and S. Clark Smith in early December 2002. Vegetation sampling was completed along the same lines and sites where soils had already been collected (Fig. 12). As summarized by Smith (2002), plant roots, with the aid of bacteria, are the main organs of metal uptake. Organic acids with pH values as low as one are produced around roots. The type and quantity of elements taken up by plants is dependent upon the species.

The vegetation samples at Gap comprise two plant species: sagebrush and shadscale. Typically in northern Nevada, as one moves away from ranges toward the more arid center of a basin, available vegetation changes from sagebrush to shadscale owing to decreased precipitation and increased salt

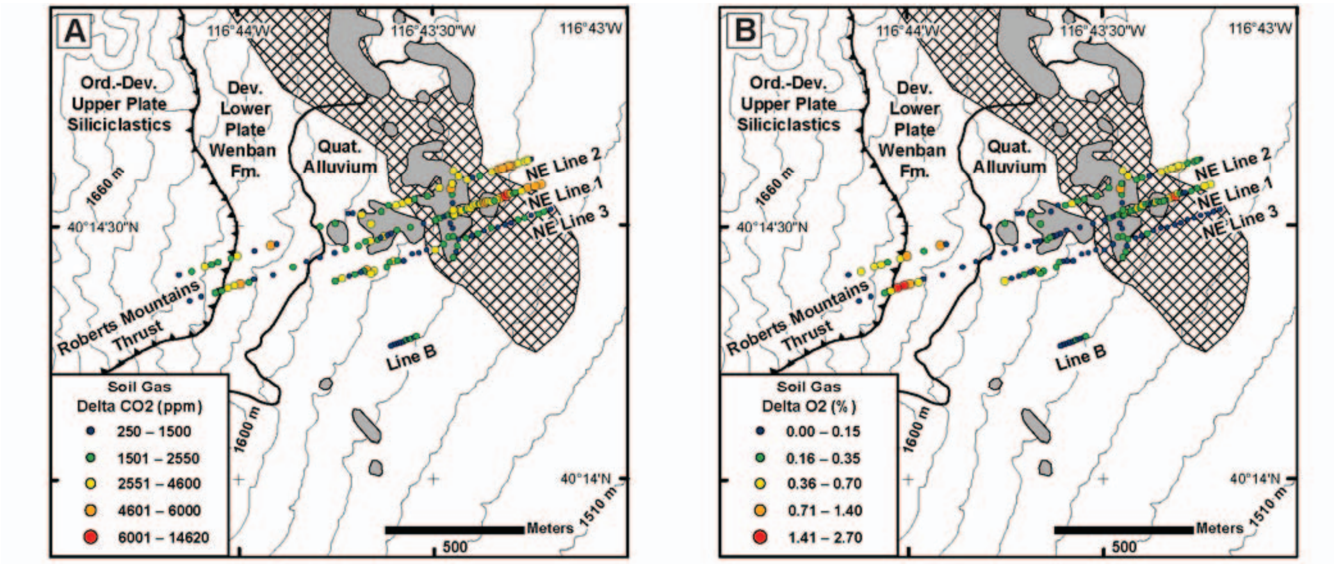

FIG. 11. Results of the soil gas orientation survey at Gap. A. ΔCO_2 B. ΔO_2. The gray zones are the surface projections of covered Au ore. The cross-hatched zones are the surface projections of marble that locally contains base metal-bearing skarn. Main geologic contacts are shown as well as topographic contours with an interval of 15 m. Maps are of the same area as Figure 2.

content in the basin. The twigs of sagebrush and live bark of shadscale are the preferred vegetation media for Au exploration (Smith and Kretschmer, 1992). As Figure 12 shows, the western and northern portions of the survey area had available sagebrush. Shadscale was sampled in the southern and eastern portions of the survey area. Collected sagebrush twig (Fig. 3C) and shadscale bark (Fig 3D) samples were washed and pelletized by S.Clark Smith and then analyzed by neutron activation by Bequerel Laboratories for Au and a multielement suite. The difference in vegetation sample type can be important in interpretation of biogeochemical data. While concentrations of elements such as Br were not readily comparable between sagebrush and shadscale, the concentrations of Au, As, Sb, Zn, Cd, and W were comparable, and therefore, the data were not leveled.

Gold in the combined sagebrush and shadscale samples provides a reasonably robust anomaly associated with underlying ore at Gap (Fig. 12A). A number of samples from the most anomalous population, from 6.1 to 15.3 ppb Au, are located above ore, and a quiet background of less than 3.3 ppb Au extends to the south away from known underlying ore. Unlike the soils, the sagebrush and shadscale samples do not show nearly as many spikes away from known ore. The shadscale samples are most elevated in Au at the eastern ends of NE lines 1-3. Contamination from the Pipeline mining operations, which in 2002 were located just to the east of Figure 2, is a possible concern here; however, the Au concentrations do not exceed 4.6 ppb in the washed shadscale samples. Furthermore, the highest Au concentrations are not located in samples closest to the pit, as would be expected were contamination the unique source of Au in these samples.

Arsenic in mixed sagebrush and shadscale vegetation at Gap provides a distinct anomaly over the top of the shallow buried ore to the north, and a spotty pattern over the main ore zone (Fig. 12B). Low As values in samples in both species to the south and west are consistent with an absence of known covered ore. Antimony in mixed vegetation provides a pattern similar to that for Au and As, but with only a weak expression above the shallow ore at the north end of Gap. Spotty high Sb concentrations occur over the main ore zone, and like Au and As, persistently high values occur at the east end of NE lines 1 to 3 (Fig. 12C). Zinc in mixed vegetation provides a strong anomaly expression spatially associated with underlying Au ore and marble-skarn (Fig. 12D). Zinc is mostly below 16 ppm away from buried ore along the western ends of NE lines 1 to 3 and the southern end of the NS line. Cadmium shows a similar pattern to Zn. The highest W concentrations are restricted to areas overlying ore, but the overall pattern of elevated W concentrations is much less systematic with respect to ore than Zn or Cd.

Profile views of the Gap orientation data

Figure 13 synthesizes the results of the orientation survey as series of profiles along NE line 1, which goes over the main ore zone at Gap. Anomalies can be better interpreted in profile than in map view. In profile view, subtle anomalies can be recognized, which in map view may appear as background or noise. Also, anomalies are considered more reliable if they have shoulders in profile view, meaning values that gradually increase and decrease rather than single-point spikes. This type of pattern is strictly related to spacing. Because we reduced sample spacing based on gas anomalies, we were, in effect, mapping leakage halos from faults penetrating ore.

The interpreted geologic cross section in Figure 13, which is based on drilling, shows the ore zones are spatially associated with four interpreted northwest-striking faults. The eastern half of the ore zones spatially overlap zones of marble, skarn, and base-metal–rich gossan. The eastern ore zones are generally deeper than the western ore zones.

Fire assay and ZARG analyses of Au in soil show very similar patterns along NE line 1. The local, interpreted threshold for the fire assay Au (4 ppb) is slightly higher than that for

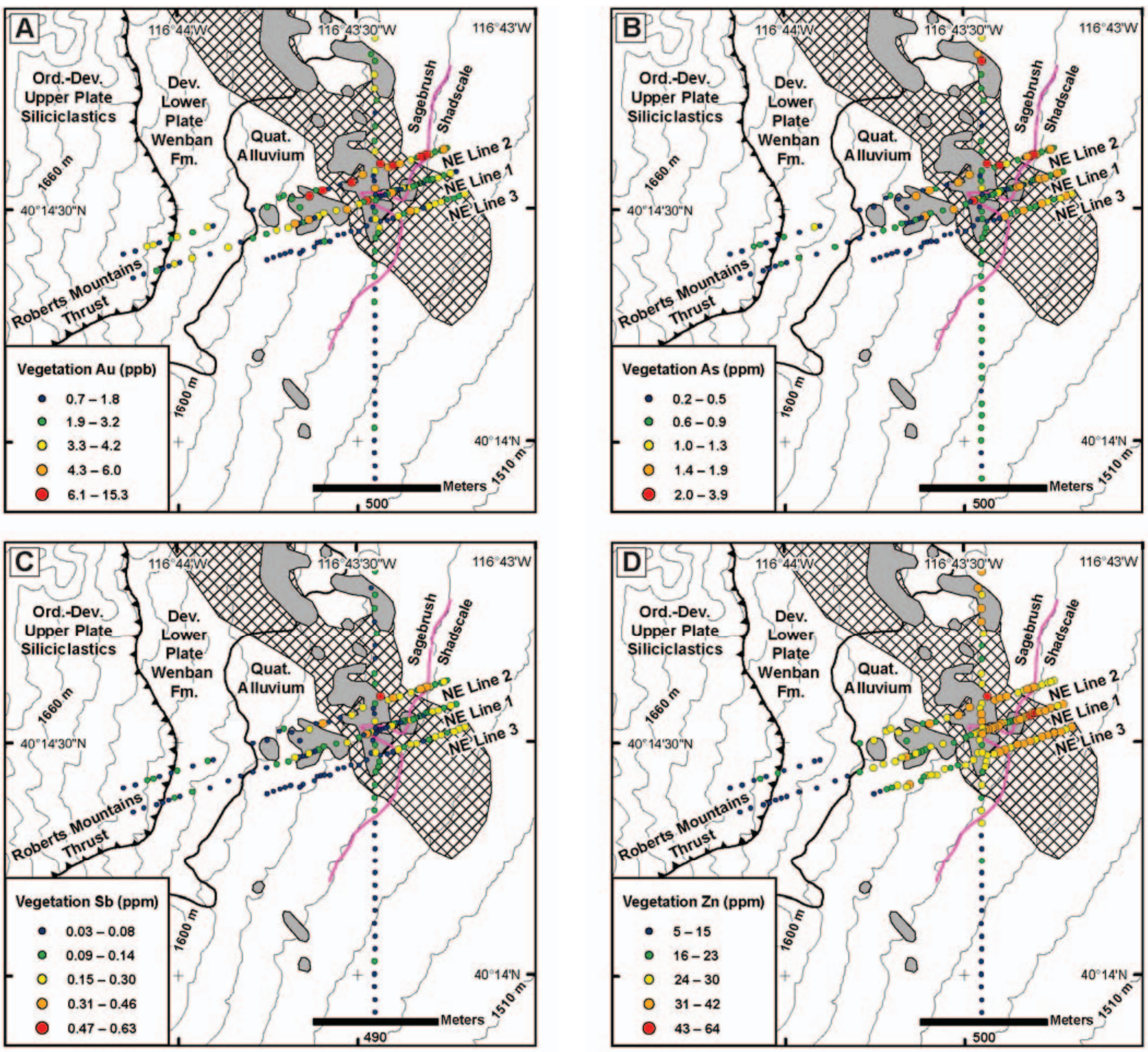

FIG. 12. Results of the vegetation orientation survey at Gap. A. Au, B. As, C. Sb, and D. Zn. Magenta line shows the boundary between sagebrush and shadscale samples. The gray zones are the surface projections of covered Au ore. The cross-hatched zones are the surface projections of marble that locally contains base metal-bearing skarn. Main geologic contacts are shown as well as topographic contours with an interval of 15 m. Maps are of the same area as Figure 2.

ZARG Au (2 ppb); however, the anomaly to background contrast is very similar for the two methods. The high values are on the east side of the line, with the highest value spatially associated with the easternmost northwest-striking fault. High values of CO_2 in soil gas and As and Zn in soil coincide with the northwest-striking fault as well. These high values lie along the margin of the interpreted underlying zones of Au ore and marble-skarn-gossan; based on drilling at the end of 2002. The most coherent Au anomaly along NE line 1 lies directly above the center of the main ore zone at Gap. The anomaly is defined by 11 consecutive samples, collected over a distance of 120 m, that range from 3 to 14 ppb Au by fire assay and 2.6 to 10.2 ppb Au by ZARG. That anomaly is accompanied by high As (>30 ppm) and Zn (>400 ppm) concentrations. Delta CO_2 values in soil gas are consistently above 1,500, the interpreted threshold, and form three distinct anomalies within the coherent Au anomaly.

The western part of NE line 1 that overlies and extends beyond the western half of the ore zone is characterized by noisier data and by Au anomalies in soil that are much narrower (one to two points above interpreted local threshold) and lower in contrast (<2:1). The As and Zn soil concentrations, however, form a coherent anomaly over the western half of the ore zone, but at much lower contrast than the eastern half. Arsenic concentrations are mainly >15 ppm and Zn values >150 ppm. Zinc values west of the ore zones are <110

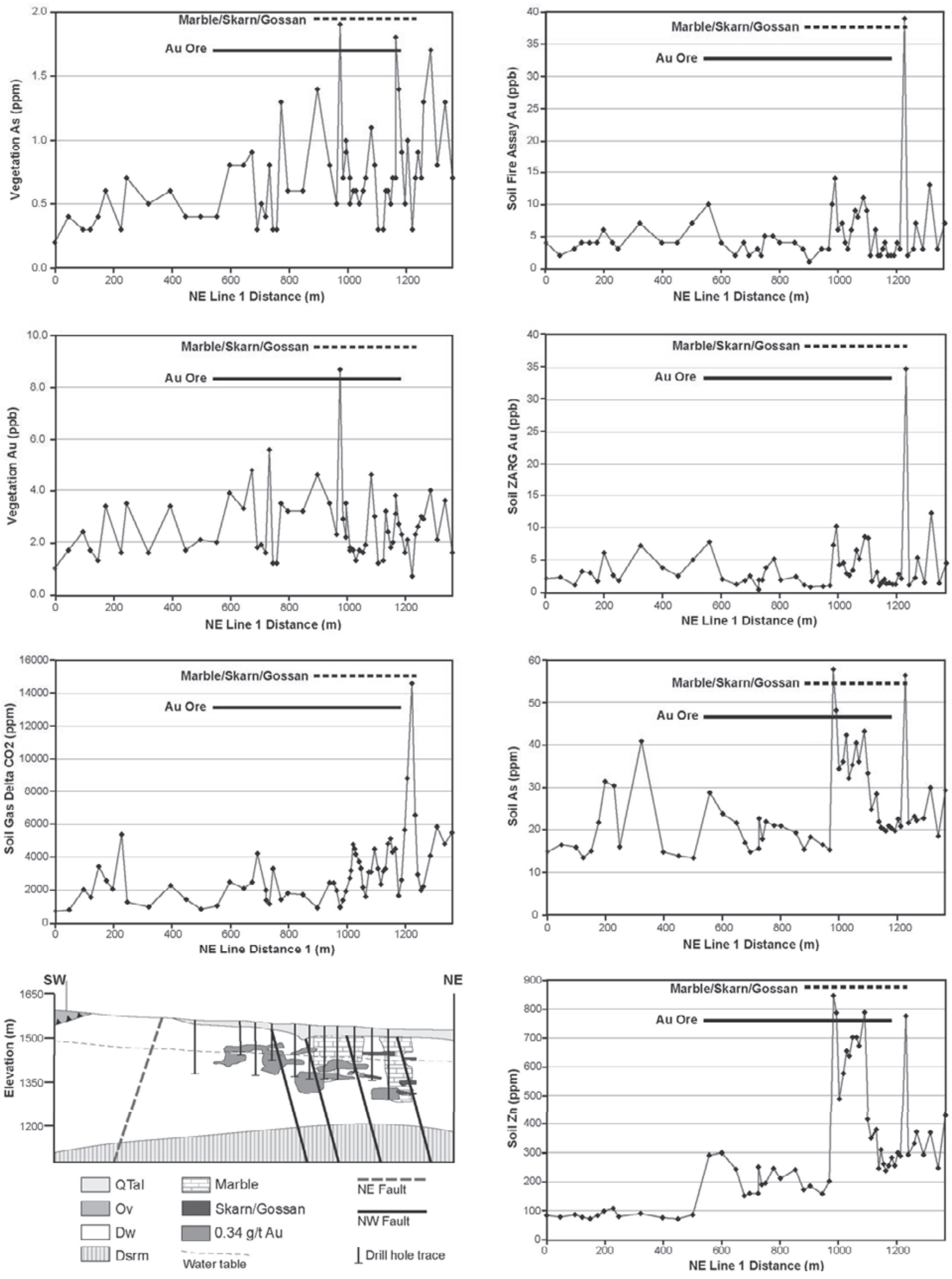

FIG. 13. Profile views of the Gap orientation survey along NE line 1 showing selected soil, soil gas, and vegetation data in relationship to underlying geology, Au ore, and marble zones that locally contain base metal-bearing skarn. DSrm = Devonian-Silurian Roberts Mountains Formation, Dw = Devonian Wenban Formation, Ov = Ordovician Vinini Formation, QTal = Tertiary-Quaternary unconsolidated alluvium. Geology was provided by T. Thompson, Cortez mine staff geologist.

ppm and form a flat pattern. On the other hand, As concentrations form 2 anomalies west of the ore zone, a three-point anomaly and single-point anomaly of 41 ppm. Delta CO_2 values in soil gas over the western half of the ore zones are mainly above 1,500 ppm but are not nearly as high as over the eastern half of NE line 1. A coherent 6-point anomaly, ranging up to 5,370 ppm, occurs near the western end of NE line 1 appears to be related to the Roberts Mountain thrust.

The vegetation data in profile view along NE line 1 are much noisier and show much lower contrast with interpreted thresholds than the soil and soil gas data. Nevertheless, inspection of the profiles shows Au and especially As concentrations are higher along the eastern half of NE line 1. A fairly coherent Au anomaly with 10 consecutive points that spans 223 m and has concentrations greater than 2 ppb and a high of 8.7 ppb occurs over the center of the main ore zone. The anomaly occurs to the east and partially overlaps the coherent Au in soil anomaly pointed out previously. A stronger, more robust Au anomaly occurs along NE line 2 (profile not shown, but see Fig. 9A), where an 8-point anomaly with concentrations ranging from 3.3 to 15.3 ppb Au sits directly above the main ore zone. Arsenic concentrations in vegetation are mainly >0.5 ppm, ranging up to 1.8 ppm over the ore zones and the east half of NE line 1, whereas concentrations are mainly <0.5 ppm west of the ore zones.

The Gap orientation survey provides an opportunity to assess the effect of sample spacing on recognition of anomalies and their relationship to underlying ore zones. As pointed out, the sampling lines had a nominal 50-m spacing with infill sampling in areas of elevated CO_2 in soil gas. Figure 14 shows profile views of Au and As in soil along the NS line in relationship to the interpreted underlying geology. For both Au and As, two profile views are shown. One shows all the data collected during the orientation survey, and the second shows the data at a 100-m spacing, with the intervening data removed. The Au profiles show the main ore zone at Gap would be missed using a 100-m spacing. The main ore zone is apparent in the 50-m spacing and infill—a 4-point anomaly ranging up to 13 ppb Au. Both Au profiles show some narrow anomalies at the south end of the line where there is no known underlying Au ore. The shallowly buried ore at the north end of the line is apparent at both 100- and 50-m spacings. Arsenic in soil is also effective in detecting the shallow ore zones at both sample spacings, but better resolves the main ore zone with the survey design employing the 50-m spacing and soil gas-guided infill.

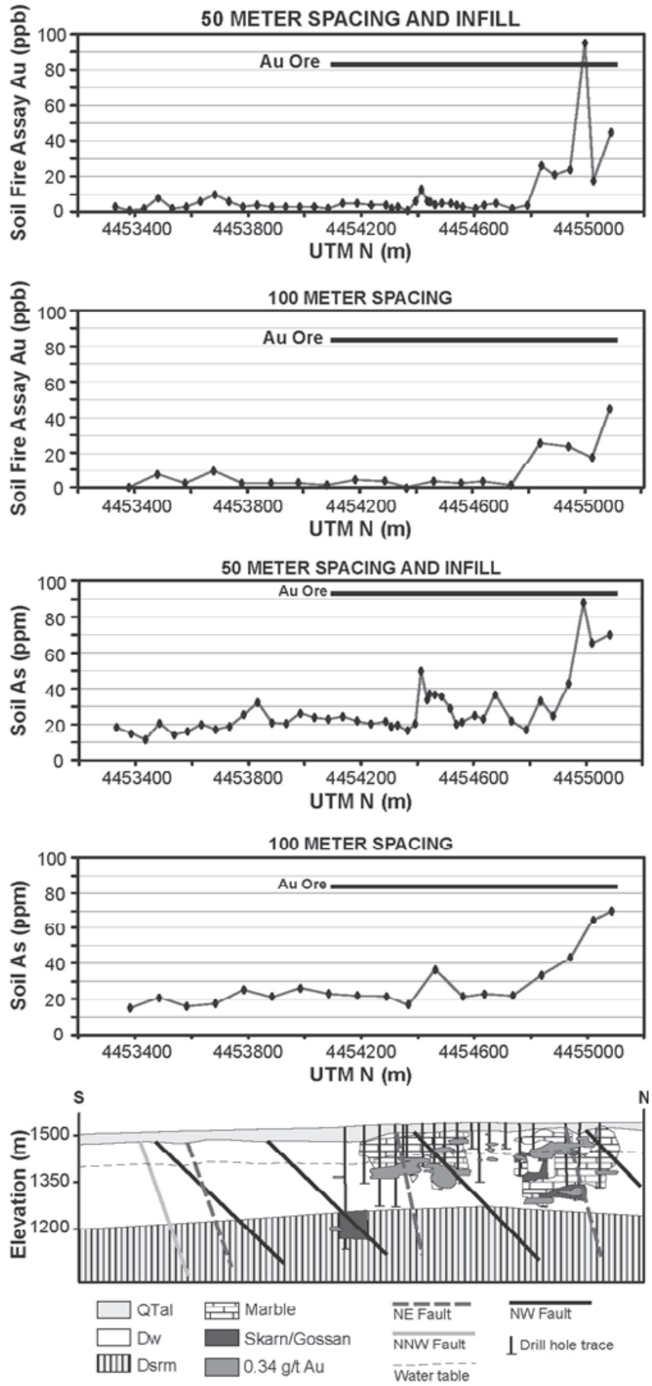

FIG. 14. Profile views of the Gap orientation survey along NS line 1 showing Au fire assays and As analyses in relationship to underlying geology and Au ore at both the original 50-m spacing with infill, and at 100-m spacing, in which intervening data were removed. See text for discussion on effect of sample spacing in recognizing the anomalies. DSrm = Devonian-Silurian Roberts Mountains Formation, Dw = Devonian Wenban Formation, QTal = Tertiary-Quaternary unconsolidated alluvium. Geology was provided by T. Thompson, Cortez mine staff geologist.

Summary of results

The ore zones at Gap that are buried by variable amounts of transported overburden and pre-ore bedrock can be detected by geochemical methods employing soils, vegetation, and soil gas. Loam soils, collected at 6- to 12-cm depth, provide a consistent and uniformly available sample medium. Gold ore under 10 m of gravel cover in the northern portion of the Gap deposit is readily detected by analysis of Au in these loam soils. Arsenic in loam soils also locates the Au ore at the northern end, but also forms a robust anomaly over most of the main ore zone at Gap, where there is 25 to 50 m of gravel cover. However, several narrow, low-contrast anomalies in several elements also occur in areas not underlain by ore. Zinc and Bi concentrations in soil show the most coherent spatial relationship with underlying Au ore. Unlike the other elements, concentrations of Zn and Bi are consistently below threshold values away from known ore.

The higher values of Au, As, and other elements in soil over the main ore zone also coincide with the underlying zone of marble with local skarn and base-metal–rich gossan. Elevated CO_2 values in soil gas are also associated with the underlying marble with the highest values occurring above the northeast margin of the marble. The high CO_2 is likely the result of dissolution of marble by reaction with acid generated by oxidation of sulfide zones in the marble and skarn. As discussed at the end of the paper, the generation of CO_2 and other gases in an actively weathering environment may have served as a carrier gas for metals from the mineralized bedrock to the surface gravels.

Elevated Au in mixed vegetation occurs over most of the areas underlain by ore zones; however, the vegetation data are much noisier than the soil data. Unlike the soils, the highest Au concentrations in vegetation surprisingly occur over the deeply buried main ore zone rather the shallowly buried northern zone. Arsenic, on the other hand, forms a stronger anomaly over the shallow northern zone than over the main ore zone. Like soils, elevated Zn shows the most coherent spatial relationship with underlying Au ore throughout the survey area.

Elevated values of several elements in soil and especially vegetation, as well as CO_2 in soil gas, occur just east of the main ore zone, near the ends of lines NE 1, 2, and 3. The significance of the high values east of the known ore zones was not determined based on the drill pattern at the end of 2002.

Greater Pipeline Area

Base of pediment gold footprint

Efficient exploration requires understanding the size and significance of the buried targets around large Au systems. This section examines whether Au in the covered bedrock surface and in the basal gravels eroded from that surface can provide a large drill target. When Au deposits are overlain by pediment gravels typical of the basins of Nevada, the explorationist in a drilling program is presented with targets of varying size (Fig. 15). The Au ore itself represents the smallest target, the one most difficult to intercept. Alteration and lithogeochemical enrichment in bedrock represents a larger target than the Au ore, and unconformity gravels, akin to paleoplacers derived by erosion, could represent an even larger target to the explorationist drilling through cover.

For the greater Pipeline area, a drill hole database containing 1,859 holes was assembled in 2002. Routine procedures at Cortez had historically involved recovering samples from 3-m intervals and completing fire assays of Au. Three-meter sampling intervals did not always end and begin exactly at the base of gravels and the top of bedrock. Overlap between bedrock and gravel cover exists in the "lowest gravel interval" and the "top bedrock interval" extracted from the drill hole database. To avoid mixing bedrock with alluvium in the data set, drill interval populations were extracted from the "second" bedrock interval and the "next to last" gravel interval. These data populations are shown in Figure 16. Multi-element analyses had been completed on only a limited number of drill holes; thus, only Au is considered here.

The elevation of the bedrock surface also was extracted from the drill hole database. Fifty meter contour intervals of this surface are displayed in Figure 16. There are some unusual points on the contour surface where the bedrock elevation was probably not accurately recorded, but the general trend of the bedrock surface slopes from west to east. Northwest-trending drainages are apparent in the contours.

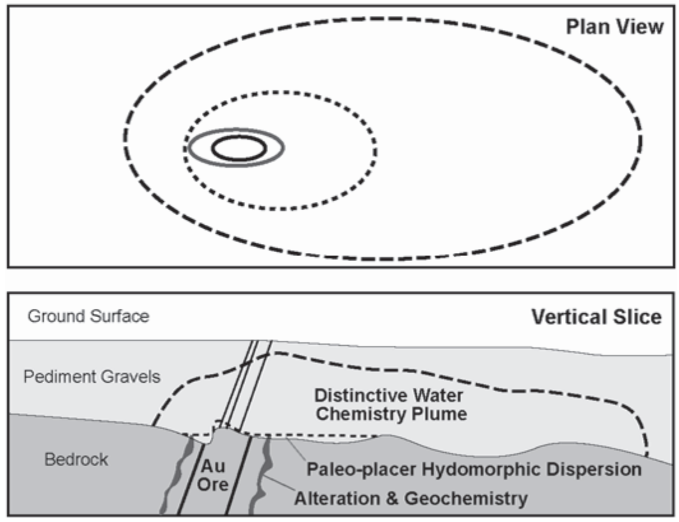

FIG. 15. Schematic diagram showing size and shape of dispersion halos in various sampling media expected to occur around orebodies covered by pediment gravels.

The dense, northwest-trending cluster of drill holes in Figure 16 defines the Pipeline deposit as of 2002. The deposit is covered by alluvium that ranges in thickness from 25 m on the northwest end to nearly 250 m on the southeast end. Ore locally crops out at the bedrock-alluvium unconformity at the northwest end of the deposit, and the top of ore ranges down to about 130 m below the unconformity.

Drilling ore-grade intercepts at the top of bedrock from surface is not common, even at a giant gold deposit such as Pipeline. Top of bedrock intersections of >3,200 ppb Au (red and orange dots in Fig. 16A) occur in 69 holes, or 3.7 percent of the holes in Figure 16A. The size or surface footprint of the lithogeochemical target is larger than the size of the Au ore target at the top of bedrock. As one considers the dimensions of footprints at lower and lower Au concentrations, it is clear the target size gets larger. At some low Au concentration level, the target size becomes very large but the target margins blur with background; target resolution is lost; and the top of bedrock lithogeochemical approach becomes ineffective.

At >400 ppb Au (red, orange, and yellow dots in Fig. 16A) the target sizes increases. Concentrations of >400 ppb Au occur in 285 holes, which is 15 percent of the 1,859 holes. At 50 ppb, the target increases but is still smaller than the surface projection of the underlying ore body. Concentrations of >50 ppb Au occur in 714 holes, 38 percent of the 1,859 holes. Holes with >50 ppb at the top of the bedrock occur up to 1.2 km east of the surface projection of the orebody; however, they are intermingled with holes with <50 ppb. Even within the surface projection of the orebody, holes with >50 ppb do not from a coherent pattern.

Gravels at the bedrock-alluvium unconformity are derived at least in part from bedrock mineralization when mineralized

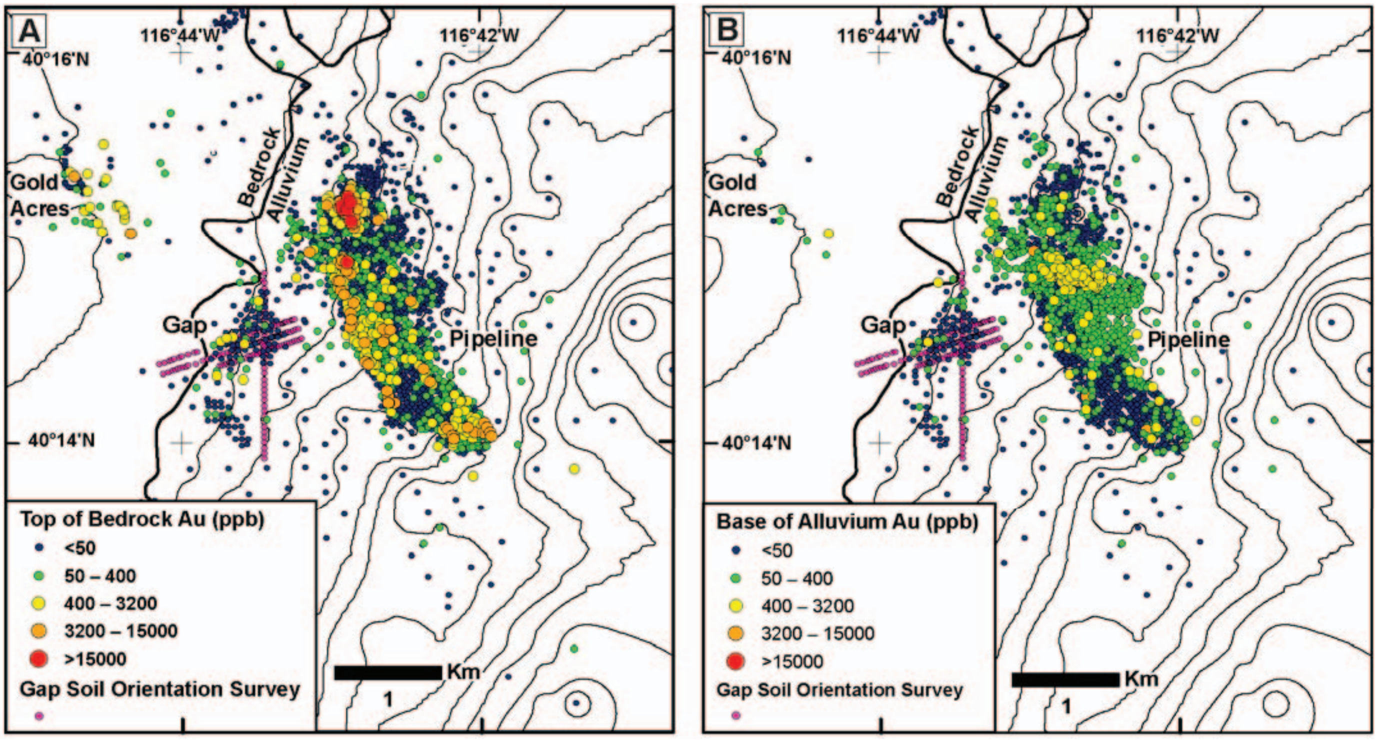

FIG. 16. Maps of Au fire assays surrounding the Pipeline deposit, based on analyses of drill hole samples at A. the top of bedrock, and B. the base of alluvium. Also shown are elevation contours on the top of bedrock (50-m intervals), the locations of soil samples from the Gap orientation survey, and the bedrock-alluvium unconformity at the surface. See text for discussion.

bedrock immediately underlies gravel cover. Gold in unconformity gravels is both diluted and "smeared" during the erosion of the orebody or mineralized bedrock above the orebody. Also, hydromorphic dispersion of Au and trace elements from mineralized bedrock into overlying alluvium is a strong possibility. In comparing Au in top of bedrock samples with Au in basal gravel samples, one would naturally anticipate alluvial Au anomalies, at relatively lower Au concentrations, and anomaly shapes determined by the topography of the bedrock surface.

Figure 16B shows Au concentrations in the next to last gravel sample interval. Note the various Au concentrations form coherent patterns that can be contoured. The east-west trend of >400 ppb Au values (yellow dots in Fig. 16B) is associated with a channel in the bedrock. The >50 ppb Au anomaly (green dots in Fig. 16B) is large, covering almost the entire surface projection of the orebody and extends, in a rather coherent manner, about 1.5 km east-southeast of the orebody. In stark contrast to the top of bedrock data, many fewer, <50 ppb, samples are intermingled with samples that have >50 ppb Au. The overall >50 ppb anomaly that trends southeast is at least 3.5 km long and 1.5 km wide.

Hydrogeochemistry

Groundwater chemistry has been applied to mineral exploration for several decades (cf. Leybourne and Cameron, 2010); however, few studies of the groundwater chemistry around Au deposits in Nevada have been published. Grimes et al. (1995) demonstrated anomalies of Au, As, Sb, and W in groundwater down the hydraulic gradient from Carlin-type gold deposits in the Getchell district. Groundwater chemistry from wells in the mine area, required for permitting and environmental monitoring of Pipeline, was provided by the Cortez mine staff and is shown in Figure 17. Prior to the start-up of dewatering at Pipeline in 1996, groundwater flow was generally east-southeastward, downslope from the range, across the Pipeline deposit, and into Crescent Valley. The groundwater table was approximately 100 m below the surface (Cortez Pipeline EIS, 1996). By 2002, the cone of depression, centered on Pipeline, covered most of the area shown in Figure 17 (Pipeline-South Pipeline EIS, 2004). Water levels in the wells located directly adjacent to the pit (most of the wells shown in Fig. 17) had dropped approximately 180 m from 1996 to 2002. The earliest available analysis for each well is plotted in Figure 17. The dates of the analyses in Figure 17 range from 1992 to 2002, and the majority of the analyses are from 1997.

Well waters are characterized by neutral to weakly alkaline pH values (Fig. 17A). The pH is likely buffered by carbonates in the lower plate of the Roberts Mountain thrust. The buffering by the carbonates inhibits formation of strongly acidic groundwater with contained metals, but elevated concentrations of anions, including sulfate, arsenate, and fluoride, still are likely in this setting.

Sulfate in well waters provides a clear indication of sulfide oxidation in the Pipeline area (Fig. 17B). Even after pH is neutralized by rock buffering, sulfate anions remain dissolved and mobile in the ground water system around Pipeline. The higher sulfate concentrations (>125 ppm), however, are to the north and northwest, rather than down gradient from Pipeline.

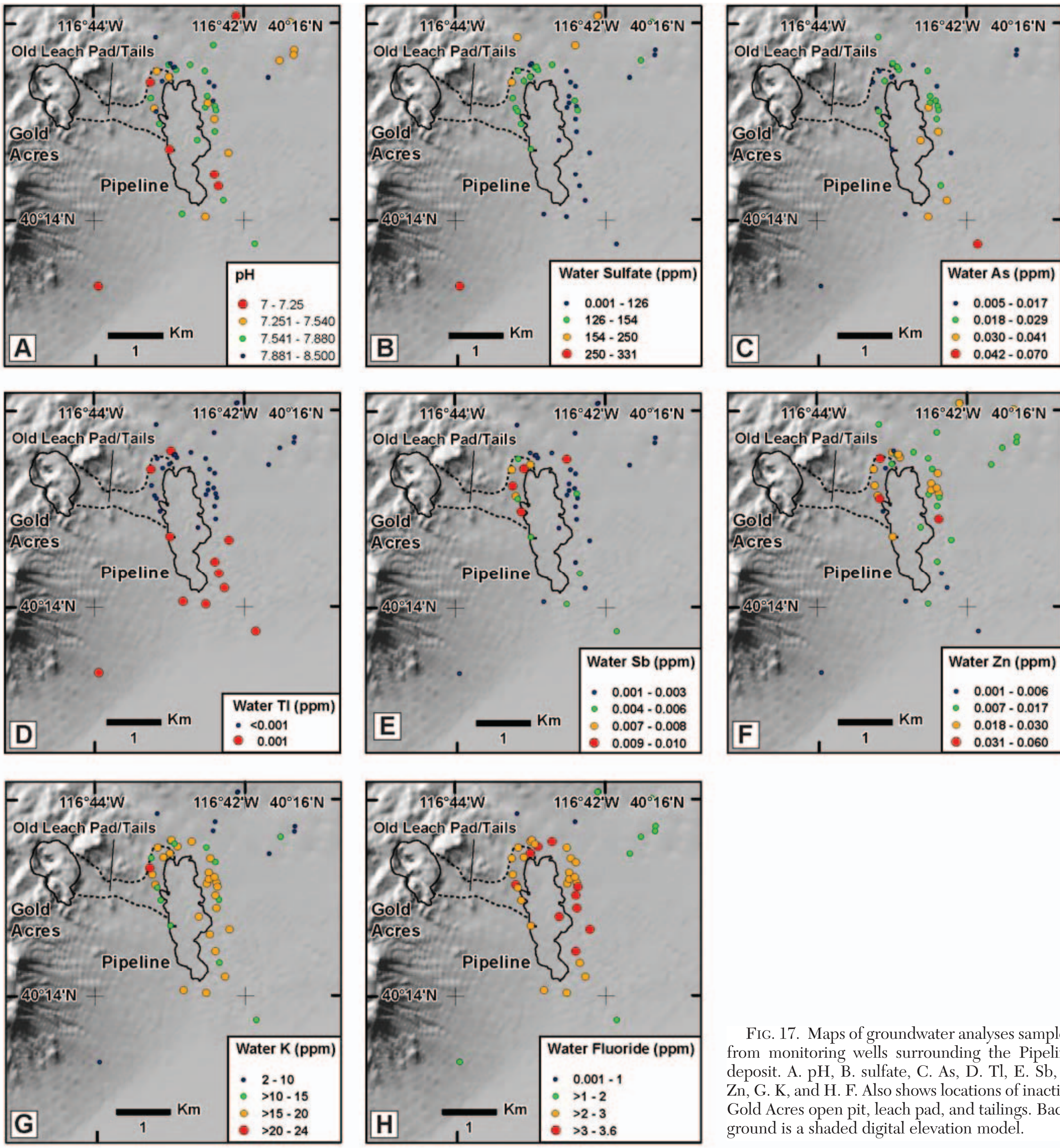

FIG. 17. Maps of groundwater analyses sampled from monitoring wells surrounding the Pipeline deposit. A. pH, B. sulfate, C. As, D. Tl, E. Sb, F. Zn, G. K, and H. F. Also shows locations of inactive Gold Acres open pit, leach pad, and tailings. Background is a shaded digital elevation model.

The source of sulfate may be oxidizing sulfides at the Gold Acres deposit, the old Gold Acres tailings and leach pads, and/or the Tenabo deposit, which is a few kilometers north of Pipeline.

In the acid-neutralized ground waters around Pipeline, As is soluble as an oxyanion and is mobile in this environment. In contrast to sulfate, the higher As concentrations occur east and southeast, up to at least 1 km down gradient from Pipeline, suggesting the As in the groundwater was sourced from Pipeline (Fig. 17C). The magnitude of the As anomalies and the distance of dispersion is similar to what Grimes et al. (1995) reported for the Getchell district. The same pattern occurs for Tl (Fig. 17D); however, Tl concentrations were very low in the well waters, either below detection or right at the detection limit.

In contrast, Sb and Zn concentrations show a pattern similar to sulfate (Fig. 17E-F). The highest values of Sb are northwest of Pipeline, down gradient from Gold Acres and its tailings and leach pads. Zinc is one of the most mobile and soluble metals in natural groundwater. Elevated Zn concentrations occur all around the northern end of Pipeline and, similar to Zn in soils and vegetation at Gap, forms a large, coherent anomaly. The Zn could be derived from oxidation of base metal sulfides in skarn in the Gold Acres, Gap, and Tenabo areas.

Pipeline also is characterized by elevated K and F in groundwater (Fig. 17G-H). The concentrations of K and F are highest directly adjacent to Pipeline and attenuate away from the deposit. Illite-bearing alteration might be the source of elevated the K concentrations. Spectral reflectance studies indicate ore at Pipeline is strongly associated with illite that has deep, sharp absorption features (Tarnocai and Muntean, 2000). The F is likely present as fluoride anion. Possible sources include clays and micas as well as fluorite, which has been reported from the Horse Canyon Carlin-type gold deposit (Foo and Hebert, 1987) on the east side of Crescent Valley (Fig. 1).

Discussion

Comparison with other Nevada studies

Few data sets on the surface geochemical signatures of deposits covered by transported overburden in Nevada have been published, especially ones that integrate multiple methods. Table 2 summarizes published data from surveys at the covered Mike (Cameron et al., 2004, 2005), Gold Bar (Doherty, 2000; Doherty et al., 2000), Marigold (Smee, 1998) and Pinson (Smith and Kretschmer, 1992) Carlin-type gold deposits.

Soil surveys at Mike and Gold Bar showed anomalies of Au and trace elements over known mineralization with contrasts of ~2–3:1. However, the responses over mineralization at Mike and Gold Bar were weaker and noisier than at Gap. In a way similar to Gap, some of the strongest Au and trace element anomalies at Mike and Gold Bar occur over interpreted faults on the edges of the deposits. Also as at Gap, Enzyme Leach and MMI did not result in significant enhancement of anomalies of gold and associated trace elements at Mike, relative to fire assays and analyses using an aqua regia digestion. As at Gap, Au strongly correlates with Ca at Mike, Gold Bar, and Marigold.

Results of soil gas surveys at Mike and Gold Bar were similar to those at Gap. Both Mike and Gold Bar had ΔCO_2 values that were typically higher in areas over ore relative to background. At Gold Bar, high ΔCO_2 values were coincident with faults that cut both the bedrock and cover. Results at Gold Bar also showed that the soil gas responses in both anomalous and background populations were suppressed in the fall relative to spring, underscoring the importance of doing large surveys over a relatively short period. The higher signal in the spring may be related to groundwater recharge, which likely releases a pulse of acid and CO_2 from carbonate. Nonetheless, the results from Gold Bar showed the patterns to be reproducible, despite the decrease in magnitude of the signal from spring to the fall.

Gold and As in sagebrush twigs showed the best response over covered ore at Gold Bar. The anomalies had contrasts ranging up to 10:1. As at Gap, the vegetation data had a quieter background than the soil data. Unlike soil gas, the vegetation surveys at Gold Bar showed a suppressed signal in the spring relative to the fall. Although ashed samples had higher concentrations, they correlated linearly with pelletized samples indicating ashing is not necessary in sample preparation. Sagebrush surveys at Pinson showed a strong Au response over the covered Mag orebody but not over the nearby CX orebody. Smith and Kretschmer (1992) argue the main reason for the lack of response over the CX orebody is that it sits well above the water table, whereas the Mag orebody straddles the water table.

Transport mechanisms

Given the presence of anomalies in Au and several other trace metals in both soils and vegetation at Gap, metals clearly were transported upward to the surface through up to nearly 100 m of transported alluvial cover. Cameron et al. (2004) argued that advective transport of groundwater or air along with their dissolved or gaseous constituents is the only viable means of moving elements to the surface in arid to semi-arid environments with a thick vadose zone such as in the alluvial basins in Nevada, where the water table is commonly greater than 100 m below the surface. They point out the downward advective flux of elements dissolved in groundwater is one to three orders of magnitude greater than the upward diffusive flux of elements through groundwater that incompletely fills pores in the vadose zone.

Although water and its dissolved constituents typically flow down gradient, there are processes that induce upward flow. Cameron et al. (2004) argue that mineralized groundwater can be pumped upward by seismic activity. Water stored in fractures is forced upward along faults when fractures are closed during earthquakes, which can cause dramatic effusions of groundwater at the surface (cf. Sibson, 1981). Uncertainty remains over whether such events occurred at Gap that would have caused groundwater to rise 100 m to the surface. Other mechanisms for advective transport of groundwater and solutes to the surface include deep plant roots and capillary action. However, the depth of sagebrush roots rarely exceeds a few meters, while the limiting depth for capillarity is probably 20 m (cf. Cameron et al., 2004), suggesting roots and capillary action are viable processes only for the north end of Gap. Nonetheless, Gap formed prior to its burial by alluvium. Metals dissolved in groundwater could have incrementally migrated upward shorter distances (by seismic pumping, roots, or capillary action) through increasing thicknesses of alluvium as Gap was progressively buried.

The enhanced signal of ΔCO_2 in soil gas over the ore zones at Gap is likely caused by oxidation of sulfides and resultant acid reaction with the carbonate host rocks. As indicated earlier, most of the ore at Gap is oxidized and ore zones occur both above and below the pre-mining water table. Oxidized sulfides include the very fine-grained Au-bearing arsenian pyrite characteristic of Carlin-type gold deposits. However, the strong spatial relationship of high ΔCO_2 values with underlying skarn and gossan zones on the east side of the main ore zone suggests oxidation of pre-ore base metal sulfides was a major cause for the high values.

This flux of CO_2 is important in that investigators have suggested that trace metals can be transported by gases either as

TABLE 2. Summary of Other Geochemical Surveys Completed Over Covered Carlin-Type Gold Deposits

Deposit	Description	Nature of cover	Soil results	Soil gas results	Vegetation results	References
Mike	• Carlin-type Au deposit on the Carlin trend located 3 km northwest of the Gold quarry Carlin-type Au deposit • 8.6 Moz Au (1999 mineral inventory) with significant overlapping Cu and Zn mineralization • Au ores are mostly oxidized • Located at intersection of NW- and NE-striking high-angle faults • Hosted by Devonian carbonate rocks	• <5 m of Quaternary gravel and 120–240 m of post-mineral Miocene Carlin Fm, which consists of piedmont gravel, finer clastic sediments, waterlain tuff and a basal conglomerate that contains mineralized (oxidized) clasts • Perched water table is 50 m below the surface; deeper aquifer in Paleozoic rocks	• One NW-trending 1600 m line across the deposit, oriented perpendicular to NE-striking faults; samples spaced 30 m apart • Au correlates strongly with Ca • Soil samples collected at 40–50 cm depth, from a weak B horizon • Strongest Au, Cu, and Cd anomalies located across a NE-trending drainage interpreted to be a Quaternary fault that penetrates the underlying Paleozoic rocks and is located along the SE edge of the underlying deposit • Aqua regia Au, Cu, Cd data show anomalies over ore with ~2-3 contrast • Hydroxlyamine, MMI-A, and to lesser extent, Enzyme Leach selective leach data for Cu show similar patterns as the aqua regia data • Much weaker anomalies across similar NE-trending drainage on NW edge of deposit	• One NW- and two NE-trending lines across the deposit; analyses spaced 30 m apart 159 sites • Higher ΔCO_2 values occur both over the deposit and areas remote from it, but the survey did not extend over the NE-trending Quaternary fault that bounded the SE margin of the deposits that had the strong Au, Cu, and Cd soil anomalies		• Cameron et al. (2004, 2005) • Norby and Orobona (2002)
Gold Bar	• Carlin-type Au deposit on the Battle Mountain-Eureka trend • ~0.36 Moz Au in production and reserves • Sampling lines occur over unmined covered, mostly oxidized resource • Hosted by Devonian carbonates • Controlled mainly by NNW-striking faults, especially at intersections with ENE-trending faults • Late motion along ENE-trending faults	• ~150 m of post-mineral volcanic and transported alluvial cover	• Two sampling lines oriented NE and one sampling line oriented NW with samples spaced ≤15 m apart • Soils collected from weakly developed B horizon at ~35 cm depth; caliche was located below this layer • Noisy BLEG Au (up to 12 ppb) and aqua regia As (up to 20 ppm) responses, with ~2–3:1 contrast over and to the SE of covered ore • Enzyme and ascorbic-enzyme leaches showed no discernable response • Repressed signal in the fall relative to the spring	• Nine sampling lines oriented NE, EW, and NW with samples spaced ≤15 m apart • Higher ΔCO_2 values occur over the covered mineralization and high-angle faults away from mineralization • Fault-controlled anomalies are narrow apical patterns with the strongest response at fault intersections • Suppressed signal in the fall relative to the spring	• Au and As in sagebrush twigs showed good anomalies with ~2–10 contrast directly over ore • Better response from sagebrush twigs relative to sagebrush flowers • Linear correlation between pelletized and ashed samples • Woody stalks contain more Au than younger growth • Suppressed signal in the spring relative to the fall	• Doherty (2000) • Doherty et al. (2000) • French et al. (1996)
Marigold	• Carlin-type Au deposit on the Battle Mountain-Eureka trend • Survey was over the 5 North and 8 North deposits • <0.5 Moz Au • Deposits are elongated N-S • Hosted by variably calcareous clastic rocks of the Pennsyvanian-Permian Antler Sequence	• 5 North and 8 North deposits are covered along the sampling lines by 15–35 m of Tertiary and 90 m of Quaternary alluvium, respectively • Alluvium is mostly unconsolidated gravels with interlayered lacustrine clay	• Two lines (580 m long) over both the 5 North and 8 North deposits; they were centered over the deposits with 11 sample locations spaced 15 m apart over mineralization, samples spacing progressively widened to 120 m on the edges of the lines • Soil samples collected at 40–50 cm depth at the top of caliche zone • Weak fire assay Au and hydroxylamine As anomalies directly over 5 North; no Au or As anomalies occur over 8 North • Aqua regia Ca and Sr form the best anomalies over 5 and 8 North • No enzyme leach response in As, Sb, Fe, Cu, Pb, Zn and Ni over 5 and 8 North			• Smee (1998)

TABLE 2. (*Cont.*)

Deposit	Description	Nature of cover	Soil results	Soil gas results	Vegetation results	References
Pinson	• Surveys done over the CX and Mag orebodies at the Pinson Carlin-type Au deposit deposit in the Getchell district • Hosted by Cambrian-Ordovician carbonates and variably calcareous shales • CX orebody controlled by NNE-striking faults; Mag orebody controlled by NNW and NE structures • CX ores oxidized down to 150 m; Mag ore oxidized to 60–120 m	• CX covered by 15–40 m and Mag covered by 12–60 m of Tertiary-Quaternary alluvium, respectively • Groundwater table is 65–105 m below the surface	• Soil surveys using aqua regia digestion only showed weak Hg anomalies		• Line A (910 m long) crossed the northern margin of the CX and the north Mag orebodies; line B (970 m long) crossed the center of the CX and the south end of the Mag • Sagebrush twigs sampled at 30 m intervals; samples were pelletized • Both lines showed good Au responses (up to 11 ppb) over the Mag deposit but no response over the CX deposits • As, Sb, and W are less diagnostic	• Smith and Kretschmer (1992)

ultrafine particulates (e.g., Xie et al., 1999) or volatile metal compounds (Clark et al., 1997). In a manner similar to solutes in water, such metals in carrier gases migrate upward by diffusion through air or water, but far more rapidly by upward advection, mainly by barometric pumping of air (Cameron et al., 2004). During cycles of high and low barometric pressure, air is first forced into the earth and then a mixture of the air and gases in the rock is withdrawn. The process is only viable in fractured rock and is not significant in unfractured material, even if permeable. Studies of simulated underground nuclear tests at the Nevada test site indicated SF_6 gas released from a bottle near a charge in a chamber adjacent to a fault 400 m below the surface was detected 50 days after detonation during a strong barometric depression (Carrigan et al., 1996). ^3He was also released from a separate bottle away from the fault, but it was detected 375 days after detonation. ^3He has a much higher diffusivity and should have reached the surface prior to SF_6 if diffusion was the dominant mechanism. In a separate study at the Nevada test site (Hall et al., 1997), analyses of soils across a slump crater caused by an underground nuclear test, 10 years prior, showed I and As anomalies over the crater. Both I and As can form volatile compounds.

Klusman (2009) refined an electrochemical dispersion model for elements proposed by Hamilton (1998), in which a chimney of reduced gases can form above a weathering, oxidizing sulfide-bearing orebody hosted by carbonaceous carbonates at the water table. He modeled the upward migration of As from the orebody to the surface as the reduced volatile compound $As(CH_3)_3$ (trimethylarsine), which can be microbially generated at the redox interface of an ore body. He postulated that shallow microbial oxidation would then produce oxidized species of As, which may then be absorbed onto by oxyhydroxide components of the soil. Such reduced gases would also be oxidized at the surface to form CO_2 anomalies in soil gas. Klusman (2009) also demonstrated by modeling that submicron particulate Au could be transported to the surface by air during barometric pumping. Such processes could explain the presence of Au (<20 ppt) and As (<10 ppm) anomalies in seasonal snow accumulations above a buried massive sulfide orebody in Sweden (Kristiansson et al., 1990).

Aqua regia versus selective leaches

Results from the soil survey at Gap revealed that Enzyme Leach and MMI-B did not show significantly enhanced anomalies in gold and trace elements relative to conventional aqua regia digestion. The same conclusion can be drawn from the soil surveys at the Mike deposit (Cameron et al., 2004). To understand why aqua regia appears to be as effective as weaker selective leaches, it is best to first summarize various components in the soil as they relate to elemental dispersion. Table 3 describes six types of components, which are schematically illustrated in Figure 18.

Both endogenic and exogenic components are targeted in a residual soil survey, in which a strong leach such as aqua regia is appropriate. In a situation with postore cover, such as transported alluvium or residual soils over postore volcanic rocks, exogenic components should be targeted. Methods such as selective leaches that preferentially analyze the exogenic phases and minimize leaching of endogenic phases are desirable. Geochemical anomalies associated with endogenic phases

TABLE 3. Descriptions of Soil Components that Pertain to Elemental Dispersion

Phase	Description
Primary	Unaltered mineral or lithic fragment derived from physical weathering
Secondary	Crystalline chemical precipitate or a mineral or lithic fragment altered by chemical weathering
Precursor	Unstable phase that includes adsorbed cations, colloids, and amorphous oxides
Endogenic	Primary or secondary mineral derived from physical weathering or mechanical dispersion; can also be termed substrate
Exogenic	Exotic secondary or precursor phase that has been added to the soil, commonly by hydromorphic or gaseous dispersion
Receptor	A phase that accepts a migrating element, generally a secondary or precursor phase

could have laterally distant sources in transported cover. Also, false anomalies can be caused by variability in composition and physical parameters (such as pH) of the soils. Soils with different endogenic phases can have different capacities to adsorb migrating elements.

As discussed by Cameron et al. (2004), anomaly formation is an incremental process, with exogenic metals being introduced in water-soluble or gaseous form, commonly as precursor phases than can include metallic cations adsorbed onto clays, metal-bearing colloids, or amorphous Fe-Mn oxides. Over time these precursor phases are converted and incorporated into more resistant secondary phases such as goethite or calcite. The data suggest that the surface anomalies over Gap and other deposits are mature anomalies that could have developed over millions of years, and that a significant proportion of the exogenic metals are hosted in relatively resistant secondary minerals which are more readily dissolved by aqua regia than by weaker selective leaches.

More importantly, the soils at Cortez are lacking Mn oxides targeted by Enzyme Leach and are likely too alkaline to provide optimal results by MMI-B. As pointed out previously, horizons with abundant Fe- and Mn-oxides were not consistently present in the soil test pits. By the same token, the alkaline nature of the Cortez soils likely buffers the MMI-B leach to the extent that metals cannot be as effectively liberated from the soil. If the sampled soil media does not match the type of leach used in terms of targeting specific residence sites for metals in the soil, the survey will yield poor results. This is a common problem with geochemical surveys conducted in areas of covered terrain.

Future work

Increased understanding of the processes involved in formation of geochemical anomalies over deposits covered by transported overburden will lead to increased confidence in

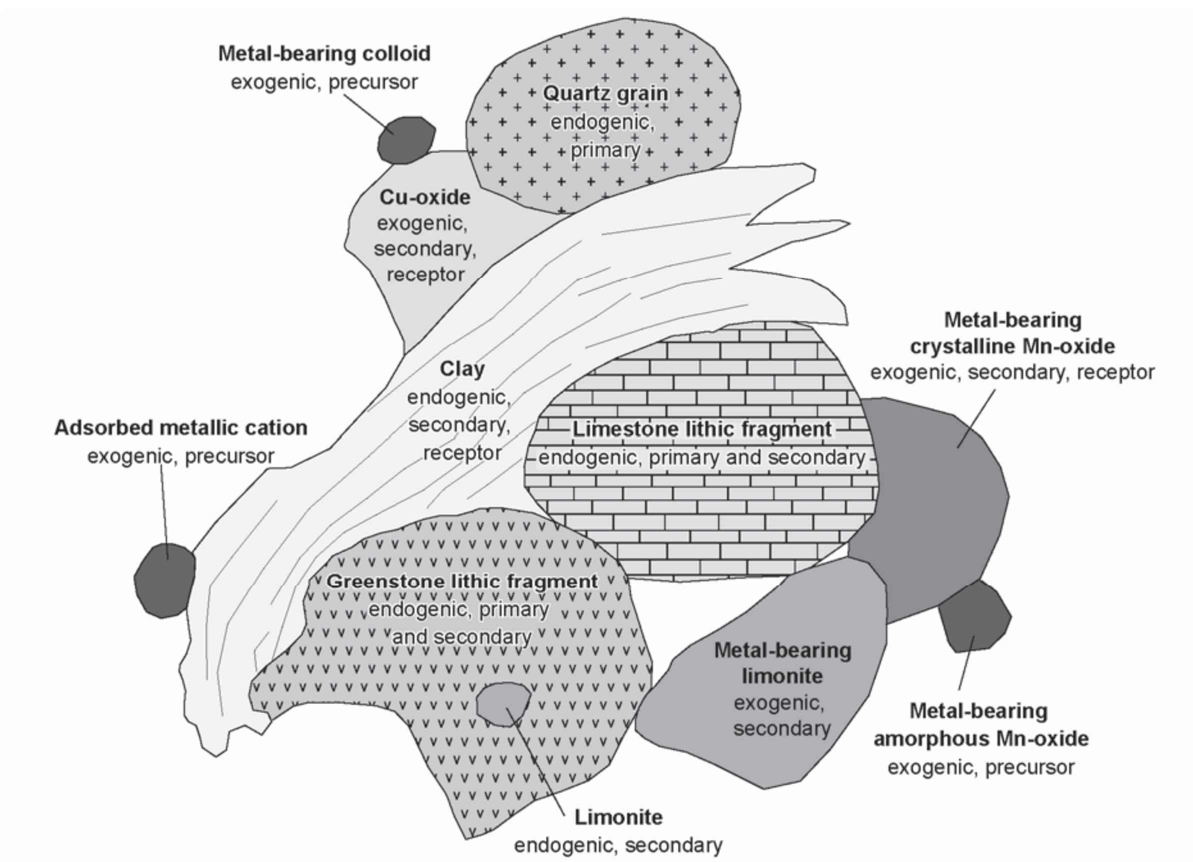

FIG. 18. Schematic diagram illustrating relationships in soil between primary, secondary, precursor, endogenic, exogenic, and receptor components described in Table 3.

application of surface geochemistry in covered terrains. Much could be gained by studying the geochemistry of the alluvial cover in three dimensions. Gap is now part of the Pipeline open pit, and alluvium is well-exposed in pit walls. Studies should include detailed mapping and sampling of the alluvium throughout the overburden column. Emphasis should be placed on deciphering the geometry and kinematic history of faults and fractures that cut the alluvium. Geochemical surveys of alluvium across fracture zones, using a variety of methods including various leaches and desorption methods, would lead to a better understanding of the upward migratory pathways of metals through the cover. Detailed mineralogical and geochemical studies of various secondary minerals in alluvium and soil, including caliche, limonite, and clays, would lead to better understanding of the residence sites of metals. Isotopic studies, such as Pb isotopes in bedrock ores, secondary minerals in overlying alluvium, and groundwater, could constrain the sources of surface and hydrogeochemical anomalies (e.g., Simonetti et al., 1996; Leybourne and Cameron, 2010). Carbon isotopes in soil gas can distinguish whether CO_2 was evolved by microbial oxidation of carbonaceous matter or inorganic dissolution of carbonates. The authors attempted such a carbon isotope study, but results were inconclusive owing to contamination from rubber septa used to sample the soil gas.

Key Findings and Recommendations

The most definitive orientation surveys are completed over known, well-defined mineralized systems and ore zones, undisturbed save for drilling. The orientation surveys presented in this paper and the results of the other surveys completed by the authors in the Cortez window on the eastern side of Crescent Valley demonstrated that geochemistry can identify buried Au mineralization at various scales of exploration. Key findings and recommended approaches described below were applied by Placer Dome to varying degrees of success on covered targets in Nevada and elsewhere after completion of this study.

Soil sampling over the Gap deposit located buried Au ore under up to nearly 100 m of transported postore alluvium. Selection of appropriate, consistent soil sample media that is matched with the digestion method is critical to survey success. Selection of inconsistent sample media likely would have led to generation of equivocal, uncertain data, and poor definition of buried mineralization. Results indicated that analyses of –80 mesh soils at 6- to 12-cm depth using an aqua regia digestion is appropriate, likely for much of Nevada. Other, more expensive partial and selective leach procedures at the time of this study appeared to provide no apparent, practical advantage to aqua regia digestions when soils of consistent and appropriate composition were selected. An ultratrace level gold method utilizing an aqua regia digestion, such as the ZARG method used in this study, is recommended for analyses of Au in soils. ZARG provided anomaly features similar to fire assay but was ten times more sensitive, avoided encapsulated, endogenic Au, and compared well with fire assay and MMI-B Au analyses completed in this study.

CO_2 and O_2 in soil gas indicated underlying mineralized carbonates at Gap, where sulfide weathering reactions likely caused CO_2 generation from acid reaction with carbonate. Sharp soil gas anomalies were spatially associated with high-angle faults that cut the Carlin-type Au and base metal skarn mineralization, as well as with thrust faults away from ore.

Careful, consistent vegetation sampling at Gap yielded anomaly features spatially coincident with known buried mineralization in a suite of elements, including Au, As, Sb, W, Zn, and Cd, using a mixed species population of washed sagebrush twigs and shadscale bark. Use of vegetation should be considered in the cost and efficiency context of alternative media including soils, and applied when consistent soils are not available. Preferably a single species should be sampled in a survey, unless, as in this study, there is no appreciable difference in results from different species. Otherwise, one will have to level the data between species.

Sampling of soil gas, soils, and vegetation is appropriate at the local scale of drill targeting (~<2 km^2). Examination of each landscape and regolith setting, identification of local processes controlling element mobility, and selection of appropriate, consistent sample media are considered crucial for successful survey design and execution. Soil gas surveys should proceed or accompany soil or vegetation surveys to identify fault and fracture zones in target areas, and sample spacing should be adjusted according to "real-time" soil gas readings. Soil gas and soil sampling layouts should be preceded by structural analysis of target areas, and generally follow cross-structure sample lines, with relatively tight sample spacing along sample lines. Results of all surveys should not only be looked at in map views but also in profile views.

The results from the greater Pipeline deposit area are instructive at broader scales of several square kilometers. There is a 4- to 5-km^2 Au "footprint" at the basin gravel-bedrock unconformity centered on the Pipeline Carlin-type gold deposit. Samples of basal alluvium provide the most widespread and coherent Au anomalies at Pipeline. Both top-of-bedrock and basal alluvium sampling intervals should be carefully collected and analyzed in routine exploration drill programs in Nevada. The useful threshold value to recognize patterns in both bedrock and alluvium at Pipeline was 50 ppb Au. Knowledge of bedrock topography is especially useful in interpretation of basal alluvium Au anomalies and establishing the direction of the origin of the alluvium. The template at Pipeline presented in this paper could be used as a basis of comparison with other, either new or old, exploration drilling programs through cover.

Another recommended, broader-scale method would be conventional stream sediment sampling (e.g., Ludington et al., 2006). In addition to sampling the sediment in the active channel, the authors found that sampling of vegetation within drainages and sampling stream drainage soils within the drainage depression but outside the active channel are potentially effective broader scale methods.

Groundwater is an under-utilized reconnaissance-scale sample medium in Nevada. Enriched As, Tl, K, and F in groundwater provide a hydrogeochemical footprint around Pipeline that was at least as large as the Au footprint along the basin gravel-bedrock unconformity. The higher As and Tl concentrations occurred down gradient from Pipeline indicating Carlin-type Au ore is the source of the enrichment. The groundwater in the Cortez mine area is generally neutral to alkaline. Gold is likely to be soluble in this environment, and could provide a direct indicator of blind covered Au ore (e.g., Grimes et al., 1995).

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REFERENCES

Arehart, G.B., and Donelick, R.A., 2006, Thermal and isotopic profiling of the Pipeline hydrothermal system: Application to exploration for Carlin-type gold deposits: Journal of Geochemical Exploration, v. 91, p. 27–40.

Bettles, K., 2002, Exploration and geology, 1962 to 2002, at the Goldstrike property, Carlin trend, Nevada: Society of Economic Geologists Special Publication 9, p. 275–298.

Cameron, E.M., Hamilton, S.M., Leybourne, M.I., Hall, G.E.M., and McClenaghan, M.B., 2004, Finding deeply buried deposits using geochemistry: Geochemistry: Exploration, Environment, Analysis, v. 2, p. 7–32.

Cameron, E.M., Leybourne, M.I., and Kelley, D.L., 2005, Exploring for deposits under deep cover using geochemistry: SEG Newsletter, no. 63, p. 5, 9–13.

Carrigan, C.R., Heinle, R.A., Hudson, G.B., Nitao, J.J., and Zucca, J.J., 1996, Trace gas emissions on geological faults as indicators of underground nuclear testing: Nature, v. 382, p. 528–531.

Chevillon, V., Berentsen, E., Gingrich, M., Howald, B., and Zbinden, E., 2000, Geologic overview of the Getchell gold mine geology, exploration, and ore deposits, Humboldt County, Nevada: Society of Economic Geologists Guidebook Series, v. 32, pt. 2, p. 195–201.

Clark, J.R., 1993, Enzyme-induced leaching of B-horizon soils for mineral exploration in areas of glacial overburden: Transactions of the Institute of Mining and Metallurgy (Section B, Applied Earth Sciences), v. 102, p. 19–29.

Clark, J.R., Yeager, J.R., Rogers, P. and Hoffman, E.L., 1997, Innovative enzyme leach provides cost-effective overburden/bedrock penetration, *in* Gibins, A.G., ed., Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration, Geo F/X, Toronto, Canada, p. 371–374.

Cline, J.S., Hofstra, A.H., Muntean, J L., Tosdal, R.M., and Hickey, K.A., 2005, Carlin-type gold deposits in Nevada: Critical geologic characteristics and viable models: Economic Geology 100th Anniversary Volume, p. 451–484.

Clode, C.H., Grusing, S.R., Johnston, I.M., and Heitt, D.G., 2002, Geology of the Deep Star gold deposit: Nevada Bureau of Mines and Geology, Bulletin 111, p. 76–90.

Cope, E., Hipsley, R., Dobak, P., Arbonies, D. and Brower, S., 2008, South Arturo: A recent gold discovery on the Carlin trend: Mining Engineering, v. 60, p. 19–25.

Cortez Pipeline gold deposit final environmental impact statement, 1996, U.S. Department of Interior, Bureau of Land Management.

Dilles, P.A., Wright, W.A., Monteleone, S.E., Russell, K.D., Marlowe, K.E., Wood, R.A., and Margolis, J., 1996, The geology of the West Archimedes deposit: A new gold discovery in the Eureka mining district, Eureka County, Nevada, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Reno, Nevada, Geological Society of Nevada, Symposium Proceedings, p. 159–171.

Doherty, M.E., 2000, Seasonal variations in soil gas, sagebrush and soils: Implications for geochemical dispersion processes, Great Basin, Nevada: Association of Exploration Geochemists, Geological Society of Nevada Symposium, Geochemical Methods for Buried Ore Deposits, Short Course Notes, 22 p.

Doherty, M.E., Bratland, C.T., Highsmith, R.P., and Jaacks, J.A., 2000, Detection of buried gold mineralization by selective extractions of soil samples, sagebrush and soil gases [abs.]: Geological Society of Nevada, Geology and Ore Deposits 2000: The Great Basin and Beyond, Symposium, Program with Abstracts, p. 44–45.

Erickson, R.L., Van Sickle, G.H., Nakagawa, H.M., McCarthy, J.H. Jr., and Leong, K.W., 1966, Gold geochemistry anomaly in the Cortez district, Nevada: U.S. Geological Survey Circular 534, 9 p.

Foo, S.T., and Hebert, J.P., 1987, Geology of the Horse Canyon deposit, Eureka County, Nevada, *in* Johnson, J.L., ed., Geology Bulk Mineable Precious Metal Deposits of the Western United States, Guidebook for Field Trips: Reno, Geological Society of Nevada, p. 326–332.

Foo, S. T., Hays, R. C. Jr., and McCormack J. K., 1996a, Geology and mineralization of the Pipeline gold deposit, Lander County, Nevada, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and ore deposits of the American Cordillera: Reno, Geological Society of Nevada, p. 95–109.

——1996b, Geology and mineralization of the South Pipeline gold deposit, Lander County, Nevada, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and ore deposits of the American Cordillera: Reno, Geological Society of Nevada, p. 111–121.

French, G. McN., Fenne, F.K., Maus, A., Rennebaum, T.D., and Jennings, T.A., 1996, Geology and mineralization of the Gold Bar district, southern Roberts Mountains, Eureka County, Nevada: in Green, S.M., and Struhsacker, E., eds., Geology and Ore Deposits of the American Cordillera, Field Trip Guidebook Compendium: Reno, Geological Society of Nevada, p. 309–315.

Gilluly, J., and Gates, O., 1965, Tectonic and igneous geology of the northern Shoshone Range, Nevada: U.S. Geological Survey Professional Paper 465, 153 p.

Gilluly, J., and Masursky, H., 1965, Geology of the Cortez quadrangle, Nevada, with a section on gravity and aeromagnetic surveys by D.R. Mabey: U.S. Geological Survey, Bulletin 1175, 117 p.

Grimes, D.J., Ficklin, W.H., Meier, A.L., and McHugh, J.B., 1995, Anomalous gold, antimony, arsenic, and tungsten in ground water and alluvium around disseminated gold along the Getchell Trend, Humboldt County, Nevada: Journal of Geochemical Exploration, v. 52, p. 351–371.

Hall, G.E.M., Vaive, J.E., and Button, P., 1997, Detection of past underground nuclear events by geochemical signatures in soils: Journal of Geochemical Exploration, v. 59, p. 145–162.

Hamilton, S.M. 1998, Electrochemical mass transport in overburden: a new model to account for the formation of selective leach geochemical anomalies in glacial terrain: Journal of Geochemical Exploration, v. 63, p. 155–172.

Hays, B., Koehler, S., Hart, K., and Lewis, T., 2007, Pipeline, Gold Acres, Cortez, Cortez Hills/Pediment Deposits, *in* Johnston, M.K., ed., Faults, folds, and mineral belts: Regional structural systems, gold mineralization, and exploration potential in the Great Basin: Geological Society of Nevada, 2007 Fall Field Trip Guidebook, Special Publication no. 46, p. 141–151.

Hays, R.C., Jr, and Foo, S.T., 1991, Geology and mineralization of the Gold Acres deposit, Lander county, Nevada, in Raines, G.L., Lisle, R.E., Schafer, R.W. and Wilkinson, W.H., eds., Geology and Ore Deposits of the Great Basin: Reno, Geological Society of Nevada, p. 677-685.

Hays, R.C., and Thompson, T.G., 2003, The Cortez Hills deposit, a recent discovery in a historic mining district, Lander County, Nevada: NewGen-Gold Conference Proceedings 2003, p. 119–126.

Highsmith, P., 2000, Soil gas carbon dioxide and oxygen for mineral exploration: Explore, no. 122, p. 14–15.

Jackson, M., Lane, M., Leach, B., 2002, Geology of the West Leeville deposit: Nevada Bureau of Mines and Geology Bulletin 111, p. 106–114.

John, D.A., Henry, C.D., and Colgan, J.P., 2008, Magmatic and tectonic evolution of the Caetano caldera, north-central Nevada: A tilted, mid-Tertiary eruptive center and source of the Caetano tuff: Geosphere, v. 4, p. 75–106.

Jones, M., 2005, Jerritt Canyon district, Independence Mountains, Elko County Nevada, gold's at fault: Geological Society of Nevada Symposium, Window to the World, 2005, Geological Society of Nevada Field Trip Guidebook 8, p. 99–122.
Jory, J., 2002, Stratigraphy and host rock controls of gold deposits of the northern Carlin trend: Gold deposits of the Carlin trend, Nevada Bureau of Mines and Geology, Bulletin 111, p. 20–34.
Kelley, D.L., Kelley, K.D., Coker, W.B., Caughlin, B., and Doherty, M.E., 2006, Beyond the obvious limits of ore deposits: the use of mineralogical, geochemical, and biological features for the remote detection of mineralization: ECONOMIC GEOLOGY, v. 101, p. 729–752.
Klusman, R.W., 1993, Soil gas and related methods for natural resource exploration: Chichester, UK, John Wiley and Sons, 483 p.
——2009, Transport of ultratrace reduced gases and particulate, near-surface oxidation, metal deposition and adsorption: Geochemistry: Exploration, Environment, Analysis, v. 9, p. 203–213.
Kotlyar, B.B., Theodore, T.G., Singer, D.A., Moss, K., Campo, A.M., and Johnson, S.D., 1998, Geochemistry of the gold skarn environment at Copper Canyon, Nevada: Mineralogical Association of Canada Short Course Series, v. 26, p. 415–443.
Kristiansson, K., Malmqvist, L., and Persson, W., 1990, Geogas prospecting: A new tool in the search for concealed mineralization: Endeavour, New Series, v. 14, p. 28–33.
Leybourne, M.I., and Cameron, E.M., 2010, Groundwater in geochemical exploration: Geochemistry: Exploration, Environment, Analysis, v. 10, p. 99–118.
Lintern, M.J., 2001, Exploration for gold using calcrete—lessons from the Yilgarn craton, Western Australia: Geochemistry: Exploration, Environment, Analysis, v. 1, p. 237–252.
Livermore, J.S., 1996, Carlin-type gold exploration in Nevada since the Newmont discovery in 1961: Mining Engineering, v. 48, p. 69–73.
Lovell, J.S., 2000, Oxygen and carbon dioxide in soil air, *in* Hale, M., and Govett, G.J.S., eds., Geochemical remote sensing of the subsurface: Amsterdam, Elsevier, Handbook of Exploration Geochemistry, v. 7, p. 451–469.
Ludington, S., Folger, H., Kotlyar, B., Mossotti, V.G., Coombs, M.J., and Hildenbrand, T.G., 2006, Regional surficial geochemistry of the northern Great Basin: ECONOMIC GEOLOGY, v. 101, p. 33–57.
Mann, A.W., Birrell, A.T., Mann, A.T., Humphreys, D.B., and Perdrix, J.L., 1998, Application of the mobile metal ion technique to routine geochemical exploration: Journal of Geochemical Exploration, v. 61, p. 87–102.
McCarthy, H., and McGuire, E., 1998, Soil gas studies along the Carlin Trend, Eureka and Elko Counties, Nevada: U.S. Geological Survey Open File Report 98-338, p. 243–250.
McMillin, S.L., 2005, The discovery, production, and continued exploration of the SSX mine area, Jerritt Canyon, Nevada, *in* Rhoden, H.N., Steininger, R.C., and Vikre, P.G., eds., Window to the World: Geological Society of Nevada Symposium, 2005, p. 453–468.
Muntean, J.L., 2010, Major precious metal deposits: Nevada Bureau of Mines and Geology, The Nevada mineral industry 2009, Special Publication MI-2009, p. 68–192.
Norby, J.W., and Orobona, M.J.T., 2002, Geology and mineral systems of the Mike deposit: Nevada Bureau of Mines and Geology, Bulletin 111, p. 143–167.
Nutt, C.J., Hofstra, A.H., Hart, K.S., and Mortensen, J.K., 2000, Structural setting and genesis of gold deposits in the Bald Mountain-Alligator Ridge area, east-central Nevada, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F, and Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond, Geological Society of Nevada Symposium Proceedings, p 513–537.
Pipeline/South Pipeline Pit environmental impact statement, 2004: U.S. Department of Interior, Bureau of Land Management, expansion project, draft supplemental statement.
Powell, J.L., 2007, Structural development of Gold Quarry, a giant Carlin-type deposit in the central Carlin trend, Eureka County, Nevada, *in* Johnston, M.K., ed., Faults, Folds, and Mineral Belts: Regional Structural Systems, Gold Mineralization, and Exploration Potential in the Great Basin, 2007 Fall Field Trip Guidebook, Geological Society of Nevada Special Publication no. 46, p. 155–161.
Price, J.G., 2010, Overview: in The Nevada mineral industry 2009: Nevada Bureau of Mines and Geology Special Publication MI-2009, p. 3-–26.
Reith, F., Wakelin, S.A., Gregg, A.L., Mumm, A.S., 2009, A microbial pathway for the formation of gold-anomalous calcrete: Chemical Geology, v. 258, p. 315–326.
Schull, H.W. and Sutherland, S.M., 2005, Discovery and exploration of the Alligator Ridge gold deposits, White Pine, County, Nevada, *in* Hollister, V.F., ed., Discoveries of epithermal precious metal deposits: New York, Society of Mining Engineers, p. 1–3.
Sibson, R.H., 1981, Fluid flow accompanying faulting: Field evidence and models, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake predication: An international review: American Geophysical Union, Maurice Ewing Series, v. 4, p. 593–603.
Sillitoe, R.H., 1995, Exploration and discovery of base- and precious-metal deposits in the Circum-Pacific region during the last 25 years: Resource Geology Special Issue no. 19, 119 p.
Simonetti, A., Bell, K., and Hall, G.E.M., 1996, Pb isotopic ratios and elemental abundances for selective leachates from near-surface till: implications for mineral exploration: Applied Geochemistry, v. 11, p. 721–734.
Smee, B.W., 1998, A new theory to explain the formation of soil geochemical responses over deeply covered gold mineralization in arid environments: Journal of Geochemical Exploration, v. 61, p. 149–172.
Smith, S.C., 2002, Biogeochemistry, discovery using metal concentrations in plants: SEG2002 Workshop, Exploration Technology: Discovery thru Innovation, Short Course notes.
Smith, S.C., and Kretschmer, E.L., 1992, Gold patterns in big sagebrush over the CX and Mag deposits, Pinson mine, Humboldt County, Nevada: Journal of Geochemical Exploration, v. 46, p. 147–161.
Stewart, J.H., and Carlson, J.E., 1978, Geologic map of Nevada: U.S. Geological Survey map, scale 1:500,000.
Tarnocai, C.A., and Muntean, J.L., 2000, Evaluation of hydrothermal alteration in the Pipeline area by PIMA II: Unpublished report for Placer Dome Exploration, 41 p.
Theodore, T.G., 2000, Geology of pluton-related gold mineralization at Battle Mountain, Nevada: Tucson, Arizona, Center for Mineral Resources, The University of Arizona, Monographs in Mineral Resource Science, no. 2, 271 p.
Wells, J.D., Stoiser, L.R., and Elliot, J.E., 1969, Geology and geochemistry of the Cortez gold deposit, Nevada: ECONOMIC GEOLOGY, v. 64, p. 526–587.
Wrucke, C.T., and Armbrustmacher, T.J., 1975, Geochemical and geologic relationships of gold and other elements at the Gold Acres open pit mine, Lander County, Nevada: U.S. Geological Survey Professional Paper 860, 21 p.
Xie, X., Wang, X., Xu, L., Kremenetsky, A.A., and Kheifets, V.K., 1999, Regional orientation of strategic deep penetration geochemical methods in the central Kyzylkum desert terrain, Uzbekistan: Journal of Geochemical Exploration, v. 66, p. 135–143.