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Orbicular Alteration at the Clementine Porphyry Copper Prospect of Southwest Montana: Defining the Edges of Advective Flow in the Porphyry Copper Paradigm

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The Need to Explore for Deep Subsurface Porphyry Copper Deposits

Over the next 26 years, the projected increase in world requirements for copper will necessitate mining more copper than was mined in all prior human history (Schaffer, 2018). Junior exploration companies are expected to account for about 70 percent of the discoveries (Schaffer, 2018). It is now widely accepted that opportunities to discover shallow orebodies have diminished significantly throughout much of the world (Wood, 2016). Hence, there is a compelling need to abandon a predominantly surface to near-surface target approach and embrace instead deep exploration, thus placing a serious challenge on junior exploration companies. Particularly daunting is the fact that (1) the discovery rate of major orebodies had been falling from the early 1970s onward, while expenditures have continued to rise, and (2) the depth of discovery was mostly 200 to 300 m or less and has largely remained the same up to now (Schodde, 2013). Wood and Hedenquist (2019) assert that overall, "exploration efforts since 2010 have been wealth destructive." A pressing need has existed for a decade or more for a decisive change in how the search for new orebodies is designed, funded, and implemented. This is a daunting challenge, as many types of ore bodies with their tops located 500 to 1,000 m or more below surface are unlikely to exhibit the obvious signs on the surface that have guided past geological mapping that is the pivotal activity of exploration. An effective exploration strategy for junior exploration companies is required to map and describe new surficial geological evidence of deep mineralization sufficiently compelling for major companies to enter into partnerships to support the requisite deep drilling of targets. The current paradigm for porphyry copper deposits (Sillitoe, 2010; fig. 1) is based in part on two papers published almost half a century ago by Lowell and Guilbert (1970) and Gustafson and Hunt (1975). Sillitoe and others (2016) summarized the current discovery climate: "in the past decade, deep exploration for porphyry copper deposits completely concealed beneath extensive lithocaps has become increasingly common as near-surface mineralization becomes scarcer, but with rare exceptions there have been few successes." This raises the question as to what features, besides lithocaps, may prove to be more effective guides to locating the porphyry copper hypogene mineralization center? In this study we focus on orbicular textural features beneath the lithocap in both the porphyry to epithermal transition and the deeper porphyry level (fig. 1). In addition to the Bingham district, where Atkinson and Einaudi (1978) logged mineralized orbs in core, orbs have been described, though not mapped, at three deposits in Chile: Caspiche, La Escondida, and El Hueso (Sillitoe and others, 2013); Cajamarca in Peru; Morenci and Fortitude Copper Canyon in the U.S.; Cananea in Mexico; and Oyu Tolgoi in Mongolia (Marco Einaudi, written commun., 2019). This paper describes our fieldwork at the pre-drilling phase to map and interpret extensive orbicular alteration as part of lateral zoning at the Clementine prospect, a possible new deep porphyry copper system in Montana. The intent is to develop within the porphyry copper paradigm a powerful and predictive mapping tool for better locating the center and defining the edges of hypogene hydrothermal fluid flow that has evaded recent exploration efforts searching beneath lithocaps.

The Connection between Base Metal Vein Systems and Porphyry Deposits

Our approach to exploration at Clementine focuses on the observation that Cordilleran base metal vein systems exposed on the surface may have genetically related porphyry copper deposit root zones amenable to underground mining methods. The relation between polymetallic veins and porphyry-style mineralization was first brought to light by Meyer (1965) in the Butte District of Montana. During the past few decades (Bendezú and Fontbote, 2009), extensive mining and exploration in mature vein districts have revealed that some of these polymetallic ores can be the shallow expression of porphyry-Cu-(Au, Mo) and/or skarn mineralization centers (e.g., Quiruvilca, Noble and McKee, 1999; Yauricocha, Alvarez and Noble, 1988; Magma, Manske and Paul, 2002; Vinchos, Farfán Bernales, 2006; Morococha, Bendezú, 2007; Catchpole and others, 2008; and Kouzmanov and others, 2008). Fontboté and Bendezú (2009) further highlighted the connection between Cordilleran polymetallic vein deposits and Butte-type veins and replacement bodies, and grouped them into a deposit class in porphyry copper systems.

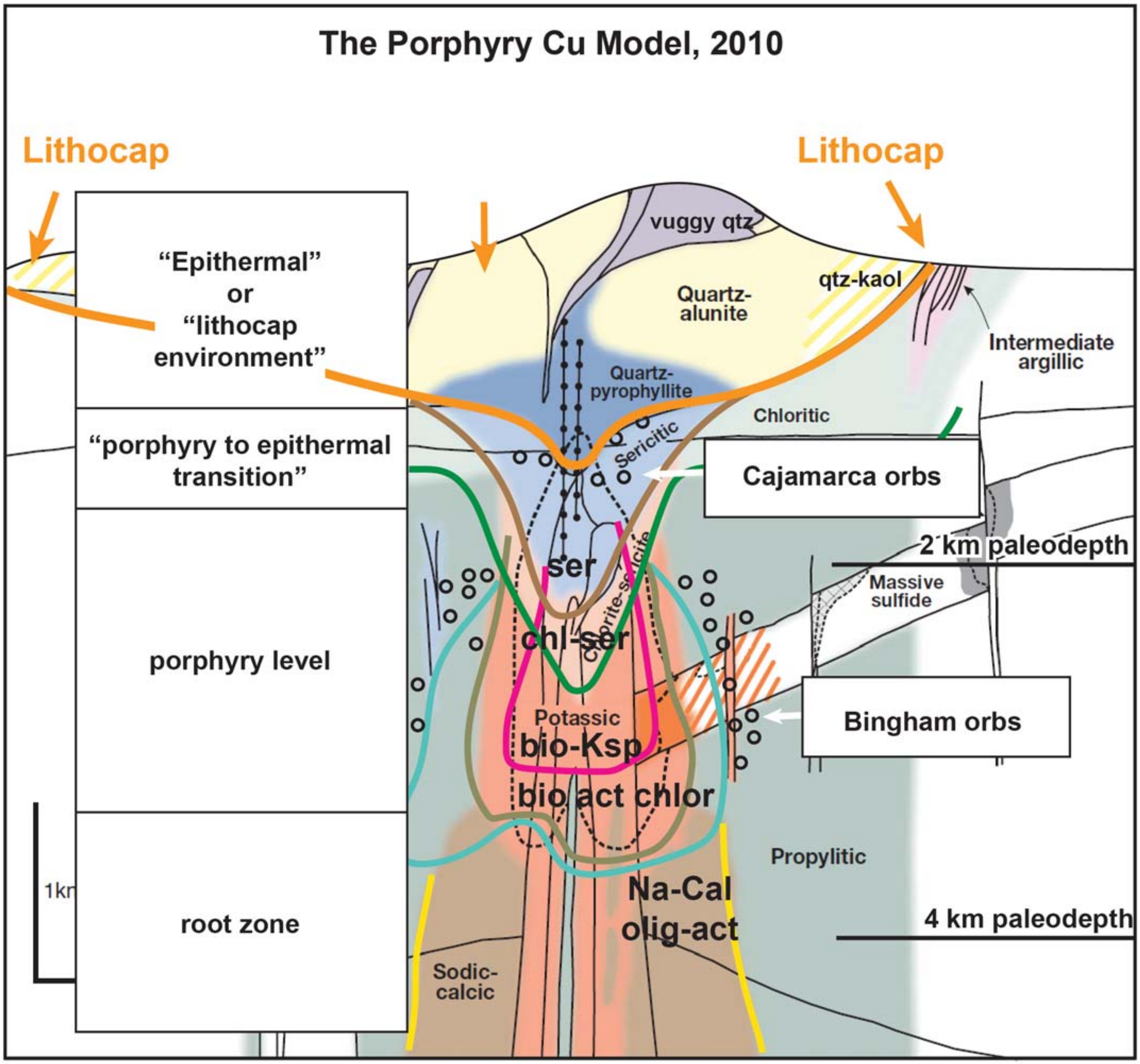

Figure 1. The porphyry copper model modified from Sillitoe (2010). The lithocap is shown with peripheral strata-bound advanced argillic alteration surrounding a central hypogene silicic core with structurally controlled high sulfidation sulfides with sericitic alteration extending to depth into the porphyry level. The porphyry Cu level has concentric alteration zones that transition outwards from central chlorite-sericite, to biotite-K-feldspar, biotite, actinolite, and finally to a chlorite outer shell. Orbicular alteration at Bingham described in Atkinson and Einaudi (1978) are related to the deeper porphyry level while orbs at Cajamarca, Peru occur at the porphyry to epithermal transition (Nobel and others, 2011).

Preparing for 21st Century Mining Methods and Implications for Exploration Strategy

Concurrent with the shift to deeper exploration, there has been an evolution of mass mining technology away from open pit to underground bulk mining techniques that are both economic and more deserving of a social license. Final approval for development nowadays involves much more than economics alone, even on private lands. While underground mining, especially with paste backfill, drastically reduces both subsidence and surface storage of voluminous waste rock and has relatively minor surface expression, public perception and concerns about the outfall of past mining practices continue to influence attitudes about mining in Montana and even threaten the future of the industry in the U.S. Of particular concern in Montana is water quality, both in the short and long term, given the importance of its blue ribbon-quality freshwater fisheries and their economic and natural value to the State's citizens and active outdoor community. The mine life cycle must address the full range of concerns, from formulating a suitable scientific exploration target, discovery drilling, engineering design, economic planning, and earning a social license with all stakeholders, to ensuring that the environmental quality of the mined land surface and hydrological system be maintained day to day and ultimately be restored in perpetuity as a healthy ecosystem.

Selecting Drilling Targets

While porphyry copper exploration targets are very large, drill targeting is challenging as it must address three major aspects of how the Cordilleran vein system on the surface relates to the deeper porphyry copper deposit.

(1) Finding the porphyry copper center

As yet unexposed deep porphyry copper deposits are the primary exploration target, using the overlying Cordilleran vein systems and wall rock alteration patterns as guides to what mineralization may occur below. The characteristics of an exposed Cordilleran vein system vary considerably in this model. The nearby ore deposits at Butte provide perhaps the best example of a high-grade, zoned base metal vein network descending into older, fracture-controlled, disseminated copper and molybdenum ore (fig. 2; Brimhall, 1977, 1979, 1980; Brimhall and Ghiorso, 1983). The plan map of the 2800 mine level of the Butte District (Brimhall, 1979) shows how the vein system only partially overlaps the deep porphyry copper system. The Main Stage veins are zoned such that the Badger (B) and Anselmo (A) produced mostly zinc, while the Lexington (X) produced mostly manganese, and the Mt. Con (C), Kelley (K), Leonard (L), Steward (S), and Belmont (Bt) produced mostly copper. Hence, search for deep porphyry copper deposits relies on exploring below the copper-rich portions of the Cordilleran vein system because drilling beneath the peripheral zinc, lead, and silver veins may entirely miss the porphyry copper center. Only in the Leonard (L) area is there advanced argillic alteration with high sulfidation state covellite–chalcocite–enargite mineral assemblages that could be considered as having some of the attributes of a lithocap. Instead, elsewhere in the district completely unaltered fresh Butte granite occurs at the surface between the large high-grade vein alteration envelopes.

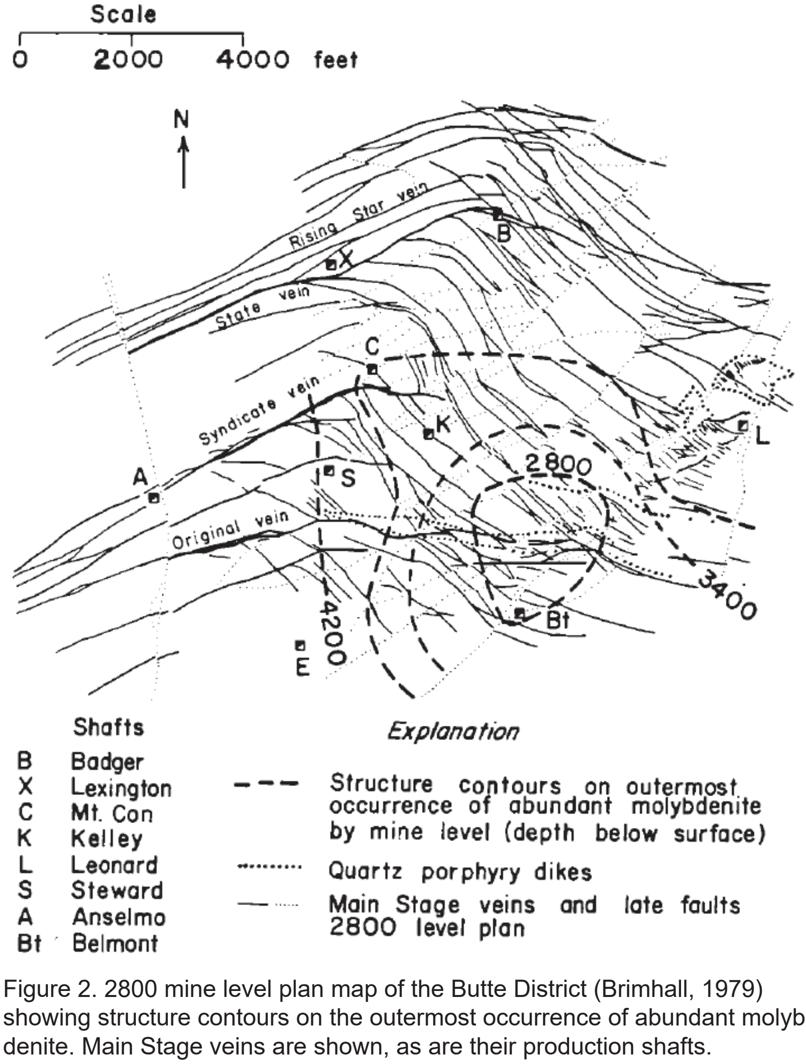

Figure 2. 2800 mine level plan map of the Butte District (Brimhall, 1979) showing structure contours on the outermost occurrence of abundant molybdenite. Main Stage veins are shown, as are their production shafts.

(2) Predicting the potential size of the porphyry copper target

The second complication relates to the potential size of the porphyry copper target. We followed an intriguing suggestion that the porphyry systems with the highest contained copper are a "closed system" as described by Oyarzun and others (2001) that did not vent, or out-gas. Sillitoe (2010) reaffirmed the importance of this containment factor in porphyry ore formation in the largest scale systems. Finally, another key factor to consider in gauging the potential size of a deep porphyry copper target in early stage exploration is its likely dimensions in plan view. Any and all discernible features that can be systematically mapped are potentially useful in estimating the dimensions of the possible porphyry system at depth. However, we show here that orbicular alteration offers unique insights as to both the center of the hypogene system sought and its likely size.

(3) Relying on observations rather than models: Extending the porphyry copper paradigm

Applying exploration models for porphyry copper deposits developed in Arizona (Lowell and Guilbert, 1970; John and others, 2010), or Chile (Gustafson and Hunt, 1975), to new territory can invite interpretive shortcomings. Especially concerning is the fact that most of the models describe systems where the pre-mine landscape surface intersected midway down into the well-mineralized part of the cylindrical porphyry copper deposit column, which can extend as far down from the paleosurface as 7 or 8 km (John and others, 2010). Stated differently, geological knowledge applied in exploration often reflects a clear proximity to economically mineable ore rather than to the less well known tops of the systems, which may in fact depart distinctly from the highly mineralized portions at depth.

The Location of the Clementine Prospect

Given the prevailing wisdom regarding clustering (Oyarzun and others, 2001; Tosdal and Richards, 2001), our target selection was based on searching as close to the Butte ore deposit as possible using a regional tectonic model in combination with maps of active and historic mining districts (Brimhall and Marsh, 2017). Our search focused on areas where the closed system model described by Oyarzun and others (2001) and Sillitoe (2010) would apply as a key element in the generation of large porphyry copper deposits. Subsurface containment of magmas and early stage hydrothermal fluids is a central part of our exploration strategy, much like the stratigraphic and structural anticlinal traps explored in the petroleum industry. However, instead of searching for a porous and permeable reservoir rock for hydrocarbons, we search for intact stratigraphic traps providing containment for porphyry copper mineralization without dissipative metal loss upwards into more permeable zones in an open system. Within this context, we also search for systems where the early hydrothermal footprint is largest and, presumably, indicative of a significant porphyry copper deposit at depth. These constraints are tempered by the realization that in a fold and thrust belt, once an early stage of porphyry mineralization forms, later through-going mineralized veins are likely to develop, as with the syntectonic Main Stage vein system at Butte, which extend up above the protore and serve as guides to mineralization at depth. The nearby Pioneer Mountains have a long history of base and precious metal production useful in our regional search. Historic mining districts extend southward from Butte to Quartz Hill and end at Bannack. We sought to put Butte and the nearby deposits of the Pioneer Mountains into as broad a regional tectonic context as possible to glean useful knowledge as to controls on ore deposition. Hildenbrand and others (2000) summarized the distribution of ore deposits in the western United States in relation to regional crustal structures and showed Butte and Bingham situated along the frontal Sevier age thrust fault. The historic mines of the Pioneer Mountains in Montana south of Butte occur along a single, north–south-trending, regional anticlinal hinge of the frontal (easternmost) anticline of the Cordilleran fold and thrust belt of Sevier (Late Cretaceous) age. Many deposits, including Quartz Hill and Hecla, occur within domal structures illustrating structural and stratigraphic containment. We focused our fieldwork on the former Divide District, which had no prior history of metal production but occurs at a suggestive gap in the string of inactive mines in the Pioneer Mountains. Most importantly, through mapping we recognized a doubly plunging anticlinal fold, indicative of stratigraphic and structural containment of subsurface magmatic and hydrothermal fluids.

Geological Mapping of the Clementine Prospect

Given that much of the Divide Creek District where the Clementine prospect is located is steep terrane up to 9,200 ft high at Mount Fleecer, with dense timber below the alpine zone and largely inaccessible except on foot, GPS-supported digital mapping methods were a necessity (Brimhall and Vanegas, 2001; Brimhall and others, 2002, 2006). Much of the mapped area has a very poor rock exposure, both under tree canopy and on open grassy hillslopes. However, tree root heave mounds provide sufficiently good rock fragment samples that mapping inferred geological formation contacts is possible. Only through accurate digital mapping was it possible to map small outcrops and accurately correlate them spatially so that distinct linear belts of similar lithologies and alteration zones could be discerned. Of particular importance to our exploration strategy was discovery of a vein gossan system that provides the key evidence of Cordilleran polymetallic mineralization that might be followed to depth to find a porphyry copper deposit.

The geological mapping done over seven field seasons, from 2011 through 2018, is shown in figure 3 at a scale of 1:30,000. The prospect is in a nappe window into the Lewis Overthrust, and occurs below the Grasshopper Thrust Fault (Fraser and Waldrop, 1972) but above the frontal thrust to the east described by Ruppel (1993) and Ruppel and others (1993). While the anticline intruded by the Big Hole River (Mount Fleecer Pluton) is also shown on the Dillon 2° sheet of Ruppel and others (1993) and the more detailed 30' x 60' Butte

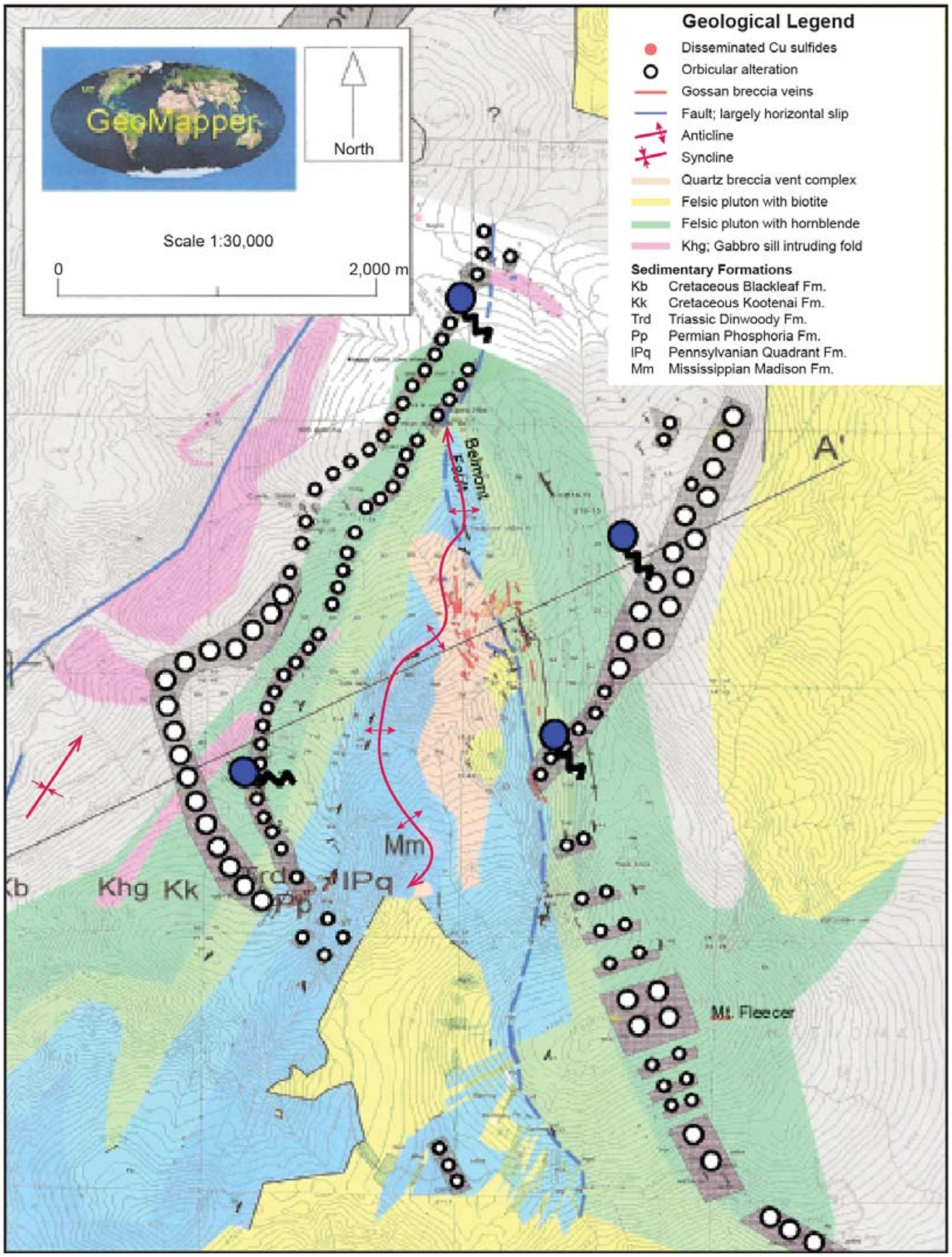

Figure 3. Bedrock geological plan map based on fieldwork from 2011 through 2018. Formation abbreviations are: Mm (Mississippian Madison), IPq (Pennsylvanian Quadrant), Trd (Triassic Dinwoody), Kk (Cretaceous Kootenai), Khg (hornblende gabbro sills), and Kb (Cretaceous Blackleaf). Four groundwater-derived springs are shown with blue circles.

South sheet of McDonald and others (2012), we have added significant new detail that leads us to interpret the structure as a mineralized and altered, syntectonic, frontal thrust, fault-bend anticline. At the anticlinal core, Mississippian Madison limestone outcrops. The Pennsylvanian Quadrant, Permian Phosphoria, and Triassic Dinwoody Formations occur in sequence above the Madison Limestone, farther away from the north–south-trending axial plane. The uppermost stratigraphic units are the Cretaceous Kootenai and overlying Blackleaf Formations. A gabbroic sill intrudes the west flank of the anticline and can be found on the eastern side of the anticline, displaced by the north–south right lateral Belmont Fault, which has a displacement of 500 to 600 ft. The lateral displacement is consistent with observed fault slickensides with a pitch of 20°. Conglomerate beds in the Blackleaf Formation were also mapped east of this fault, confirming the right lateral sense and magnitude of displacement.

Styles of Alteration

The most obvious district-scale features superimposed on the bedrock anticline are distinctive, continuous tabular zones of orbicular alteration (fig. 4) that extend over 6 km north–south and 2.5 km east–west on both sides of the anticline (fig. 3). Orbicular alteration is the outermost feature of the Clementine prospect and was discovered only through systematic digital mapping. While approaching the Clementine prospect, unaltered sedimentary lithologies were found within the Blackleaf and Kootenai Formations on the flanks of the anticline. Farther inside the anticline however, orbs occur up to 3 cm in diameter that commonly have remnants of their original green-colored silicate mineral filling. The most intact orbs we found and thin sectioned are filled with actinolite, quartz, calcite, titanite (sphene), and other minerals. Like the gabbro sills and conglomerate beds, the orbicular zones are displaced right laterally by the Belmont Fault. The orbicular rocks outcrop, unlike the siliciclastic diopside-bearing hornfels units in the footwall, and form what few outcrops occur in this area, under tree canopy and thin alpine soil cover.

One notable feature of the orbicular alteration is that all of the observed groundwater-derived springs (fig. 3) in the Mount Fleecer Area emanate nearby orbicular zones as at Tub Springs, Fleecer saddle, along the Parker Mine road on the west side of the anticline, and on the east side of the anticline. We interpret the close association of springs with the orbicular zones as being due to the relatively low permeability of both the dense hornfels rocks immediately below the orbicular zones and the orb zones themselves forcing water that infiltrated unaltered formations at higher elevations back up to the surface. Given that this area is very dry after the spring snowmelt has run off, all four of these springs constitute the principal water supply for the cattle that graze there in the summer under U.S. Forest Service rangeland permitting. There are only three watering tanks mapped in the entire area, and all three are fed by springs emanating from orbicular zones. The only other springs, which are significantly smaller, occur near the trace of the Belmont Fault. On their southern terminus, the northern plutons of the Big Hole River (Fleecer Mountain) intrusion seem to intrude the orbicular zones. Similarly, on the northern end, the plutons of the southern end of the Boulder Batholith cut off the orbicular

Figure 4. Orbicular wall rock alteration consisting of orbs lined with actinolite in fresh samples up to about 1 in diameter also containing sparse disseminations of chalcopyrite, pyrrhotite, and ilmenite in the rock matrix. Sample from the west side of the Clementine anticline above the Parker Mine. Orbs are often now voids where the original mineral filling has disappeared. Egg crate insert shows lines formed by intersecting planes.

zones.

Description of the Orbicular Zones: The Outer Ring of Wall Rock Alteration

Inside the core of the anticline in the footwall of the orbicular zones, the alteration is best described as widespread diopside hornfels that are differentially developed spatially. Of particular importance is the fact that the orbicular alteration zones have fresh, unaltered, sedimentary rock formations in their hanging walls and diopside hornfels on their footwalls that are metasomatic products of hydrothermal alteration. This transition implies that outward and upward convective fluid flow coursed up through the hornfels facies and ceased where the orbicules developed in the uppermost distal parts of the Clementine convective system. This regional spatial coincidence of orbicules exactly at the upper and outer limit of visible fractures is central to our interpretation of orb formation in low permeability upper reaches and to advancing understanding of the porphyry copper paradigm in terms of vertical and lateral zoning. The importance of the orbicular alteration in the context of porphyry copper ore formation is strengthened by the fact that orbicules have been previously observed and meticulously described at the world-class copper deposit at Bingham Utah. Tabular bodies of hydrothermal, orbicular, wall rock alteration similar to those in the Clementine prospect have been described in the contact aureole at Carr Fork, Bingham, by Atkinson and Einaudi (1978), and around breccia pipes at Cananea, Mexico, by Meinert (1982). At Clementine, the orbicular alteration alters multiple rock formations over a 6 km strike length. The formations affected at the surface include the Pennsylvanian Quadrant, Permian Phosphoria, Triassic Dinwoody, Cretaceous Kootenai, and Cretaceous Blackleaf Formations. Our mapping documents disseminated chalcopyrite and pyrrhotite associated with the orbicular zone, making the genetic parallel with Carr Fork extremely close. Furthermore, we have now recognized that the primary mineral lining the orbicular cavities at Clementine is in fact actinolite, which is consistent with the current porphyry copper model (fig. 1).

Breccias, Veins, and Plutons

Inside the tabular orbicular zone bands on both sides of the axial plane of the anticline, just west of the Belmont fault, is a large breccia complex that is 2.2 km north–south and 500 m wide. This zone contains Quadrant, Phosphoria, Dinwoody, and Kootenai Formations cut by north–south-trending, steep, tabular bodies of breccia consisting of angular fragments of quartzite in a matrix of pure milled quartz. The rock contains about 98 percent silica. Within the boundaries of the barren breccia is a smaller system of north–south-striking, mineralized-matrix, breccia-vein gossans extending over a strike length of 900 m. These mineralized breccias have iron contents up to 32 percent and represent oxidized sulfide veins, and constitute compelling evidence of Cordilleran polymetallic base metal mineralization. Near the southeast side of the copper-barren breccia complex, two new plutons have been mapped (fig. 3). The northern felsic pluton has disseminated sulfides and is highly altered. An adit, now caved, was collared in the pluton and heads eastward. The mine dump, however, contains diorite fragments typical of another pluton to the south that is completely fresh and has both fresh biotite and hornblende along with unaltered sphene.

The geometric center of the mineralization is the vein system shown in figure 3 as thin red lines, west of the Belmont Fault. East of the Belmont Fault, quartz-rich veins outcrop with a considerable strike length and obvious surface manifestation, which apparently drew historic attention to this area. Two trenches east of the Belmont Fault have rocks that assay up to 1,190 ppm copper and have colloform silica chalcedony. These silica-rich veins have been offset right laterally along the Belmont Fault. With the offset restored northward, they become the northern end of the vein gossan system on the west side of the fault.

The centrality of the vein system to the district as a whole is confirmed by surface contouring of the tabular orbicular zones, which have gentle outward dips and form a cupola in three dimensions. Mapping to date shows a general co-axiality of the orbicular alteration, the centrally located vein gossan system, and an altered pluton nearby with old workings, including the adit mentioned, as well as a shaft and two trenches east of the Belmont Fault.

Knowledge of the three-dimensional shape of the orbicular zones gained through surface contouring provides guidance in construction of an interpretive vertical cross section (fig. 5), which is based entirely on surface

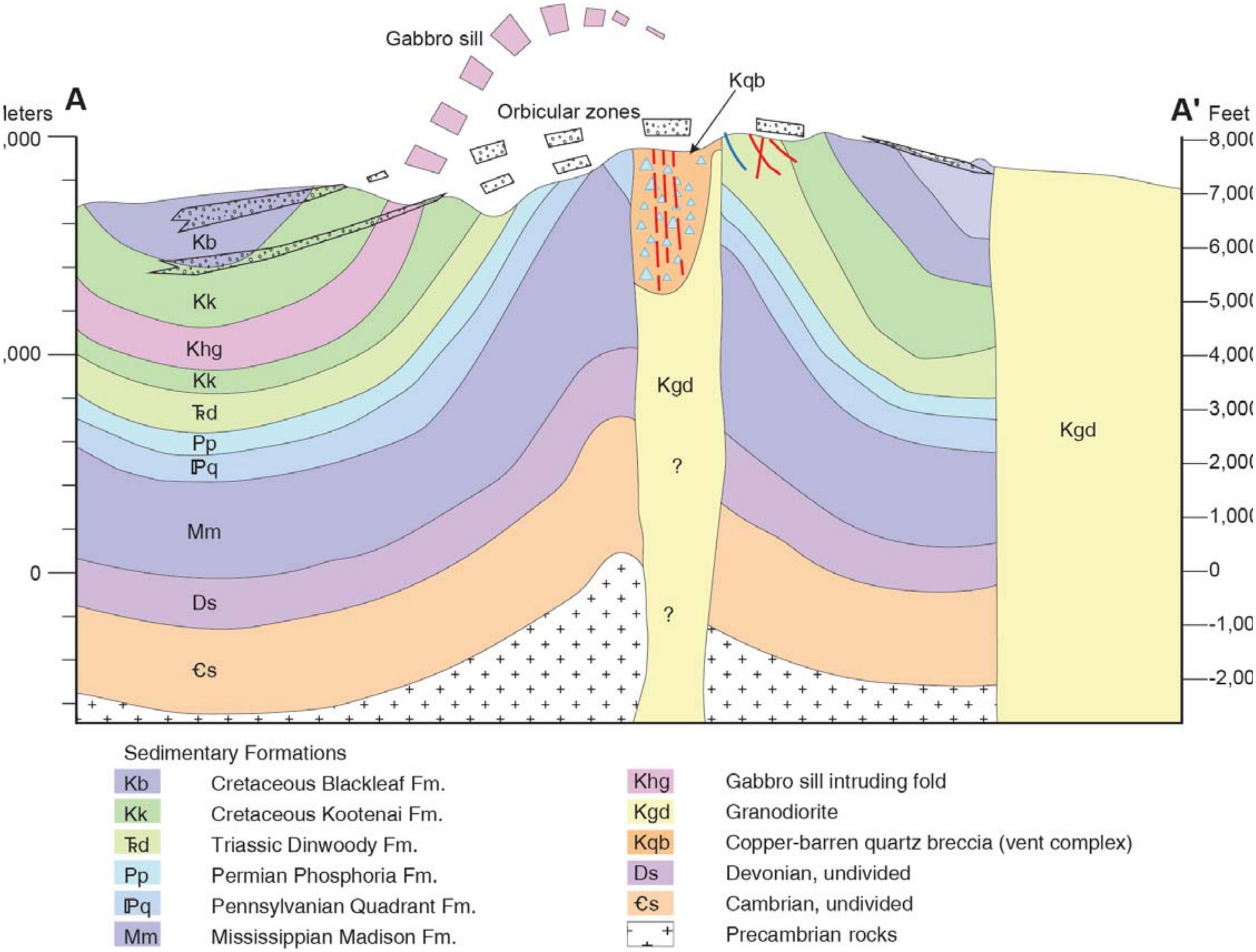

Figure 5. Interpretive vertical geological cross section of Clementine based entirely upon: (1) surface digital geological mapping and (2) approximate formation thickness. Notice the gentle outward dips of the orbicular zones and their upward closure near the present surface. Also, notice that the copper-barren breccia, with quartzite fragments occurring along the axial plane of the anticline, plots in the vertical vicinity of the orbicular zone projection. We interpret this to mean that fragmentation of the Quadrant was related to formation of the steeply dipping, tabular copper-barren breccia zones.

geological mapping shown in figure 3. Structure contouring and surface fitting using Surfer shows that the top of the orbicular zones probably occurred just east of the vein gossan system and altered felsic pluton, and intersects the folded sedimentary strata near the apical crest at the level of the Pennsylvanian Quadrant Formation projected upwards. We view the dominance of Quadrant quartzites in the copper-barren breccias and the projected position of the orbicular zone in the cross section as not accidental. The Quadrant Formation may have been ideally situated to fracture in the axial zone of the fold where, above a neutral surface, extension-related fragmentaiton is expected. Hence the breccias are dominated by locally derived, mono-mictic, Quadrant clasts.

Formation of the Orbicular Zones: Defining the Edges of Advective Flow in the Porphyry Copper Paradigm

Given our observations at Clementine that the tabular orb bodies occur right at the top of observed fracture networks with unaltered sedimentary formations above and hydrothermally altered hornfels below, our attention is drawn to crack tips on the upper edge of the convective halo and what changes occur there with regards to advection, diffusion, and reaction. These are the essential types of solute transport involved in ore genesis and wall rock alteration. Here we inspect what each of these terms mean in order to understand our field observations and to better understand the structural front represented by the continuous tabular orbicule cupola, extending 6 km in plan view. Understanding orb growth quantitatively supports our goal of significantly advancing the porphyry copper paradigm in terms of developing mapping tools to: (1) help locate the center of hydrothermal convection and (2) estimate the size of the likely mineralization system.

Throughout the formation of porphyry copper deposits, advective flow of hydrothermal solutions dominates transport of aqueous species, including ions and aqueous complexes being carried in solution or in gaseous form. Advective transport of solutes via a moving fluid is responsible for vein and veinlet formation. The other two major processes to consider in metasomatism, besides advection, are diffusion and reaction. These are responsible for the development of alteration envelopes parallel to the veins and veinlets controlling advective transport. In general, since alteration envelopes are parallel to the veins, diffusion happens normal to the veins by aqueous species migrating from areas of higher concentration to areas of lower concentration within a stationary pore fluid rather than by fluid pressure differences controlled by temperature gradients, as in convection.

The analytical expression relating changes in rock composition over time to advective transport, diffusion, and chemical reaction in one direction, x, are given in equation 1 (Garzón-Alvarado and others, 2012). Equation 1 is a statement of conservation of mass coupled with diffusion and reaction.

Equation 1:

$$\overset{(1)}{\frac{\partial Ci}{\partial t}} = -\overset{(2)}{\frac{v\partial C_i}{\partial x}} + \overset{(3)}{\frac{D_i\partial^2 Ci}{\partial x^2}} - \overset{(4)}{\frac{\partial q_i}{\partial t}}$$

In equation 1, C_i is concentration of aqueous solute (*i*) in water, t is time, v is pore or crack water flow velocity, x is distance, and D_i is the diffusion coefficient of (*i*). Term (1) is the change in solute composition over time; term (2) represents advective transport, which depends upon fluid velocity and goes down the concentration gradient; term (3) represents diffusive transport involving the curvature of the concentration gradient; and term (4) is the change in concentration in the solid mineral phases due to the sum of all chemical reactions.

Given the field observation at Clementine that the oribicular features occur at the outer extremity of hornfels and microveinlets, we assert here that the position occupied by the orbs is where advective transport slowed sufficiently that diffusional processes dominated in the absence of active fluid advection, as in the center of the district where veins occur. Additionally, the roughly spherical shapes of the orbs, in contrast to planar veins with parallel alteration envelopes, appears to be a radial-diffusive phenomena.

The relative importance of advective transport and diffusion are expressed by the Peclet number (Pe). Pe is a class of dimensionless numbers relevant in the study of transport phenomena in a continuum. It is defined to be the ratio of the rate of advection of a solute by the flow to the rate of diffusion (Huysmans and Dassargues, 2005). Dividing the advective term (2) above in equation 1 by the diffusive term (3) and substituting L for the variable x gives equation 2:

Equation 2:

$$P_e = v\frac{L}{D}$$

L is called the Characteristic Length and is given by the ratio of volume to surface area in the case of spherical structures like the Clementine orbs. For a sphere with radius r, the volume is given by $4/3\pi r^3$ and the surface area by $4\pi r^2$ so that $L = r/3$. The orbs have a radius of approximately 3 cm, so L is about 1 cm, making P_e equal to v/D. If we assume that the value of P_e was about 1, implying that the orbs formed at the edge of the convection system where diffusion was as equally important as advection, we can estimate the approximate flow velocity as $v = D$ in this case. Empirical values of diffusion coefficients D for sandstones show 3×10^{-8} cm^2/sec as typical (Boving and Grathwohl, 2001). The distance traveled by the fluid over the time span of 1 year would then be 3×10^{-8} cm/sec times 3.15×10^{7} sec, or 9.45×10^{-1} cm, or only about 1 cm per year. This markedly slow rate of fluid migration compared with the kilometric size of porphyry copper deposits is consistent with our assertion that the orbicular zone represents the outermost and uppermost advance of fracture-controlled fluid advection. Since we see in thin section that the orbs often have narrow quartz veinlets entering them, we view orb formation as being a crack-tip growth feature from both the one-dimensional conduits formed at crack intersections and planar cracks. Spherical orbs and elongate tubular orbs formed from crack intersections and individual cracks, respectively.

When the Peclet number P_e has a value of 1, then the advective flow rate, v, is equal to the diffusion coefficient or diffusivity D, which is a very small number for rocks. This implies that the fluid flow rate is similarly very, very slow. Advective flow rates on this order clearly indicate that the orbs formed as the very upper and outer edge of the convective fluid flow halo. As advective flow slowed dramatically, the oribicular zones were frozen as hydrothermal relicts created largely in place by diffusive processes and local chemical reactions. The orb front is a mappable textural change in rock fabric even in areas with poor exposure. We have observed orbs in a variety of sedimentary rock types that have one attribute in common: clastic rocks with intergranular porosity. Diffusion took place through the pore fluid medium, making orb growth possible. In other rock types lacking intergranular porosity, for example igneous rocks with interlocking grains, we suspect that orbs could be lacking or at least substantially smaller in size, perhaps occurring as splotches.

Conclusions

This report describes mapping distal wall rock alteration features likely to be encountered early on in exploration mapping as the outermost ring of concentric alteration and sparse disseminated chalcopyrite mineralization. Combining field observation on the Clementine prospect with first principle analysis of known solute transport mechanisms, we show that the district-wide orbicular alteration represents the outer edge of hydrofractured stockworks where advective flow slowed considerably and spherical orbs formed by diffusion from the uppermost crack tips or crack intersections. The utility of orb cupolas as a targeting tool then stems from the fact that orbicular zones mark the position of a key hydrodynamic boundary: the upper and outer edge of the mineralized fracture permeability network. Orb alteration makes this subtle physical feature macroscopically visible and contributes a powerful mapping tool in lithologies where orbs are likely to form in sedimentary rocks with connected pore space rather than interlocking grains. At Clementine the continuously exposed strike length of 6 km of the orbicular zones implies a remarkable continuity and large scale of the fracture network at depth. We view the large dimensions and axially symmetric disposition of the orbicular alteration, base metal vein system, and plutons at Clementine as a positive sign of a deeper and potentially large-scale porphyry copper–molybdenum deposit, possibly within reach by drilling to depths of several thousand feet. In that context, mineralized orbicular alteration is shown to be an important factor in porphyry copper exploration for closed system, confined, magmatic-hydrothermal systems, which are most likely to form large ore bodies. Orb zone mapping is a high-impact endeavor significantly enlarging the target size in early stage exploration. It is hoped here that by describing orb cupolas and discerning their origin in a sound, process-based understanding accessible through mapping and quantitative reasoning, our ideas are anchored within a framework sufficiently compelling to now formally include orb zoning to the porphyry copper model. More broadly, while lithocaps, vein systems, and breccia complexes offer useful targeting information in searching for deep porphyry copper bodies, these structurally controlled types of mineralization reflect very high-fracture permeability, usually developed relatively late in a district, and may vary from minor to major features of a new prospect. What can be much more telling about the size and proximity below the present land surface to infer possible ore masses below are the tabular orbicular alteration zones with disseminated copper sulfides. We publish this work in the hope that it will help to modify the current perception of excessive risk in greenfields exploration relative to the work in mature districts where low discovery rates have prevailed.

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Panoramic of the Cable Mine site (photo: A. Roth).