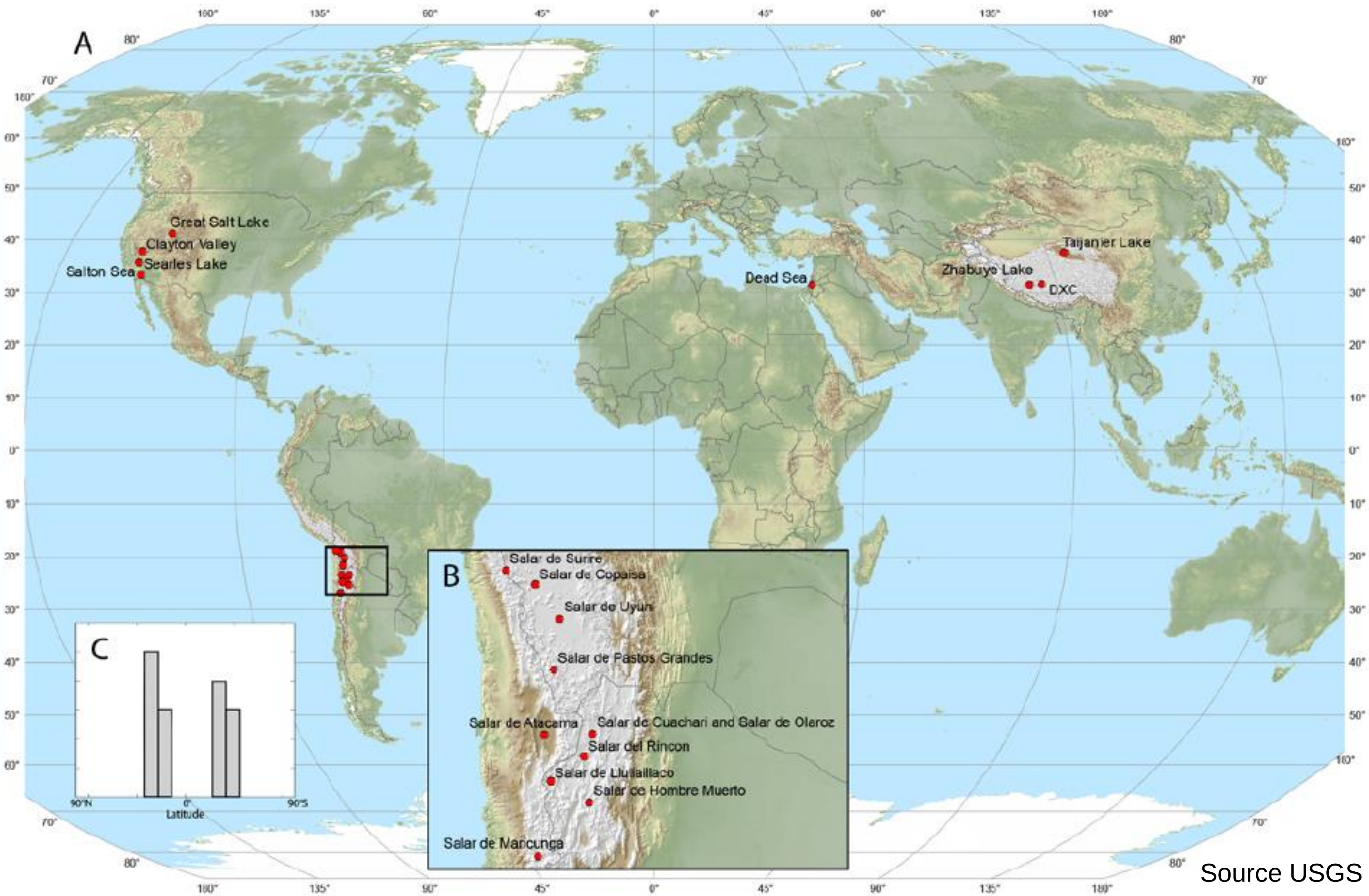
LITHIUM SALT LAKES – POWERING THE FUTURE

Salt lakes & their mineral wealth

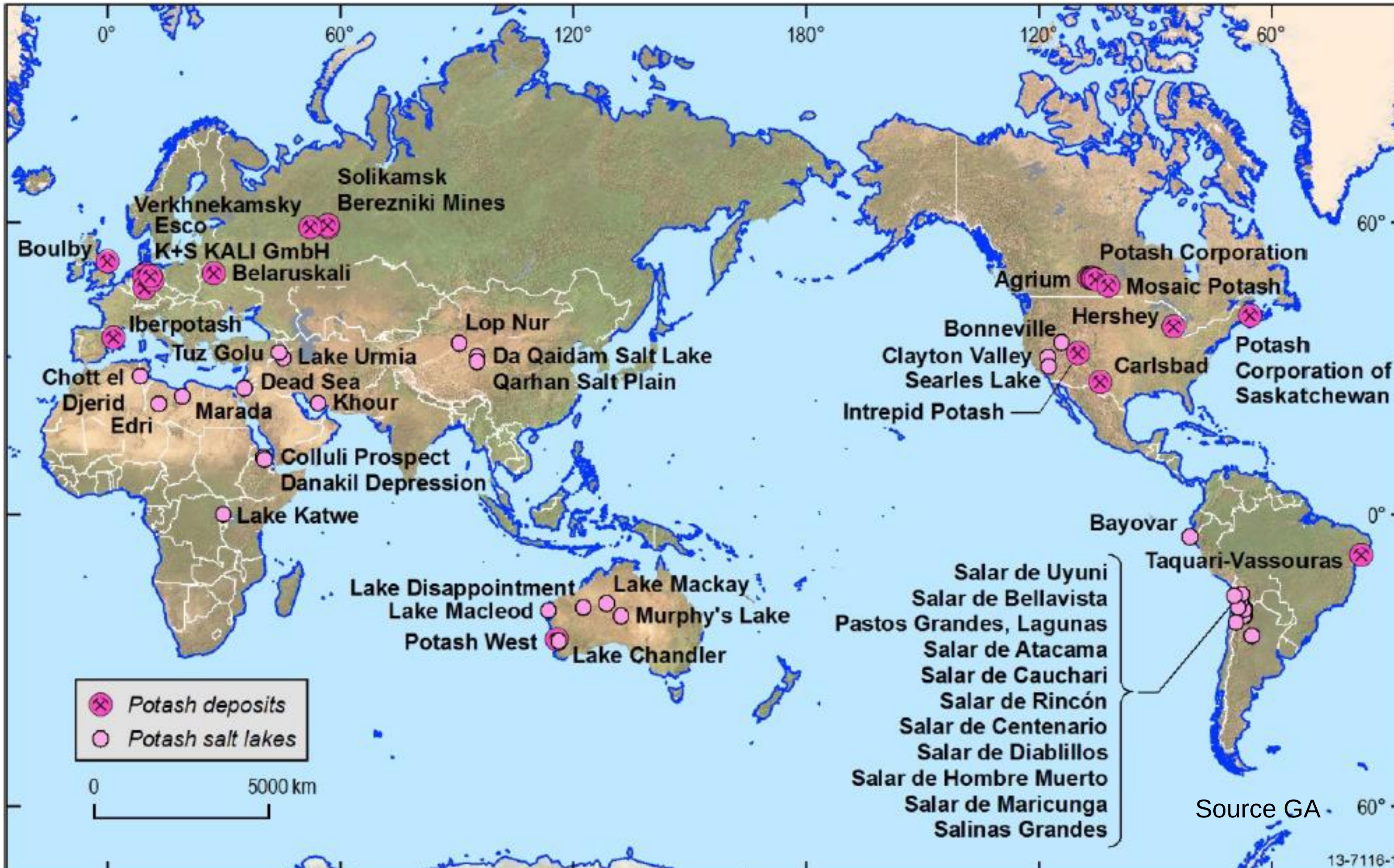
- Salt lakes are an important source of lithium (batteries), potassium (fertiliser) and boron (flux, fibre glass etc)
- Lakes include permanent water bodies i.e. Dead Sea, Great Salt Lake (USA)
- But most commonly seasonally flooded dry lakes
  - Andes of Argentina, Chile, Bolivia; Nevada and Utah USA; Qinghai Basin NW China; Central Australia
- Referred to as Playas, Salars, Salt Lakes, Dry lakes etc
- Global distribution, related to geology and climate
- Minerals and brine chemistry different from major marine evaporite deposits producing potash in Canada, USA, Europe, Africa

Global distribution – lithium brine



Source USGS

Global distribution – potash brine



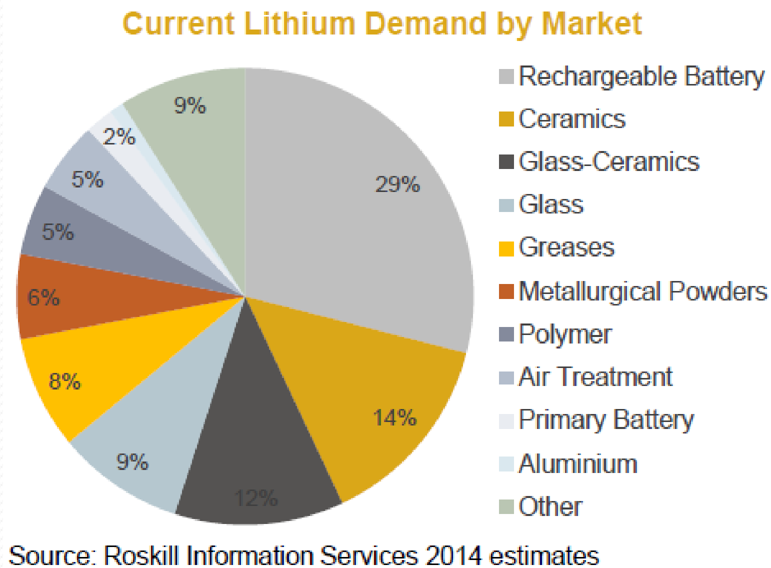
Sources GA

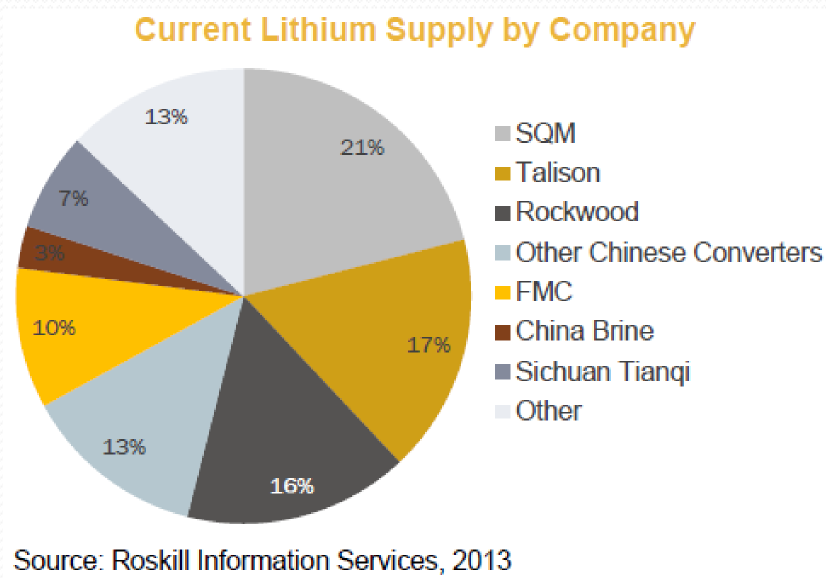
Lithium uses

Key demand drivers are:

- Electronic devices
- Electric cars
- Electricity storage – i.e. Tesla Powerwall battery storage
- Glass production
- Other industrial applications

Use of battery grade lithium in portable electronic devices has grown by ~20% annually since 2000

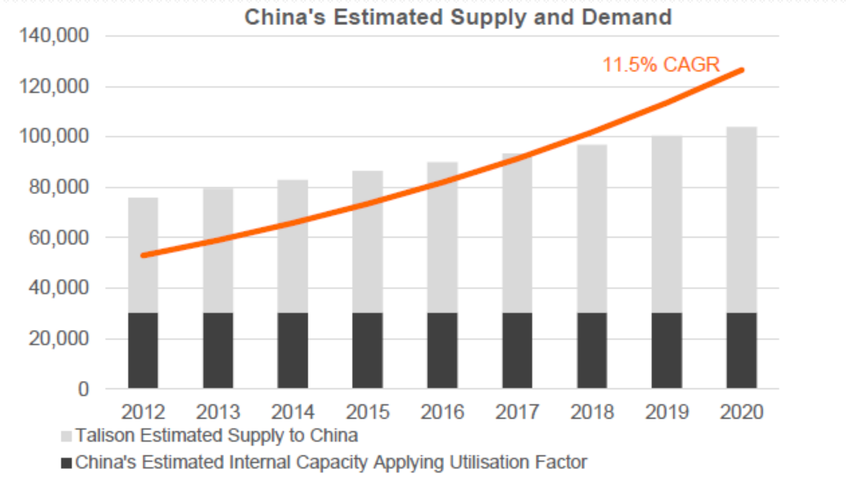


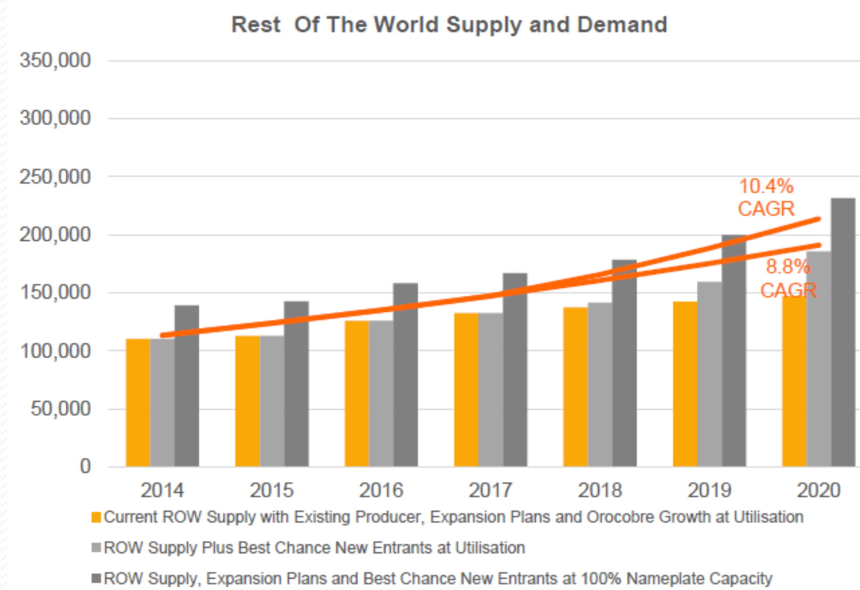


Supply challenges

One of few commodities with positive pricing expectations

- Highly concentrated supply chain
- Owned by large chemical companies
- Large industrial end users, LG Chem, Foxconn, Boston Power, Tesla, BYD
- Limited economic deposits
- Regulatory & environmental constraints in Chile
- Limited supply supporting prices
- Attracting new aspiring hard rock and clay resource developers



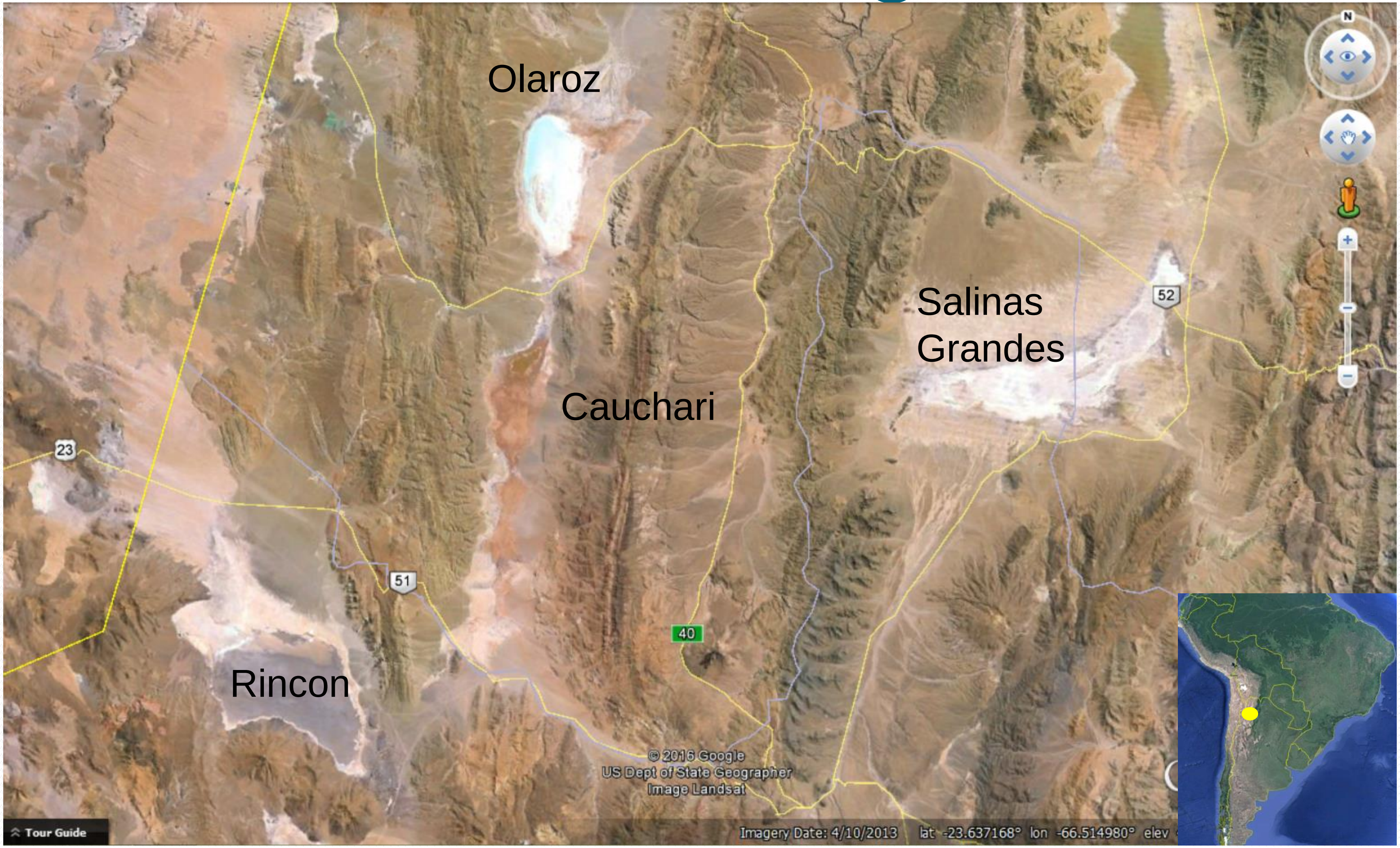


Sources Orocobre 2015

Salt lake types

- Houston (2011) divided salt lakes into two broad types
  - **Mature** – dominated by evaporites (halite, gypsum)
  - **Immature** – dominated by clay, silt, sand/gravel
- **1st generation** lithium and potash developments dominantly mature salt lakes (pre-2000)
- **2nd/new generation** of salt lake development mostly immature salt lakes (2009 onward)
- Sedimentation controlled by:
  - Climate – dry periods facilitate evaporite deposition, wet periods coarser sediment deposition
  - Tectonics – changing the geometry of depressions, uplifting mountains for erosion

Salt lake locations - Argentina



Brine deposit key ingredients

Lithium source (acid volcanic rocks - Miocene & younger in Lithium Triangle; volcanic glasses)

- Hot springs associated with volcanos or leaching of volcanic rocks. Associated boron and potassium
- Chemical ratios important for processing – Low Mg/Li, low SO4/Li

- Potassium source – weathering of micas and feldspars. Deposits more widespread than lithium, as sources more varied

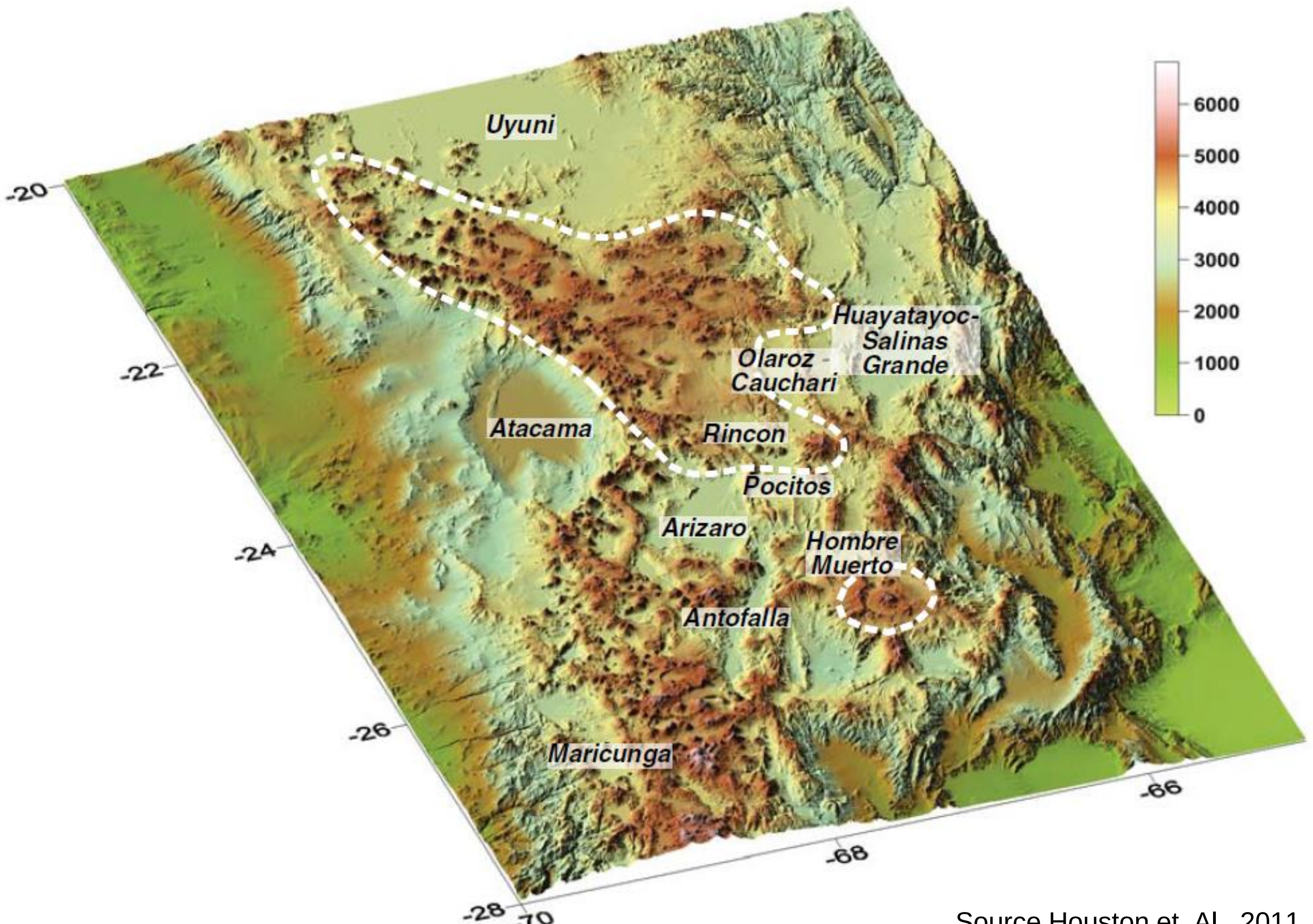
Tectonic/topographic control

- Andes - Internal drainage, thick sediments in tectonic depressions
- Central Australia - Lower topography, potash deposits in broad depressions and channels

Arid climate

- Evaporation >> seasonal rainfall, evaporative concentration generating hypersaline brines

Li source in the Andean plateau



Source Houston et. Al., 2011

Salt lake geology

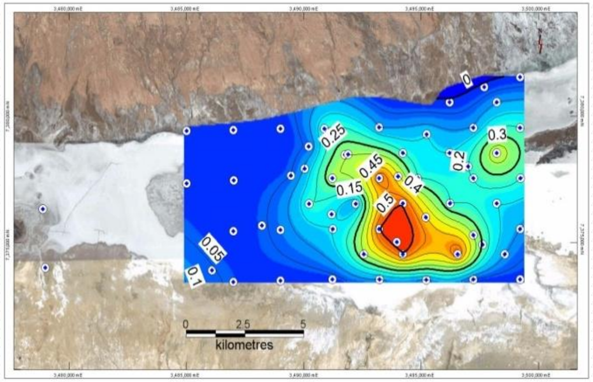
- Halite units, 10’s to hundreds of metres thick.
  - Halite porosity generally decreases with depth,
  - **Good aquifers near surface, with primary and secondary fracture porosity/permeability**
- (Basal) coarse gravel and sand in some Andean basins – **prime aquifers**
  - Sourced from alluvial fans, wet climatic periods
- Upper fine grained silt and clay sequences, often with organic rich silts
  - **Essentially leaky aquitards**
- Sedimentation reflects climatic situation, water balance and tectonics
- Upper Tertiary felsic volcanics/hot springs in the catchment

Salt layers – at surface or depth

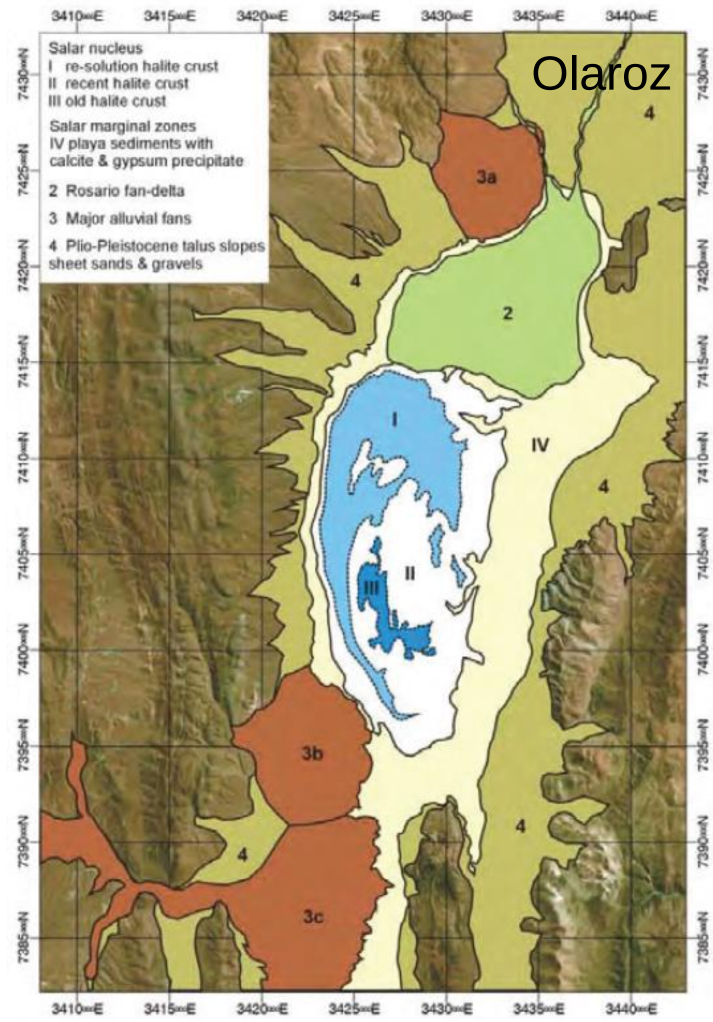
Salt crusts vary from zero thickness to hundreds of metres thick, reflecting climatic conditions, hydrology and the salt balance in each individual basin

Salt lakes dominated by halite have very different hydraulic properties to those dominated by clastic material

The halite nucleus is typically thicker than at the lake margins



Andean basin geology



Tectonic uplift generating alluvial fans
Perennial to ephemeral river inflows

Source Houston, 2011

Lithologies

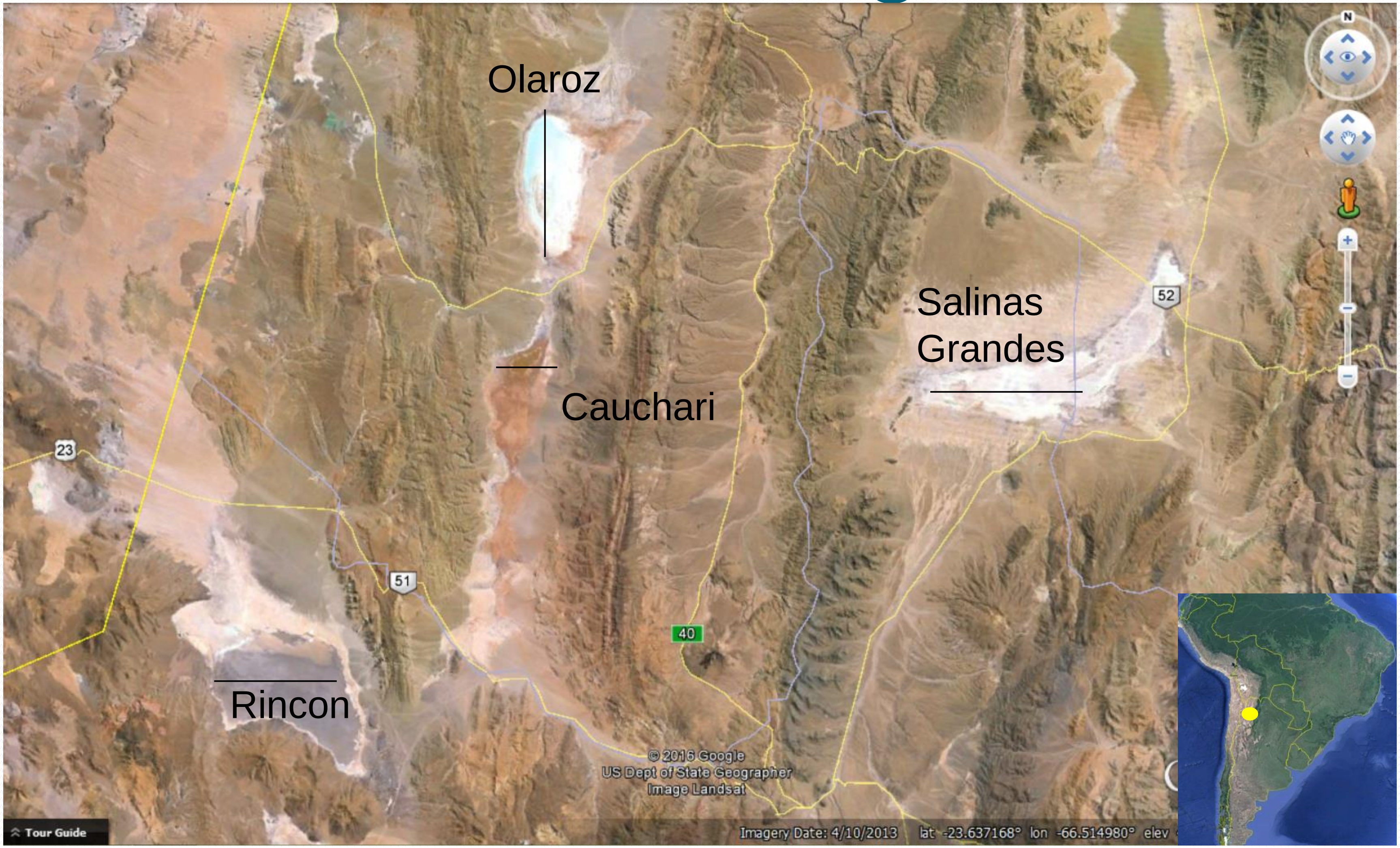

Clays, silts

Organic silts

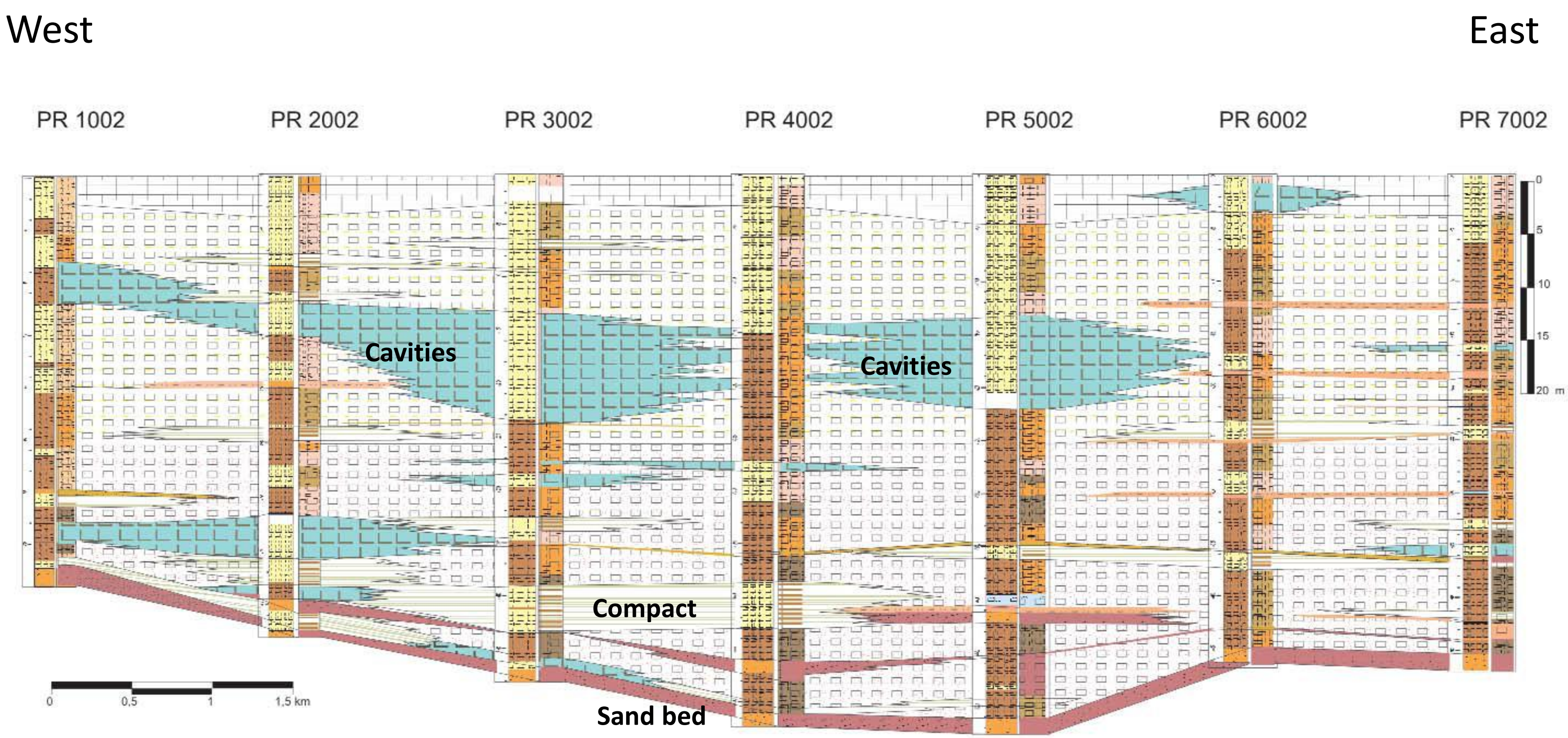

Porous halite


Compact halite

Salt lake locations - Argentina



Mature salt lake examples - Rincon



Surface salt crust

Cavity/recrystallised

Banded halite

Evapofacies halite

Mud flat

Halite evapofacies beds

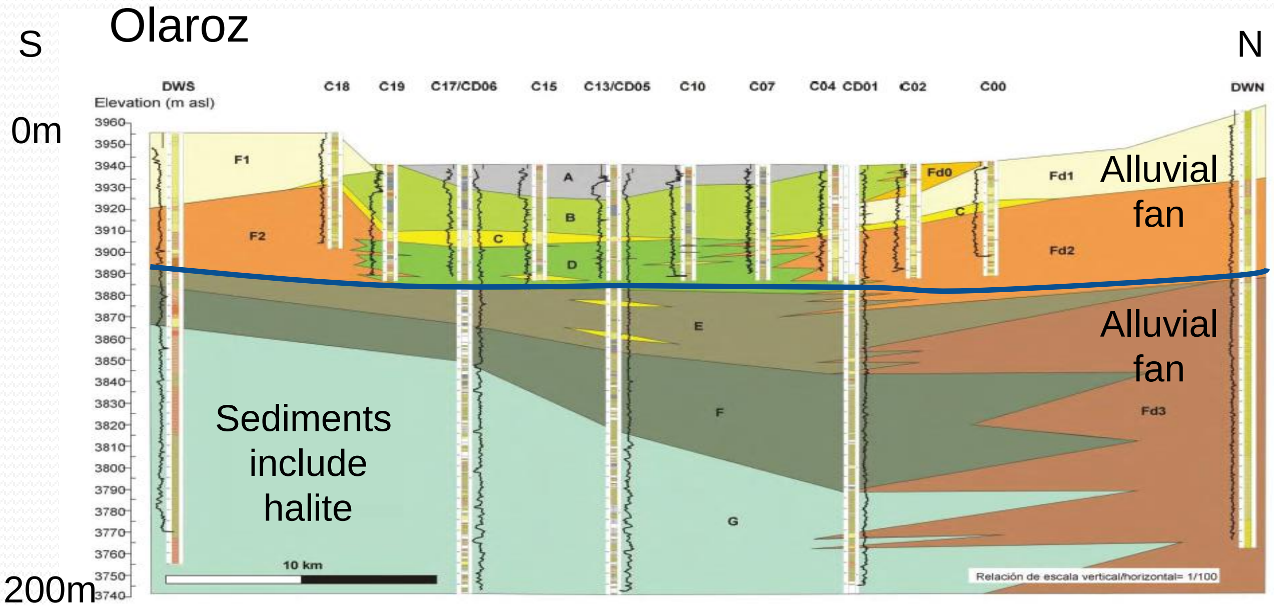
PR Piezometric surface (0.3 m)

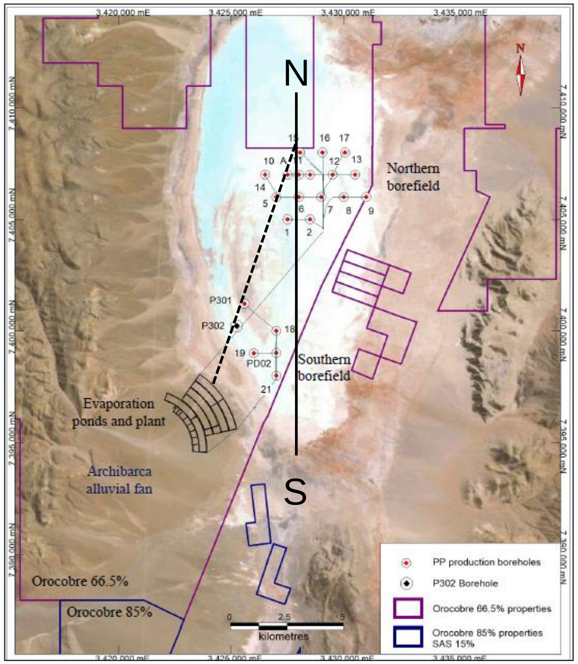
400 mg/l Li and 8000 mg/l K

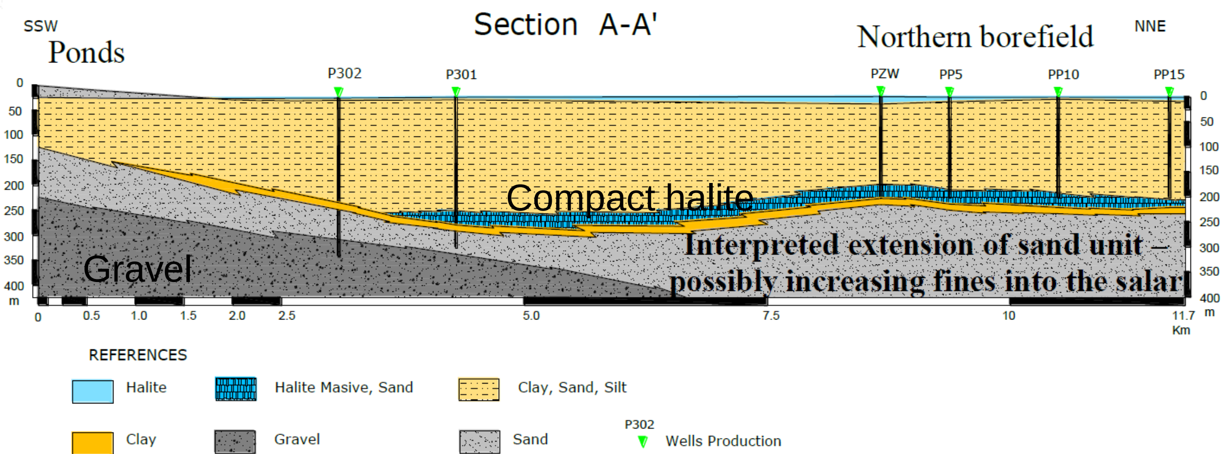
Effective porosity to 40%

Ovejero, Toledo et. Al., 2009

Immature salt lake examples I

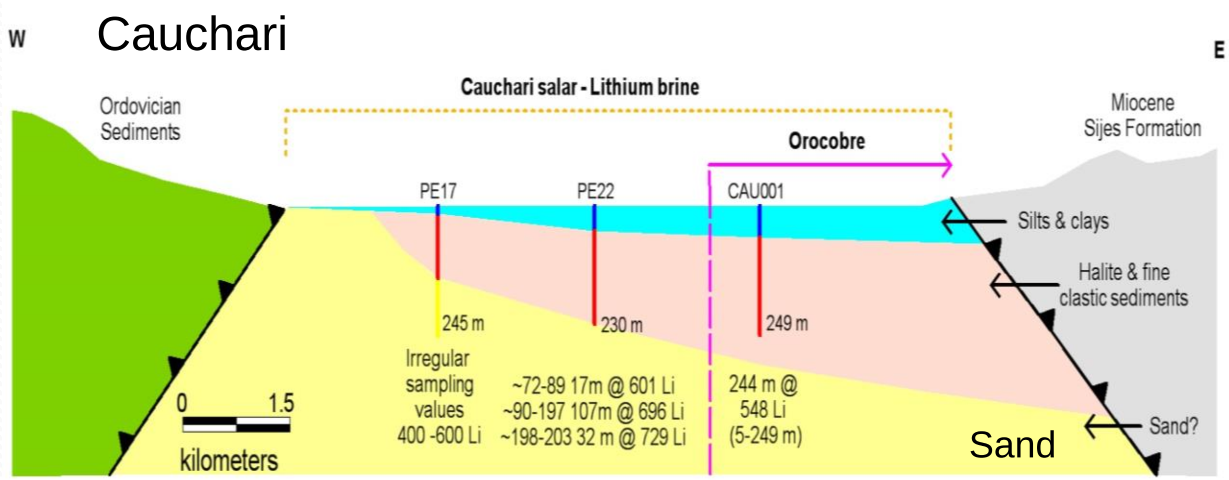


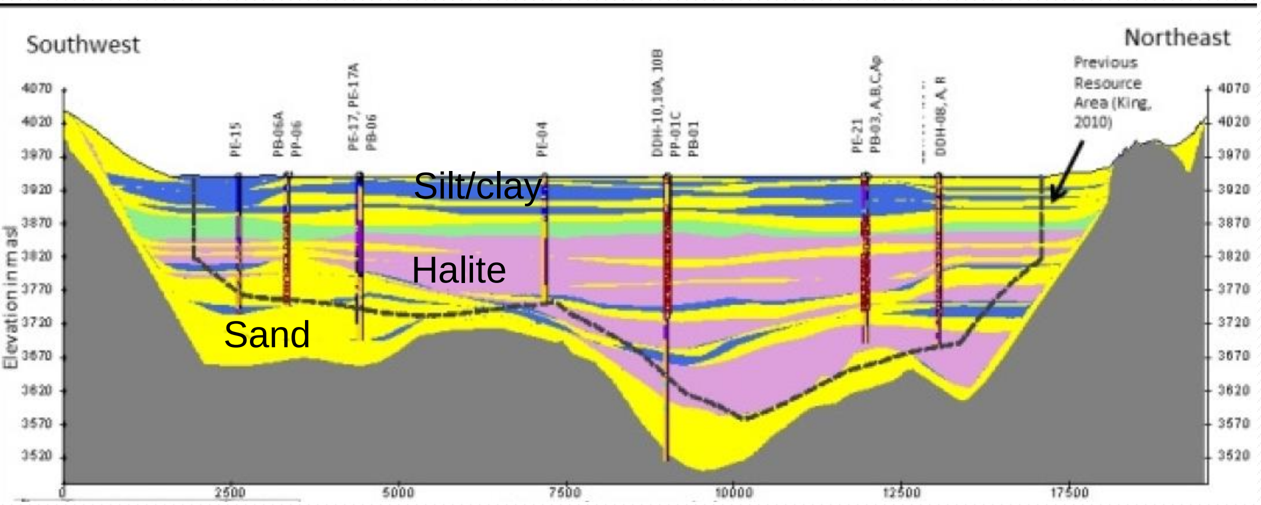




Sources Houston 2010, 2011, Orocobre 2015

Immature salt lakes example II

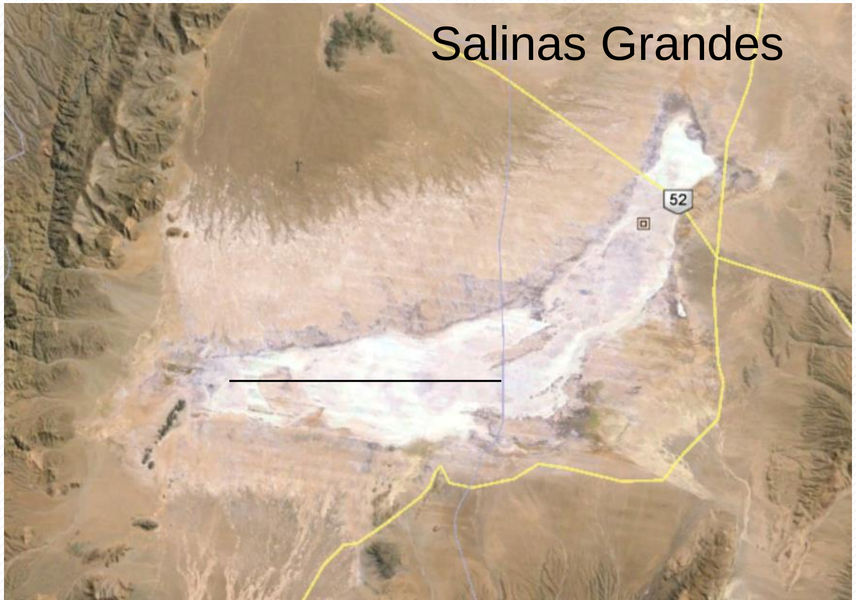


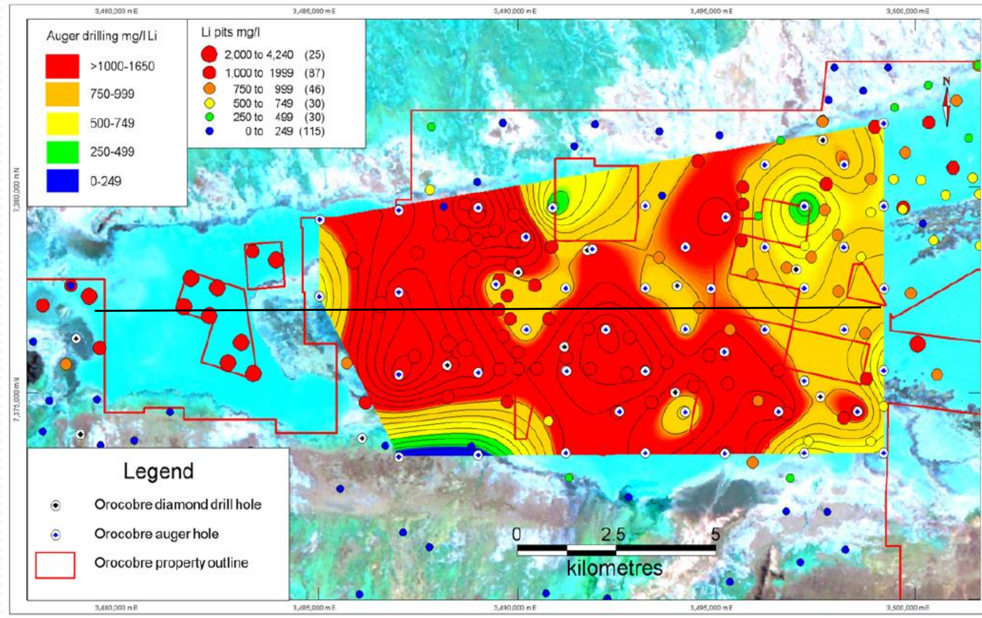


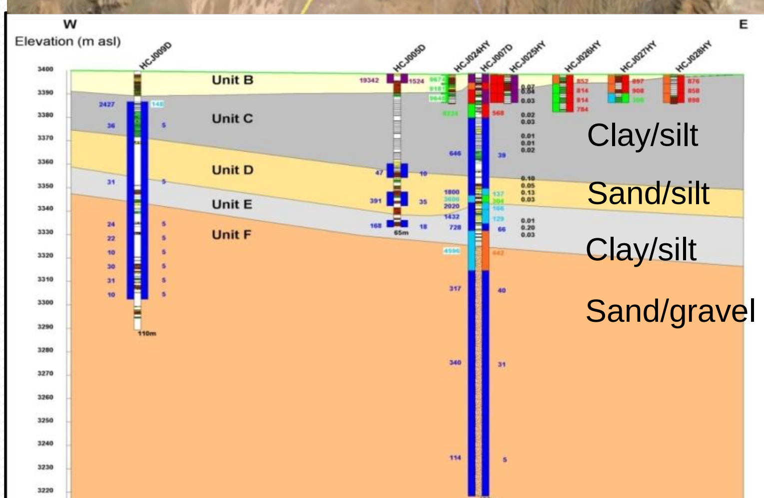
- Economic Li & K grades,
- Minimal surface halite
- Extensive halite at depth
- Basal sand sequence underlying fine clastics
- Narrower basin, with implications for pumping

Sources Orocobre 2013, Lithium Americas, 2012

Immature salt lake examples III







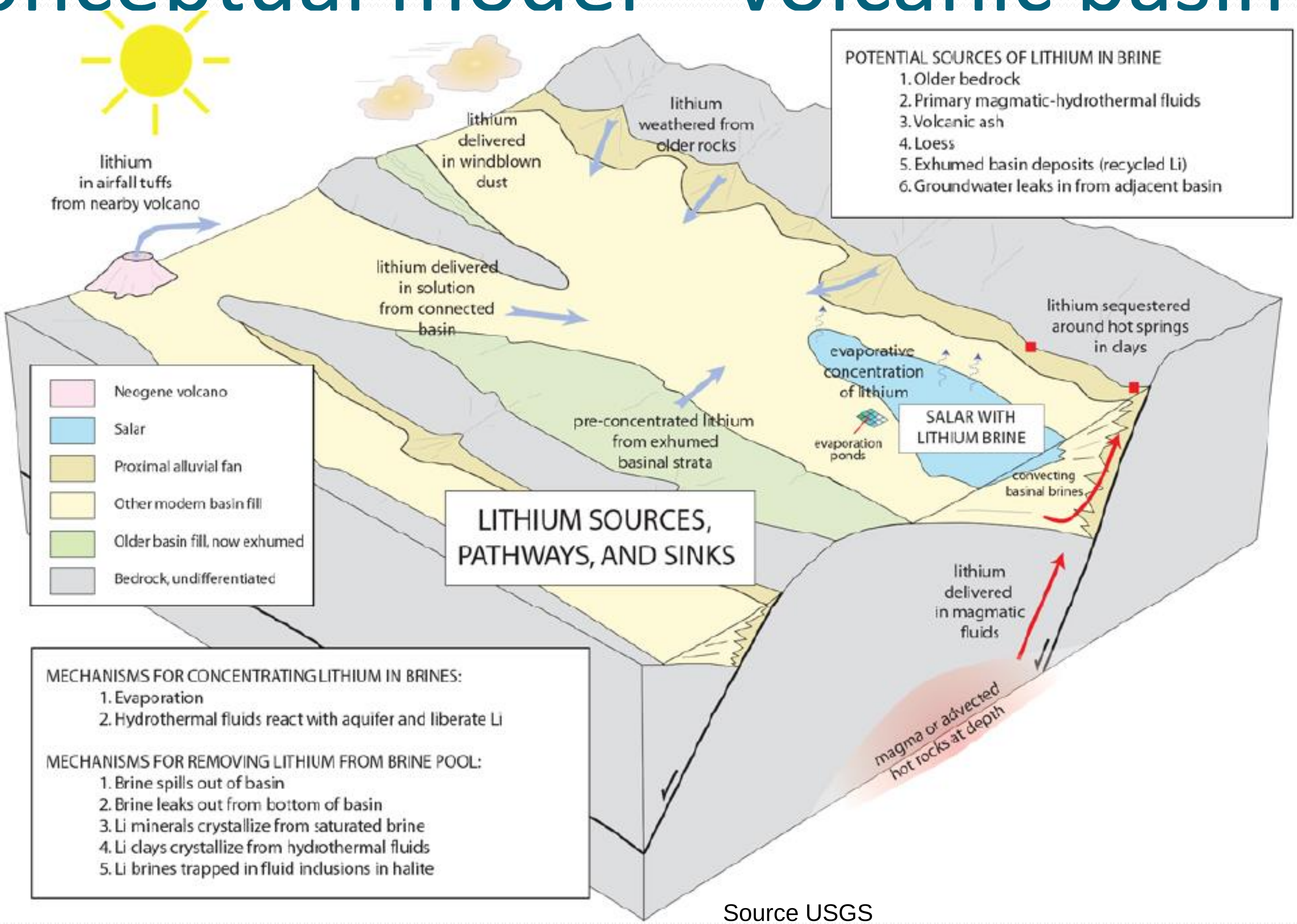
- Excellent surface Li & K grades
- Drilling shows brine forms a thin zone over less mineralised brackish water
- Large water inflows from river to south and alluvial cones to north
- Poorly developed salt lake – younger than others?

Source Orocobre 2012

Rainfall and evaporation

- **Major rainfall deficit** necessary, overall rainfall <~250 mm
- Uplift of the Puna Plateau on the border of Argentina, Bolivia & Chile created a rain shadow and arid to hyperarid environment
  - This area receives summer storms from Brazilian jungle.
  - Drier to the SW into Chile, the Atacama Desert/Salar de Atacama
  - **Central Australian lakes** annual rainfall from major storms moving inland from NW Australian coast
- Surface and groundwater inflows to salt lakes dilute (i.e. 3 mg/l Li)
- Inflows evaporate around the margins of the lakes, with increasing concentrations – 600 mg/l Li typical, 6,000 + mg/l K

Conceptual model – volcanic basin



Source USGS

Exploration

- Pit sampling provides information on Li, K grades but often high surface grades do not continue at depth
- Drilling required to determine average grades and to determine stratigraphy
- Depth sampling of brines to assess variation
- Mapping the extent of the brine body
- Analysis of cores for porosity and permeability
- Pump testing to assess longer term performance, drawdown and grade

Geophysics – looking deeper

- Salt lakes can be large, > 10 to 10's km across
- **Need thick sequences of sediments or large surface areas for economic volumes of brine**
- Fault-controlled blocks often present beneath lakes
- Sediments are low density clays, silts, sands compared to basement rocks, gravel in some basins
- Gravity can map density contrast with basement
- Seismic can detect basement contact and some layering in the sediments
- Electrical geophysics detects the limits of brine bodies, and some basement topography

Drilling – Quality Vs Cost Vs Time

Salt lakes often soft and require embankment construction or helicopter transport

- Objectives – Information on aquifers, aquitards, samples for porosity test work, brine samples
- Diamond – Generally quality sample, recovery variable
- Sonic – excellent sample, extremely expensive
- Aircore – rapid drilling, cheap, disturbed lithology samples, less control on stratigraphy
- Rotary – for installation of bores, with use of muds to support hole walls in unconsolidated sediments

Drilling methods


Diamond


Sonic


Brine drilling fluid

Physical sample test work

Porosity & Permeability

- Core samples tested for total and effective porosity and specific yield
- Specific yield – how do you actually measure it? Different labs, different methods.
  - Using a centrifuge to simulate free draining of pores
- Permeability sampling of cores to compare with pump testing
  - Need to consider potential scale factor variation between core and pump tests

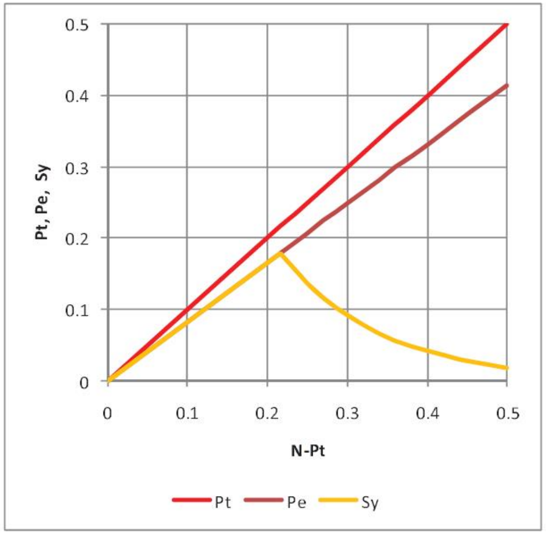
Porosity testing

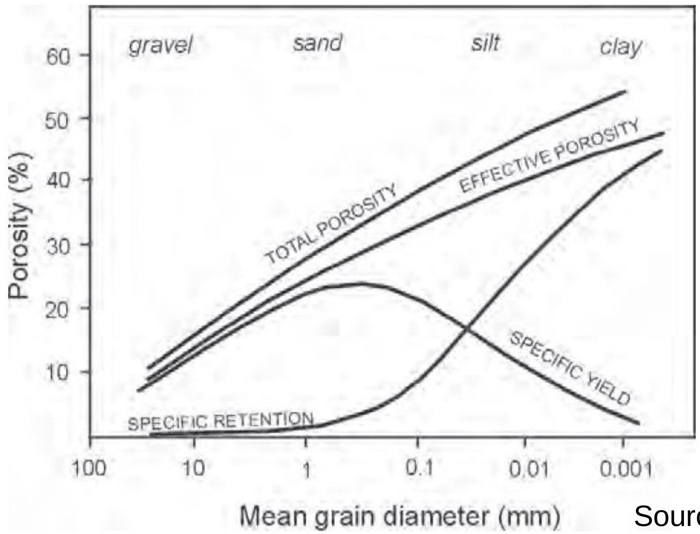
- Well sealed core samples for testing
- Liquid resaturation – effective porosity measurements
- Helium injection – used for effective porosity measurements
- Specific yield measurements using a low speed centrifuge technique to simulate the effect of pumping

Porosity relationships

- Pt (total porosity) > Pe (effective porosity) > Sy (specific yield)
- Fine grain lithologies have Sr (specific retention) >> Sy (specific yield), where n = Sy + Sr
- Neutron logs corrected with caliper data to provide a continuous porosity measure (N-Pt) that is related to Pe and Sy

	P_t site lab		P_t BGS lab		P_e BGS lab		S_y BGS lab	
	mean	SD	mean	SD	mean	SD	mean	SD
Sand dominant	0.31	±0.06	0.32	±0.08	0.26	±0.07	0.13	±0.07
Silt & sand-clay mixes	0.37	±0.08	0.38	±0.11	0.32	±0.09	0.06	±0.04
Clay dominant	0.42	±0.07	0.44	±0.06	0.37	±0.06	0.02	±0.02
Halite dominant	0.27	±0.14	0.29	±0.10	nd	nd	0.04	±0.02





Source: Orocobre, Lithium Americas

Hydraulic conductivity, storativity

- **Halite units** can have secondary porosity, with overall porosity decreasing with depth due to halite compaction
- Very high hydraulic conductivities and storativity
- **Clastic units** (clay to sand) have much lower hydraulic conductivity and storativity
- Gypsum sands in Central Australian salt lakes, when wind blown and uncemented, can have significant porosity and storage

Aquifer type	Lithology	K m/d	Effective porosity%	Specific yield%	Storativity	Source
Unconfined	Halite	200-600	5-8		5.E-02	Rincon
Unconfined	Halite	1000-6000	31-40		3.E-01	Rincon
Unconfined	Fine clastics, some halite, sand	1-2		<10	0.02-0.2	Olaroz
Confined	Fine clastics, some sand	1-2		2-4	1.0E-3 - 1.0E-4	Olaroz
Confined aquitard	Silt/Clay	0.15		2	6.E-06	Olaroz
Confined	Sand	4		10-15		Rodinia

Source: Orocobre, Rodinia

Brine sampling

Sampling of the brine is essential as the lithium is extracted from the brine. Sampling methods include:

- Bailer sampling during diamond or sonic drilling, when casing is present
- Pumping from specific intervals with packers, or from screened intervals
- Brine extraction from core samples, subsampling the interior to prevent contamination from drilling brine
- Brine near saturation – which presents a challenge
- Analysed for Li, K, B, Ca, Mg, Na, Cl, SO4, HCO3, CO3 and trace elements. Carbonate and bicarbonate low

Brine chemistry – low Mg/Li key

	Salar de Atacama Chile mean	Hombre Muerto Argentina FMC	Salar de Rincon, Argentina Sentient	Salar de Olaroz Argentina ………....	Salinas Grande* Argentina Orocobre	Guayatayoc* Argentina	Cauchari* Argentina …...……	Salar de Cauchari Argentina (LAC)	Salar de Uyuni Bolivia	Silver Peak Nevada CFC
Li	1,835	744	397	690	775	67	191	618	424	245
K	22,626	7,404	7,513	5,730	9,289	2,185	1,596	5,127	8,719	5,655
Mg	11,741	1,020	3,419	2,270	2,117	115	453	1,770	7,872	352
Ca	379	636	494	460	1,450	628	569	401	557	213
B	783	420	331	1,050	232	144	244	1,360	242	85
Density	1.223	1.205	1.220	1.211					1.211	1.297
Mg/Li	6.4	1.4	8.6	2.4	2.7	1.7	2.4	2.9	18.6	1.4

* mean values include all pit samples from nucleus and margins and are not necessarily representative of possible production values

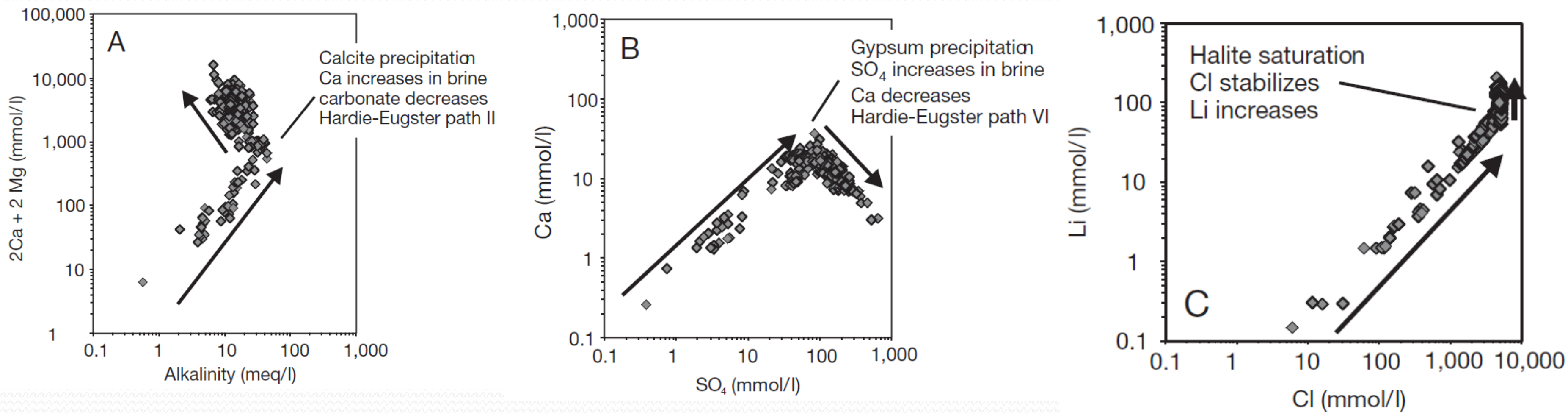
Data for Salars de Atacama, Hombre Muerto, Rincón, and Uyuni as well as Silver peak, taken from "Evaluation of The Potential of Salar del Rincon Brine Deposit as a Source of Lithium, Potash, Boron And Other Mineral Resources, by Pedro Pavlovic and Jorge Fowler, 2004. Salar de Cuachari (LAC), from NI43-101, Lithium Americas Corporations, February 15th 2010.

- Salar de Atacama is the "gold standard" salt lake, huge and high grade
- Uyuni is the true monster, but chemistry is less attractive for conventional processing, as is the project location
- Silver Peak, Nevada is a long term operation
- Olaroz came on stream as a producer in 2015
- Rincon, Cauchari and Salinas Grandes are all potential new operations

Source: Orocobre

Salt lake chemical zonation

- Typical zonation with carbonates deposited around lake margins or beyond the lake, sulphates (gypsum) and a central halite zone.
- Can be quite asymmetric, depending on the inflows to the basin



Source: Houston, 2011

Density contrasts

- Alluvial fans are developed around many salt lakes in active tectonic environments
- These have thick unsaturated zones away from the lakes & host fresh to brackish water in equilibrium with the lake brine
- Evaporation from the surface of the lake balances inflows from alluvial fans and river deltas entering the lake basins
- A gyben-Herzberg density interface develops on the margins of the lakes
- Pumping from the lake sediments is likely to results in changes to the lake hydrogeology and density gradients

Density variation - theory

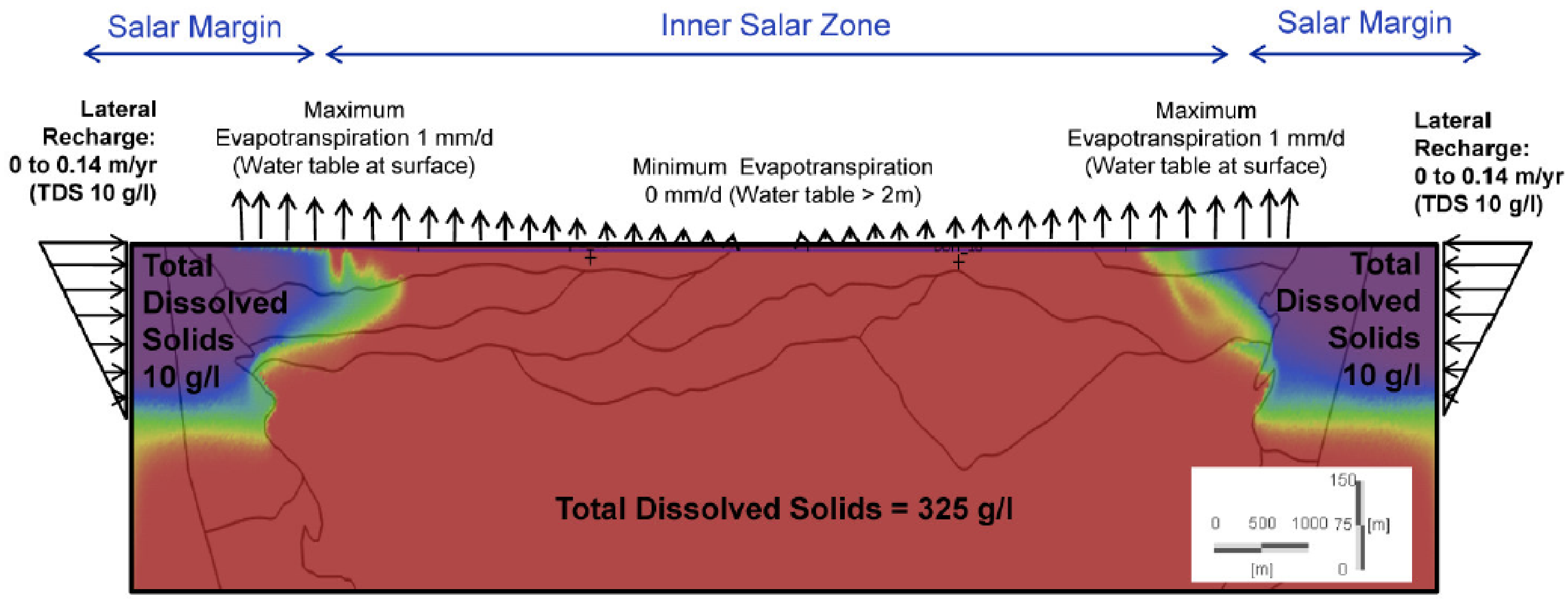


Figure 9.14: Simulation results from the two-dimensional model showing the natural steady-state configuration of the brine / fresh water interface; the equilibrium configuration of the interface is a function of the balance between fresh water inputs and evaporation / evapotranspiration outputs.

Dilution of brine by marginal less concentrated water is a groundwater management issue

Source: Lithium Americas

How much brine is there?

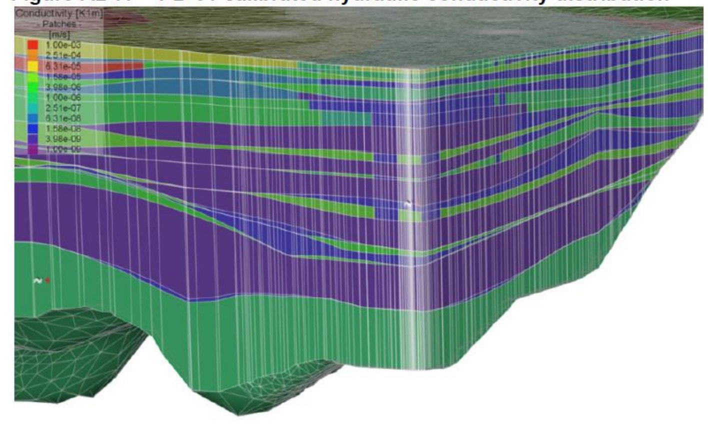
- **Defining resources** is a critical step in determining whether a salt lake has potential for economic production
- Drilling to determine how deep and what type of sediments are present
- Porosity and permeability testing of samples
- Pump testing, to evaluate brine flows
- Evaluation of brine chemistry – can you produce saleable product
- Evaporation and solar radiation measurements
- Simulating brine extraction with a groundwater model

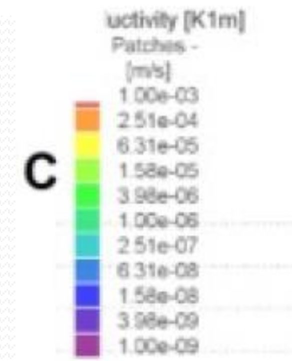
Extraction & borefield management

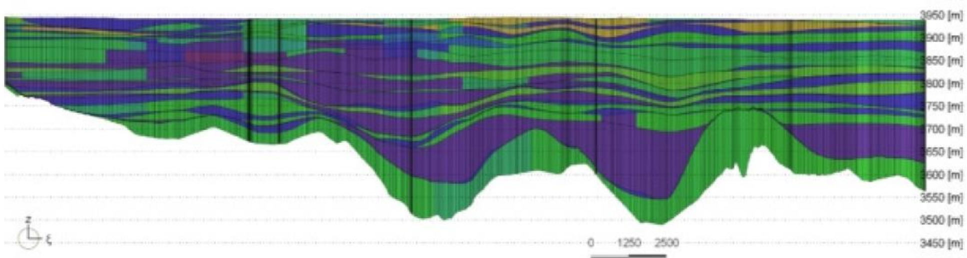
Groundwater modelling

- Unconfined to leaky confined layered aquifers
- Complex model domains with faults – how simplified can they be?
- Dual density fluid – how important is density in these layered aquifers?
- Recharge volumes over the life of extraction?
- What is the hydraulic connection with alluvial fans and deeper alluvial material around salars?
- **Modelling required to define conversion from resources to reserves and to manage extraction**

Figure A2-7: PB-01 calibrated hydraulic conductivity distribution







Source: Lithium Americas

Conclusions

- Catchment lithology influences salt lake chemistry
- Hydrology and water balance influence salt lake development
- Tectonics are important to produce deep basins, with thick sediments
- Brine chemistry is important for economic processing
- Host sediments vary from true aquifers to aquitards
- Resource definition requires adequate drilling, defining the stratigraphy and applying appropriate porosities
- Careful groundwater modelling of operating bore fields is required to simulate the long term pumping effects

Where to from here?

- Stable isotope studies on brines and fresh to brackish water in the groundwater system
- Age dating of brine from different depths
- Groundwater modelling of pumping scenarios
- Hydrogeological model completion to define production schedules and for prediction of drawdowns and to assist groundwater and stakeholder management
- Long term monitoring of bore networks
- Further drilling to address data gaps

Thanks for your attention