Identification of the expression of earthquake-induced surface flooding by groundwater using detailed regolith mapping at the buried Atlántida Deposit, northern Chile

A. E. Brown*, P. A. Winterburn & T. Bissig

Mineral Deposit Research Unit, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, 2020-2207 Main Mall, Vancouver, BC, V6T 1Z4, Canada

*Correspondence: alexandra.liz.brown@gmail.com

Present addresses: P.A.W., Vale Exploraciones Chile, Rosario Norte 615 #1202, Las Condes, Santiago, Chile; T.B., Goldcorp Inc., 666 Burrard St #5400, Vancouver, B.C., V6C 2X8, Canada

Abstract: This paper describes saline pockets (10 cm–3 m in diameter) of fine-grained material distributed on alluvial surfaces. These saline pockets are localized along structural trends at the Atlántida buried porphyry-skarn Cu–Au–(Mo) deposit in the Atacama Region of Chile. The distribution and highly saline nature of the material suggest formation by the pooling and evaporation of groundwater forced through fractures to the surface during seismic activity. These saline pockets are a surface expression of the hydrological effects of seismic activity along faults. Saline pockets with similar distribution and characteristics were also identified at three additional alluvium-covered areas, all located in the Antofagasta Region of Chile. Identification and mapping of these saline pockets relies on the ability to identify the continuation of structures through overlying gravels. Regolith mapping using high-resolution drone imagery and digital elevation modelling identified geomorphic markers of faulting which aided mapping the distribution of saline pockets. Saline pockets provide a unique opportunity to sample the direct expression of transported groundwater reaching the surface from depth and provide a prime target medium for mineral exploration through transported gravels.

Keywords: buried deposits; exploration; geochemistry; geomorphology; earthquake-induced surface flooding; seismic pumping; regolith mapping; Chile

Received 26 August 2018; revised 13 February 2019; accepted 14 February 2019
bedrock contact, extending to at least 600 m below the surface (Hope & Andersson 2015). Bedrock is covered by 25–80 m of transported alluvial gravels over the entire mineralized zone. The water table is variable across the property, though generally located at 40–50 m below the surface.

Atlántida lies between the Atacama and the Domeyko fault systems within the southern extent of the Central Depression (Bissig & Riquelme 2010). The porphyry is part of the Cretaceous porphyry copper belt (Maksaev et al. 2010). Two main intrusive phases are host to the bulk of mineralization and intrude into volcanic and limestone units. The earliest intrusive phase has a tonalitic composition and is interpreted as pre-mineralization (Hope & Andersson 2015; Pavez 2016). This phase is intruded by a
granodiorite, feldspar-rich porphyry, characterized by brecciated contact zones with the tonalite intrusion (Hope & Andersson 2015; Pavez 2016). Local skarn and carbonate replacement polymetallic veins are exposed in limestone outcrops east and west of the buried porphyry. Atlántida has average grades of 0.2% Cu and 0.34 g t⁻¹ Au inclusive of the local skarn with a preliminary resource estimate of 427.1 Mt (Hope & Andersson 2015).

Gravel cover at Atlántida is deepest in the south, where a large NE-trending valley cuts through the property area (Fig. 3). The alluvial surfaces lack the development of a true desert pavement (Laity 2009), a common characteristic of gravel surfaces in the driest parts of the Atacama Desert. The unconsolidated gravels are dominated by clastic material below the cobble surface with varying occurrences of hard or soft calcrite starting at a depth of 20–40 cm. The gypcrete and soluble nitrate horizons commonly found in northern Chile, e.g. the gypcrete horizons within coalesced alluvial fan deposits spanning over 35 km in the Calama Basin (Hartley & May 1998), are not present at Atlántida. Geomorphological relationships between surfaces indicate there have been several erosional events causing incision of alluvial deposits by younger, fluvial or alluvial material. Older alluvial surfaces at Atlántida are dominated by cobble- to boulder-sized clasts derived from local geological formations with Fe-oxide weathering and Mn-oxide crusts on clasts at the surface. Younger alluvial surfaces are compositionally similar to alluvial fans, although comprise smaller clasts on the surface with little to no Fe- or Mn-oxide coating.

Erosional fluvial channels incise older alluvial fans to depths of up to 1 m and cause channelization on the older alluvial surfaces. The beds of fluvial channels are dominantly composed of small clasts of reworked older gravels and often have an increased calcrite clast content due to the erosion of calcrite horizons exposed by channel incision. Material, derived from erosional channels, fills valleys in the central part of the property.

**Additional study sites**

The Papas, Viento and Mastodonte prospects are AngloAmerican Chile exploration projects, all located in the Antofagasta Region of Chile (Fig. 1). Varying stages of exploration for buried Cu-porphyry mineralization have been conducted at each site. Initial drilling by AngloAmerican Chile in 2006 at the Papas prospect, located 20 km NNE of the Chuquicamata mine, intersected limited Cu–Au porphyry mineralization; however, no further exploration has occurred to date. Mastodonte and Viento, located 75 km SE of Sierra Gorda and 190 km SE of Antofagasta, respectively, are greenfield prospects with only geophysical surveys and geological mapping completed to date.

Alluvial cover at both the Papas and Mastodonte prospects consists of a gently sloping cobble surface with unconsolidated gravel beneath. Laminated to massive gypsum deposits spanning over 35 km in the Calama Basin (Hartley & May 1998), are not present at Atlántida. Geomorphological relationships between surfaces indicate there have been several erosional events causing incision of alluvial deposits by younger, fluvial or alluvial material. Older alluvial surfaces at Atlántida are dominated by cobble- to boulder-sized clasts derived from local geological formations with Fe-oxide weathering and Mn-oxide crusts on clasts at the surface. Younger alluvial surfaces are compositionally similar to alluvial fans, although comprise smaller clasts on the surface with little to no Fe- or Mn-oxide coating.
alluvial surfaces have been incised by younger erosional fluvial channels, causing channelization. Mastodonte is located c. 65 km SE of the Banquedano nitrate deposits, which were mined extensively during the nineteenth and early twentieth centuries (Ericksen 1981). However, nitrate horizons are not present on the Mastodonte property. The Viento prospect is located within the Profeta Formation in the Precordillera. The landscape consists of thrusted marine sediments, creating a mountainous terrain. The terrain is deeply incised by erosional channels of younger alluvial material. Large alluvial fans derived from the thrusted sedimentary rocks consist of cobble surfaces with unconsolidated gravel and clastic material beneath. Massive gypsum generally only occurs proximal to outcrop in the area, but it is either absent or only occurs as evaporitic beds on the sides or apexes of alluvial fans across the rest of the property.

Regolith landscapes and the geomorphic evolution of an area are intrinsically related to topographic changes, including those caused by tectonic uplift and/or subsidence (Audin et al. 2003). Landforms such as alluvial fans and fluvial channels are largely controlled by these topographic changes and are therefore considered ideal indicators for the presence of fault structures continuing through cover (Molnar et al. 1994; Holbrook & Schumm 1999; Formento-Trigilio et al. 2002; Audin et al. 2003). Reactivation and movement of structures post-gravel deposition can alter the morphology of alluvial landforms on the surface, leaving geomorphic markers of faulting. High-resolution drone imagery and digital elevation modelling used together can aid regolith mapping and identification of these geomorphic markers of faulting at the surface (Fig. 4).

**Detailed regolith mapping**

Regolith landscapes and the geomorphic evolution of an area are intrinsically related to topographic changes, including those caused by tectonic uplift and/or subsidence (Audin et al. 2003). Landforms such as alluvial fans and fluvial channels are largely controlled by these topographic changes and are therefore considered ideal indicators for the presence of fault structures continuing through cover (Molnar et al. 1994; Holbrook & Schumm 1999; Formento-Trigilio et al. 2002; Audin et al. 2003). Reactivation and movement of structures post-gravel deposition can alter the morphology of alluvial landforms on the surface, leaving geomorphic markers of faulting. High-resolution drone imagery and digital elevation modelling used together can aid regolith mapping and identification of these geomorphic markers of faulting at the surface (Fig. 4).
At Atlántida, high-resolution drone imagery and digital elevation modelling were used during regolith mapping to understand surficial alluvial processes including erosional history of the area and the relative ages of the alluvial surfaces (Fig. 3). In addition, regolith mapping was used to identify the continuation of deep bedrock structures that extend through the overlying gravels and alter alluvial landforms on the surface (Fig. 3).

High-resolution imagery
The use of aerial photography and satellite imagery, such as stereoscopic aerial photo pairs for 3D visualization, has long been an integral tool for regolith mapping (Butt & Zeegers 1992). More recently, airborne-gamma ray spectrometry, in association with Landsat TM bands and digital elevation models, has been applied to regolith mapping (Wilford et al. 1997). Drone imagery colour bands can be manipulated in commercial and publicly available geographic information system (GIS) software. Enhancing colour differences between alluvial fans in the imagery aids in tracing the host geology of alluvium. Colour enhancement can identify relative ages of units, such as younger incised fluvial channels composed of smaller-sized clasts, as well as older surfaces with significant Fe- or Mn-oxide coating on clasts. For example, morphological and compositional characteristics of the Pacific palaeosurface (Atacama Pediplain (e.g. Galli-Olivier 1967)/Atacama Bench (Armijo et al. 2015)) from 18°S to 22°S were mapped by Evenstar et al. (2017) using a combination of remote sensing data from Google Earth (VNIR, visible near-infrared), Landsat (VNIR and SWIR, short wave infrared) and a digital elevation model.

Digital elevation modelling
Digital elevation models can aid the identification of areas of uplift and/or subsidence and topographic changes across alluvial surfaces too subtle to clearly identify in the field (Fig. 4). As detected by high-resolution imagery and digital elevation modelling, geomorphic markers of faulting can be easily identifiable prior to ground-truthing. First-order structural and erosional control on the spatial distribution of the saline pockets highlights the importance for detailed regolith mapping for identification in the field (Figs 3 and 4). The combination of high-resolution imagery and digital elevation modelling provided a powerful tool to determine relative ages, erosional history and structures in the area prior to ground-truthing at Atlántida. This allowed for efficient identification and mapping of the distribution of saline pockets.

Identification of saline pockets
Saline pockets of material with distinct characteristics relative to the surrounding alluvial material were identified first at Atlántida, and later at the Papas, Mastodonte and Viento prospects. The pockets are generally distributed in clusters and individual pockets are 10 cm–3 m in diameter, though can often occur as elongated clusters up to 40 m long and 20 m wide (Fig. 5). Their most distinctive
characteristic is the contrast between the confined high-conductivity material from saline pockets compared to the surrounding low-conductivity alluvial gravels (Fig. 6). Material from pockets at all four properties commonly tested above the range of the conductivity meter (20,000 microsiemens (µS), 12,800 ppm total dissolved solids (TDS)) in 1:1 volume slurries, and required dilutions of 1:4 to 1:16 for conductivity readings. The median salinity of pocket material from all properties ranges from 1.2–2.2%. In contrast, median background salinity of alluvial gravels ranges from 0.01–0.06% in areas with no gypsum, and from 0.1–0.25% in areas with high gypsum content (Fig. 7). Deionized water leach analyses of material from saline pockets from Atlántida indicate the dominant salt mineralogy is NaCl (Fig. 8). Increasing concentrations of copper porphyry pathfinder elements (Re, Se, Te and Mo) are observed with increasing concentrations of Na and Cl in the saline pockets. Refer to Brown et al. (2019) for a detailed geochemical assessment. Background alluvial material is characterized by alkaline pH values (8.5–10.5) at Atlántida, yet decreasing pH of the leachate (pH 7–8) is observed with increasing conductivity (Fig. 8).

---

**Fig. 6.** Conductivity measurements over 10 m across a saline pocket and extending into background alluvial material. High conductivity values are highly localized and drop to background levels within 50 cm of the saline pocket. Material sampled at 5 cm depth and sieved to <1 mm fraction. Conductivity measured with a field portable conductivity meter. Measurements above 20,000 µS were calculated using dilution factor of 4 for measurement of a 1:1 slurry by volume.

**Fig. 7.** Histograms of conductivity (µS) in saline pocket samples (grey) and background alluvium (black) from all properties, shown separately.

---

**Fig. 8.** Deionized water leach analyses of material from saline pockets from Atlántida indicate the dominant salt mineralogy is NaCl. Increasing concentrations of copper porphyry pathfinder elements (Re, Se, Te and Mo) are observed with increasing concentrations of Na and Cl in the saline pockets.
At all properties, characteristics of saline pockets differ considerably from those of the surrounding loose, unconsolidated gravel-dominated surface. The surface expression of saline pockets is variable. They can appear as darker surfaces or, in more arid areas, as white patches of salt on the alluvial surface (Figs 9 and 10). These characteristics can be enhanced by manipulation of the colour bands from the drone imagery, allowing for easy identification (Figs 4 and 5). Field observation of pockets may show morphological signs of pooled water at the surface (Fig. 9). The surfaces may form small depressions (10 cm–3 m in diameter) that are infilled with hardened fine-grained material with considerably fewer clasts than the surrounding alluvial surface (Figs 9 and 10). The slightly depressed surfaces contain small centres of soft, fine-grained material with a distinctive deep red or cream colour (Figs 10a and 11). Gypsum dissolution and subsequent removal of fine clay particles within the uppermost 1–4 cm of the saline pocket creates small convex centres...

Fig. 8. (a) Na plotted against Cl by deionized water leach; and (b) histogram of pH of saline pocket samples (n = 138, grey) and background alluvium (n = 196, black) from Atlántida.

Fig. 9. Saline pockets with varying surface expression at the Mastodonte and Viento prospects. As a result of the increased aridity of the northern Atacama Desert, salt is preserved on the alluvial surface at these localities. Signs of pooled water include fewer clasts on the surface (a) and slight puddle-like depressions covered with salt (b). Saline pockets can also be present on the surface as simple white patches, potentially preserving a ‘feeder system’ of fractures to the surface (c).
of vesiculated crust (Fig. 9a and c). Saline pockets identified at Mastodonte and Viento prospects also occur on the surface as simple white patches of salt with a heavily vesiculated crust, though with no observable signs of pooled water (Fig. 10c).

Despite differences in surface expression across different climatic domains, the removal of the top 4 cm of the pockets at all properties reveals material which is distinctly different than surrounding alluvial material (Fig. 12). Material from the saline pockets is very fine (Fig. 11) and has little to no clast content, while the surrounding alluvium is composed of a low-salinity gravel with a sandy matrix. The fine material continues to depth (c. 45 cm), commonly following a meandering tunnel-like vertical feature. X-ray diffraction of material from saline pockets at Atlántida indicated similar mineralogical composition to surrounding alluvial gravels, but with increased contents of halite, gypsum, calcite and amorphous materials (Fig. 13).

We propose that this fine-grained material may derive from suspended clay particles transported from depth to the surface by high pressure groundwater transport along fractures during seismic activity. Near the surface, the increasing fracture size and ascending flow can result in pressure loss (Cameron et al. 2010) causing decreased groundwater flow rate and deposition of the suspended fine-grained load at shallow depths along the fracture path and at the surface. The lack of coarse-grained sandy material, characteristic of the alluvium and windblown dust, indicates back-filling of open fractures is unlikely to be the source of the fine material in the saline pockets.

Geomorphic markers of faulting on the alluvial surface supports the presence of fracture zones, likely originating from deep bedrock faults, which extend and cut through the alluvial cover to the surface. The distribution of saline pockets along the structural trends suggests the fracture zones act as permeable pathways for groundwater to reach the surface during seismic activity. At Atlántida, several of the pockets occur directly above fractures extending from shallow depths (c. 45 cm) to the surface within alluvial fans (Fig. 14a). At the Papas prospect, saline pockets are present directly above fractures exposed on the side of uplifted alluvial fans indicating structurally controlled permeability of groundwater from bedrock to the surface (Fig. 14b). In unconsolidated sediments, open fractures may be back-filled with sediments and are no longer observable at the surface. In this case, groundwater may be transported along fracture zones in the crystalline bedrock, and then continues to follow the path of least resistance through the unconsolidated gravels to the surface. This path may create the meandering near-vertical paths of fine-grained material distinctive of saline pockets with no observable fractures on the surface. Pedogenic features, such as vertical planar features like pedon boundaries (e.g. Christie 2011, fig. 4.1) and vertical desiccation cracks, may also act as potential conduits for groundwater to the surface during seismic pumping events.

**Discussion**

**Surface expressions of saline pockets**

The variable surface expressions of saline pockets may reflect different stages of formation or alteration of the original surface on which the saline pockets formed. These alterations and variations may include:

1. erosional events resulting in the removal of the original alluvial surface and subsequent exposure of a fracture ‘feeder system’;
2. varying degrees of aridity allowing for the preservation of white salt patches at the surface;
3. rare precipitation events, causing removal of soluble salts at the surface (therefore not preserving white salt patches at the surface);
4. removal of salt crystals on the surface by wind;
(5) varying degrees of pedogenic processes, dependent on the overall salinity of the material, such as precipitation/dissolution and thermal expansion/contraction of salt minerals creating shattered clasts, stress fractures and patterned ground (Buck et al. 2008);

(6) groundwater may not reach the surface and pool during seismic pumping, and subsequent evaporation of near-surface groundwater could potentially create small patches of white salt on the surface with increasing conductivity with depth.

**Desert surface features resembling saline pockets**

Several other surficial features formed on alluvial cover in the desert environment may resemble the small depressions with little clast content, which characterizes the morphology of saline pockets. For example, sag ponds formed by extensional fault movements create small depressions on the surface at the base of fault scarps (Audin et al. 2003; Soto et al. 2005). In addition, small deflation hollows caused by wind erosion of clay or sand particles around bushes also form depressions on the surface. Both these surficial features are infilled with meteoric waters during episodic surface floods, potentially depositing fine-grained suspended material in the depressions. However, these surface features can be distinguished from the saline pockets in the field because:

1. evaporation of episodic surface meteoric flood waters would not produce the extremely high and localized conductivities measured in saline pockets;
2. windblown dust or washout material collected in depressions during flooding is dominated by sand-sized particles, and does not resemble the significant fraction of silt and clay material of the saline pockets;
3. sag pond or deflation hollow surfaces do not have a vesiculated crust as significant amounts of gypsum have not been added to the surface during their creation;
4. there is no vertical continuity of sag ponds or deflation hollows into the gravel;
5. the distribution of deflation hollows does not have an underlying structural control;
6. deflation hollows formed around plants would contain plant material or show evidence of root action.

Vegetation at

![Graph showing particle size fractions of saline pocket samples and background alluvium](https://pubs.geoscienceworld.org/geea/article-pdf/4708260/geochem2018-064.pdf)

**Fig. 11.** Particle size fractions of saline pocket samples ($n = 3$) and background alluvium ($n = 3$) from Atlántida. Photographs of size fractions from one saline pocket and one background alluvium sample are shown below the graph. All samples were sieved to 180 µm in the field prior to transport to Vancouver, therefore particle size analysis ranges from >150 to <25 µm.
Atlántida is sparse and dominated by short-lived shrubs and geophytes (Armesto et al. 1993), only identified after rain events. These geophytes have roots systems that do not extend deeper than 10 cm below the surface. No plants were found within 3 m of any saline pockets nor was any plant material or evidence of root action observed within the material of the saline pockets.

Origin of groundwater forming saline pockets at Atlántida

Decreasing pH of the leachate with increasing conductivity is observed at Atlántida (Fig. 7). This is potentially the result of the high concentrations of cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺) added to the soil during groundwater effusion, and possible displacement of ions from soil exchange sites (H⁺ and Al³⁺) (Norton & Vesely 2003). Groundwater currently in contact with buried copper porphyry deposits in the Atacama Desert is generally of neutral–alkaline pH (Leybourne & Cameron 2008; Reich et al. 2008; Cabrera 2010). Therefore, the injection of acidic groundwater is an unlikely cause of a more acidic leachate. Furthermore, the high carbonate content of the gravel material would likely buffer the groundwater pH to more alkaline values.

Groundwater sampling was attempted on existing drillholes at Atlántida, but proved to be impractical as a result of contamination during previous drilling activities. Analysis of deionized water leachates of saline soils from the Spence Deposit reported maximum concentrations of 6000 ppm Na on the surface and 10 000 ppm at 100 cm depth measured over fractures confirmed by shallow trenching (Cameron & Leybourne 2005). In contrast, leachates from saline pockets at Atlántida measure up to 30 000 ppm Na. Potentially, the highest salinity soils at Spence above fracture zones were not sampled as a result of the regularity of their sample intervals (25 m). The source of the high salinity on the surface at Spence is considered to be surface flooding of deep saline formation groundwater (Cameron & Leybourne 2005). The higher salinity at Atlántida suggests a similar type of deep saline formation groundwater is transported to the surface. Furthermore, multiple injections of saline formation groundwater may contribute to the higher salinities measured at Atlántida. Repeated activity along the faults, which could have led to multiple flooding events at Atlántida, is indicated by diversion of both older alluvial surfaces and diversion of younger channels.

Hydrological effects of distant earthquakes

Surface waves from major earthquakes can travel thousands of kilometres and remove blockages on locked faults (Cameron 2013). This reduces the effective normal stress on locked faults, potentially
triggering seismic activity at great distances (Cameron 2013). For example, 14 earthquakes were reported 11,000 km away at Mount Wrangell, Alaska, after the M9.2 Sumatra earthquake of 2004 (West et al. 2005). Triggered earthquakes may cause hydrological effects at great distances, such as surface flooding by groundwater (Brodsky et al. 2003), by increasing near-surface permeability (Rojstaczer & Wolf 1992). This implies saline pockets can form on the surface by seismic activity originating from afar.

**Exploration implications**

Geomorphic markers of faulting in combination with geophysical mapping of magnetic lineaments can identify deep-seated covered structures which have been reactivated post-gravel deposition, potentially providing a permeable pathway for groundwater to reach the surface during seismic pumping events. Detailed regolith mapping with the aid of drone imagery and digital elevation modelling can be used to identify the geomorphic effects of faulting on the alluvial cover. Although LiDAR (light detection and ranging) was not used in this study, its application would significantly enhance the identification of subtle structurally derived geomorphic features on the surface. Additionally, detailed regolith mapping aids in identifying the relative ages of alluvial fans. This ensures a medium of consistent age when sampling. Older alluvial surfaces allow for the accumulation of geochemical responses on the surface over time. Regolith mapping is also an important tool to determine alluvium provenance for consideration of the background chemistry of alluvium while sampling.

Detailed regolith mapping identified saline pockets of material on the alluvial surface. The saline pockets have distinct appearances that are identifiable by drone imagery. The distribution of saline pockets is strongly controlled by deep structures that cut through overlying gravels. Saline pockets that are identified with drone imagery can therefore be used to indicate such faults. Saline pockets can also be identified in the field by following the trend of the structures on the alluvial surface.

The process of geochemical anomaly formation at the surface in the Atacama Desert has been demonstrated by Cameron et al. (2002), Cameron & Leybourne (2005) and Leybourne & Cameron (2008). Groundwater in contact with buried mineralization is transported to the surface through fractures during seismic activity, forming geochemical anomalies of salts and metals at the surface. Characteristics of the saline pockets of material identified at Atlántida and additional prospects indicate that saline pockets are the surface expression of groundwater transported to and pooling on the alluvial surface. The saline pockets along structural trends are therefore the optimal sampling medium for geochemical exploration programmes, in contrast to the typical sampling of the <180 µm fraction of alluvium or caliche sampled at regular intervals across large alluvial plains. This sample fraction does not target material specifically affected by the process of seismic pumping. Geochemical analysis using selective leaches of the saline material would provide a more accurate indication of the fluid-rock interactions associated with seismic activity.
will reflect the geochemistry of the groundwater at depth from which the saline pockets were formed. The extended period of hyperaridity in the region, argued by some to have started 15 Ma (Jordan et al. 2014) to 3 Ma (Hartley & Chong 2002), would allow for features to be preserved on the surface without disturbance by erosional processes. Repeated injections of groundwater to the surface without significant redistribution will allow for groundwater geochemical signatures to accumulate on the surface (Cameron et al. 2002). Saline pockets have been identified in alluvial environments with varying aridity across the Atacama Desert (Fig. 1). The application of saline pocket sampling for exploration geochemistry surveys of buried deposits therefore has potential to be applied throughout the various alluvial environments of the Atacama Desert.

Current geochemical exploration programmes often follow a regular grid pattern (i.e. 1 sample per 250 × 250 m cell), without consideration of the background chemistry or relative age of the alluvial surface of the sample taken. Moreover, sampling on structures is left to chance using a grid system. At the Spence and Gaby Sur deposits, identification during surficial sampling of structures cutting through gravels was achieved by a sample spacing of 25 m laid out perpendicular to structural trend (Cameron et al. 2002). Sample spacing of 25 m is impractical for exploration geochemistry surveys designed for large prospective areas. By contrast, targeting specific fault structures extending to surface allows for a grid consisting of individual cells (250 × 250 m) to be placed along the structural trend. Within those cells, a saline pocket can be sampled as the specific target medium for mineral exploration through cover.

Conclusions

Saline pockets have been identified at four sites in the Atacama Desert of Chile. It is believed that they were formed by groundwater reaching the surface during seismic activity. Targeted sampling of saline pockets along structural trends is a unique opportunity to sample at the surface the geochemistry of groundwater, which may have interacted with buried mineralization. Detailed regolith mapping, aided by high-resolution drone imagery and digital elevation modelling, can be used to identify geomorphic markers of fault continuation at surface and thereby target saline pockets. This has the potential to be developed into a targeted exploration geochemistry methodology for the discovery of buried deposits in the Atacama Desert.

Fig. 14. (a) Left, plan view of a saline pocket with a fracture on the surface at Atlántida. White-dashed line indicates trace of where small trench was dug. Right, section view the small trench (40 cm depth) dug across the fracture. The trench reveals a fracture that extends from shallow depth to surface at an oblique angle to the trench-wall (outline by black dashed lines). (b) Left, vertical fracture cutting through overlying gravels at the Papas property. Right, a saline pocket is present on top of the fracture on the alluvial surface.
Acknowledgements We thank the sponsor companies, AngloAmerican Chile Ltda, First Quantum Minerals Ltd and Quantum Pacific Exploration for project support and logistical support in the field. The sponsor companies are thanked for their encouragement and guidance throughout this project, with special thanks to Dave Anderson, McLean Trotz and Esteban Urrutia. We thank Minera Atlântida for allowing us access to the Atlântida field site. We thank AngloAmerican Chile Ltda for access to the Manto Pende, Papas y Viento field site. Drone imagery was provided by Luis Araya Geomensura, Geomatica, Medellin and Servicios de Ingeniería (GEMAS). We thank Sara Jenkins of the MDRU for ArcGIS and technological support and for helpful conversations regarding geomorphology in desert environments. The Society of Economic Geologists (SEG) is thanked for a generous scholarship to the principal author. We are grateful to Cliff Stanley and Stephen Amor for their constructive journal reviews. This is MDRU Publication 408.

Funding This project was financially supported by AngloAmerican Chile Ltda, First Quantum Minerals Ltd and Quantum Pacific Exploration through the MDRU Atacama Gravels Project and an SEGf student research grant (to AB). Financial support for drone imagery was provided by the Institut de Recherche pour le Développement (IRD), France, and Conicyt Chile through the COPEDIM collaborative network.

Scientific editing by Scott Wood

References


Downloaded from https://pubs.geoscienceworld.org/geoa/article-pdf/4708260/geochem2018-064.pdf