ATACAMA CALICHE MINING: A PLANETARY REGOLITH MINING ANALOG. L. S. Gertsch, Missouri University of Science and Technology (Rock Mechanics and Explosives Research Center, 1006 Kingshighway, Rolla, MO, 65409-0660, United States, GertschL@mst.edu).

Introduction: In situ resource utilization on the Moon and Mars may begin with mining and processing of surface regolith. Continuous research and development efforts are producing technologies that can fragment, excavate, transport, beneficiate, and process regolith. These technologies have been tested at various analog sites.

However, successful mining requires more than technology development. To achieve the capability to reliably produce useful feedstocks from mineral deposits requires a complete architecture; in other words, a mining method. While types of mining methods are discussed in other presentations, this talk will describe the process for mining iodine, sulfate, and nitrate from caliche deposits in the Atacama Desert of Chile as an analog for planetary mining of ice-cemented regolith.

Aguas Blancas Deposit: This deposit is located on the upper slopes of several large alluvial fans in northern Chile, extending along relatively flat areas and up the slopes of low rises. It is a fairly typical deposit of the desert region along the western coast of South America.

Caliche. This is a light-colored, multi-mineral, low-density mixture (Fig. 1) that forms mainly in arid regions when groundwater containing calcium, magnesium, and other elements precipitates them between regolith grains in the form of evaporite minerals. This effectively cements the grains together about 1-2m below the surface. Caliche's low permeability then prevents deeper infiltration even if precipitation later exceeds evaporation. The nitrate content derives from atmospheric nitrogen, aided by nitrogen-fixing microbes.

Fig. 1. Caliche exposed beneath overburden [8]**.**

Caliche is similar to the worst-case scenario for lunar and martian ice-regolith mixtures, from the perspective of excavatability [1]. The environment of the Atacama Desert also is reminiscent of the surface of Mars. The main differences known at this point are lower gravity, thinner atmosphere, and very difficult access on Mars. The Moon has even lower gravity, vacuum, and shorter but still difficult access.

Deposit Geometry. The Aguas Blancas deposit varies from 6-11m in thickness with the ore zone averaging about 2m thick [2] beneath 0.2-1.0m of overburden (weakly to moderately cemented sand and gravel) [3]. Therefore the methods by which this deposit is mined are directly analogous to deposits of similar configuration on the Moon and Mars.

Caliche formations are thin and laterally extensive and form at shallow depths; however, they can be found at any level within an arid sedimentary sequence because catastrophic events such as floods and volcanic eruptions can bury them. Landslide deposits and large-impact ejecta can likewise bury cold trap deposits on the Moon. Mars permafrost can be buried by these events as well as by flood deposits. Unlike caliche, however, Mars permafrost is not expected to be confined to thin, shallow layers; thermal models indicate that water ice could extend downward several kilometers.

Sampling. The Aguas Blancas deposit has been sampled since the late 1800's [4], first with random hand-dug mine pits, later with reverse circulation drilling, trenching, air sampling (apparently unsuccessful), and calicatas (test pits). Since 2005, over 16,000 exploration holes totaling nearly 38,000m in length have been drilled at spacings of 50-200m. More than 71,000 samples from these holes were measured for iodine content, and about 7,200 samples each were measured for nitrate or sulfate content. This is the resolution of data needed for a viable orebody model, even in an industrially mature region.

Mining: This consists of exploration, mining and beneficiation, and processing.

Exploration. The ore is divided into vertical and lateral zones to match the needs and capabilities of the processing plant. Thus when the process changes, the orebody zonation also can change. The multiple products sourced from the Aguas Blancas deposit – iodine, sulfate, and nitrate – are drawn from the same as well as different minerals, depending on their chemical formulas and the elements that can substitute for each other. This can require multiple orebody models for a single deposit.

The differences between scientific theory and engineering practice must be clearly understood to create a successful mine. Elements combine to form several minerals, even in apparently identical situations. Some minerals that constitute caliche are soluble in water, some are not. These complexities are dealt with in industry by an empirical combination of ore zone definitions and sample measurement protocols. These determinations are related to, but not exclusively determined by, specific mineralogy. Engineering factors also affect the choices. Even more to the point for ISRU, mineralogy is likewise related to, but not exclusively determinable from, remote sensing. It comes down to identifying those components and properties that control the total extractability of the target element, including both the mining and the processing stages.

Scheduling. The present mining company has been operating here since 2001; at present about 15 years of reserve life remain, though this is in flux as exploration continues. Production is ramping up to 2,000 tons of iodine in 2013.

Several working areas are active at any given time, with daily work assignments made to keep the feed to the processing plant at the optimum mix for clients' needs (*i.e.*, the amounts needed of the primary and by-product outputs) as well as process/system efficiency. This requires detailed knowledge of the spatial variation of those orebody qualities discussed above. The minimum block size for scheduling the surface mining machines is 50m x 50m.

At Aguas Blancas, iodine grades 300ppm on average, in the southeastern half exceeding 1,000ppm in places. The iodine break-even cutoff grade is 260ppm at USD28.00/ton (when price goes up, cutoff grade goes down). Nitrate grades 1-5% (up to 10% along the NW-SE axis of the deposit), while mineable sulfate occurs in the eastern half at grades of 20-40%.

Mining and Beneficiation. The relatively barren overburden is removed by front end loaders loading off-road trucks. Some blasting is still used, but that is being phased out. Surface mining machines then cut swathes, each 10-50cm in depth and about 4 m wide, in a pattern intended to produce consistent mineralogical properties in the mill feed. Trucks, loaded by front-end loaders from the windrows left by the surface mining machine, haul the ore about 1km to a heap leaping pad or the agitation leach circuit.

Until recently leaching of 500m x 500m x 5m, 200 kilo-tonne heaps with water was the next step. These were built by careful dumping of the truckfuls of ore. Heaps are underlain by impermeable geo-membranes and are serviced by irrigation and solution collection systems. Eight months of leaching gives 55% iodine recovery, on average.

The heap leaching system is being replaced by an agitation-leach plant. Although more expensive, agitation leaching gives 85% iodine recovery in much less time, using 25% less water [4].

Processing. The Guggenheim process applies sodium bisulfate to reduce the iodate in the collected heap solution to iodide, in a two-step process that yields crude iodine [5,6]. Alternatively, the Turrentine process uses towers to "blow-out" the iodine as vapor from the solution after oxidation of the iodide ion to iodine by chlorination. The final product is sold mostly as prills, formed in drop-towers and sorted by size.

Nitrate is produced by mixing two water-based solutions – one made from leaching potassium chloride-bearing minerals, the other from leaching crushed caliche – then partially evaporating the mixture and separating the precipitated crystals using large solar evaporation ponds [7].

Contaminants and By-products. Atacama caliche contains measureable levels of the perchlorate ion, which is classified by the U.S. EPA as a drinking water contaminant. Iodine is the primary product sold, with sodium nitrate and sulfate as by-products.

Similar considerations for lunar and martian ice deposits will drive selection of processing techniques, which in turn will help drive selection of mining methods. Water ice might be mined as a source for drinking water and/or propellant and fuel manufacture. Each product comes with a set of maximum acceptable contaminant specifications. Thus it can be counter-productive to mine a deposit without a clear use in mind; in-spec for one product may be irrecoverably out-of-spec for another, for economic as well as technical reasons.

Conclusions: Study of some terrestrial mineral deposits and their mines as analogs for similar situations on the Moon and Mars will reduce ISRU risk.

The next crucial steps are exploration (to determine what is there) and product selection (to determine what is to be mined).

References: [1] Gertsch L., Gustafson R., and Gertsch R. (2006) *AIP Conf Proc 813*, 1093-1100. [2] Ericksen GE (1983) *American Scientist 71/4*, 366-374. [3] www.siroccomining.com/s/AguasBlancas.asp, 5 May 2012. [4] Wheeler A (2010) www.siroccomining.com/i/pdf/Technical-Report-NI-43-101-Dec-2010.pdf, 10 May 2012. [5] Lyday, P.A. (1987) *Jour Chem Educ 64/2*, 152-153. [6] www.sciencefairadventure.com/Iodine.aspx, 9 May 2012. [7] Lambert, A. (1933) US Patent 1 915 428. [8] www.arizonaminingclaims.com, 10 May 2012.