# ERUPTIONS TO ELECTRONS

## EXPLORATION FOR GEOTHERMAL RESOURCES

Dr. Catherine Hickson

January 30, 2014

# WHY GEOTHERMAL ENERGY . . . BECAUSE

- Geothermal power can be produced reliably and constantly ("base load"); it is not intermittent or unpredictable.
- The generating process is clean - there are very low to no
  - Nitrous Oxides
  - Sulphur Oxides
  - Particulates
  - CO2
- Has a small environmental footprint
- Doesn't take up much land
- Is a renewable energy - no fuel cost and continually replenished
- Low Technological Risk - plants in operation for over 100 years

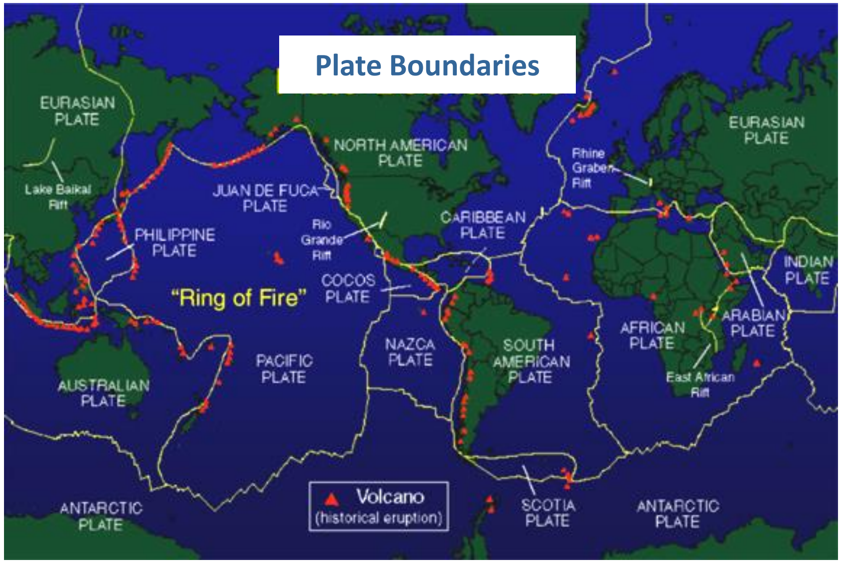
Alterra's Power Plant in Reykjanes, Iceland

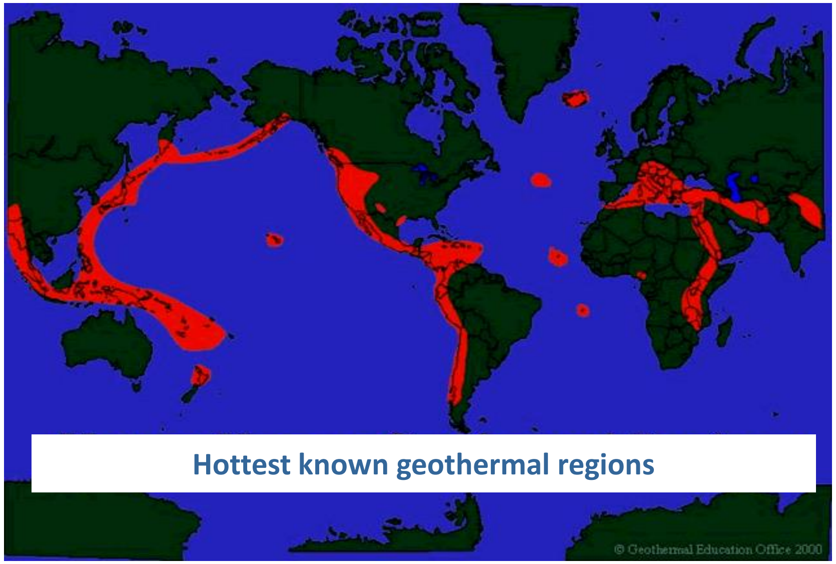
| | Geothermal | Wind | Solar | Biomass | Run-of-River | Scrubbed Coal |
|---|---|---|---|---|---|---|
| Base Load | ✓ | ✗ | ✗ | ✓ | ✗ | ✓ |
| No Fuel Cost Exposure | ✓ | ✓ | ✓ | ✗ | ✓ | ✗ |
| No GHG Emission | ✓ | ✓ | ✓ | ✗ | ✓ | ✗ |
| REC Eligible | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Low Cost Generation | ✓ | ✓ | ✗ | ✓ | ✗ | ✓ |

**GEOTHERMAL HAS A UNIQUE COMBINATION OF BENEFITS RELATIVE TO COMPETING SOURCES**

- Many regions around the globe have accessible geothermal resources, especially countries along the circum-Pacific "Ring of Fire" and other areas of active global plate boundaries.

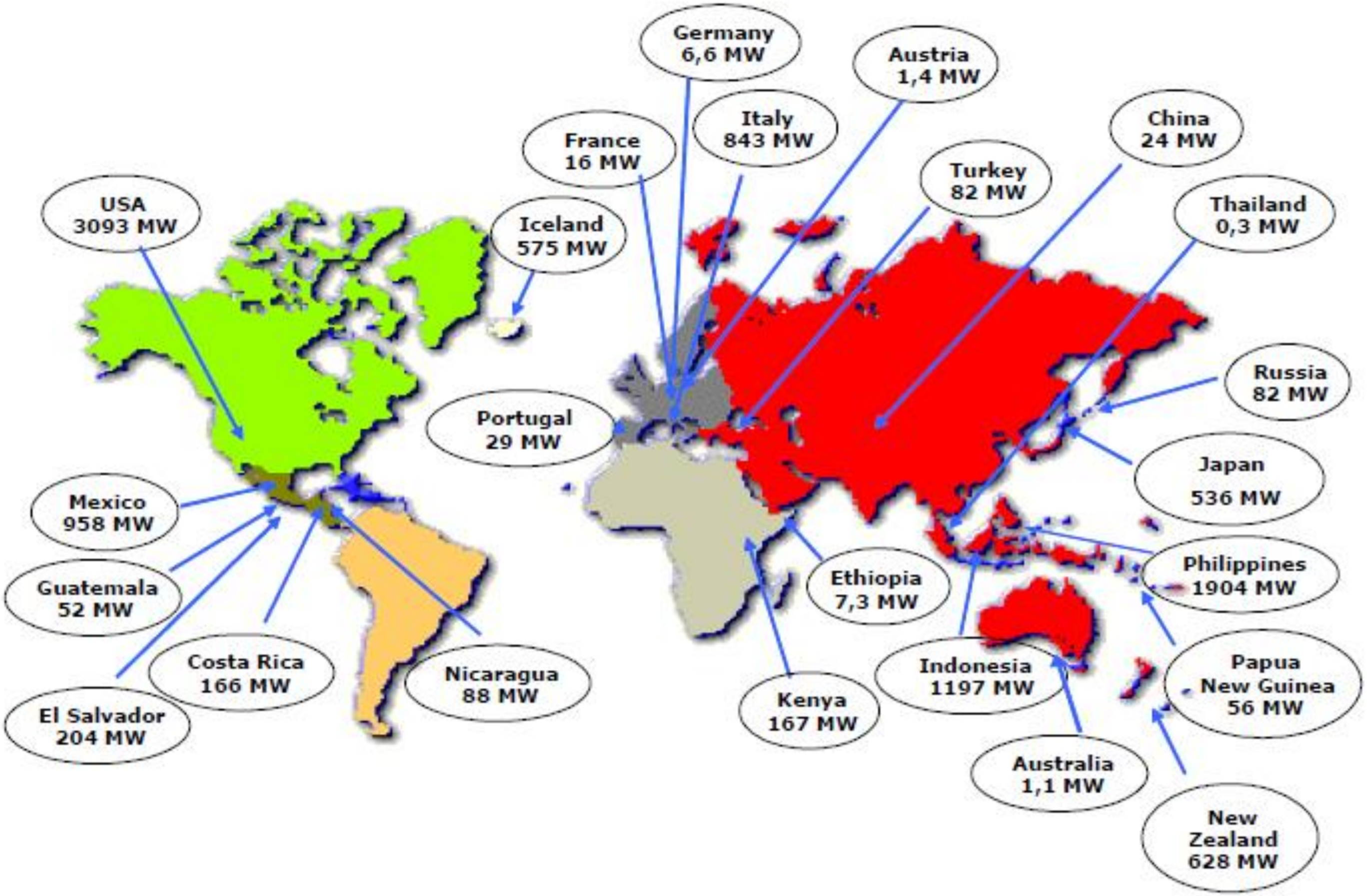
- Arcs such as found in Central America, Philippines and Indonesia are major areas for geothermal resource development; hotspots such as Iceland (on the mid Atlantic rift) is a major producer as well as the African Rift Valley.



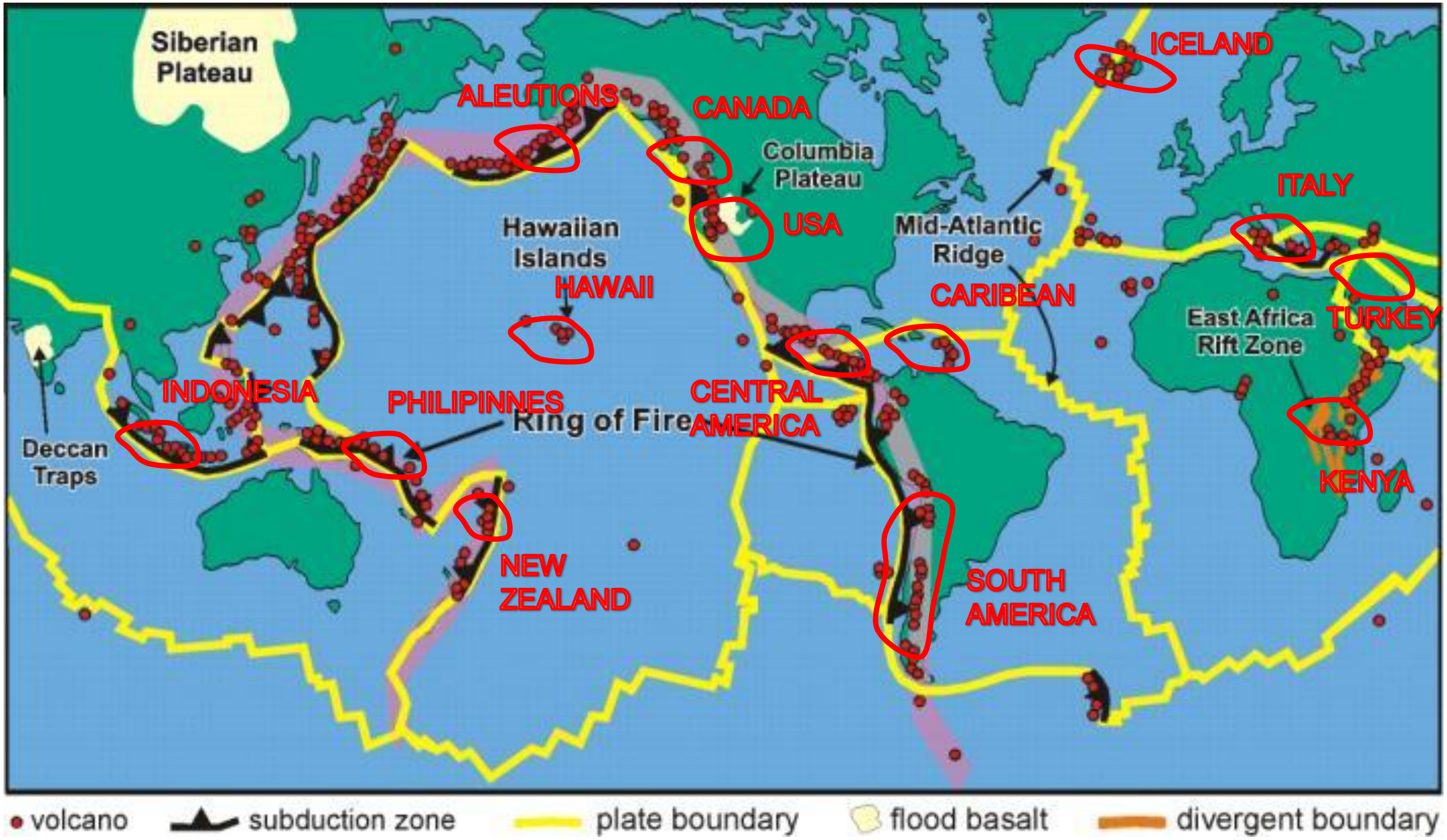

Source: GEO

# GEOTHERMAL ENERGY – WHERE IS IT?




**Installed capacity in 2010 worldwide (10.7 GW)**

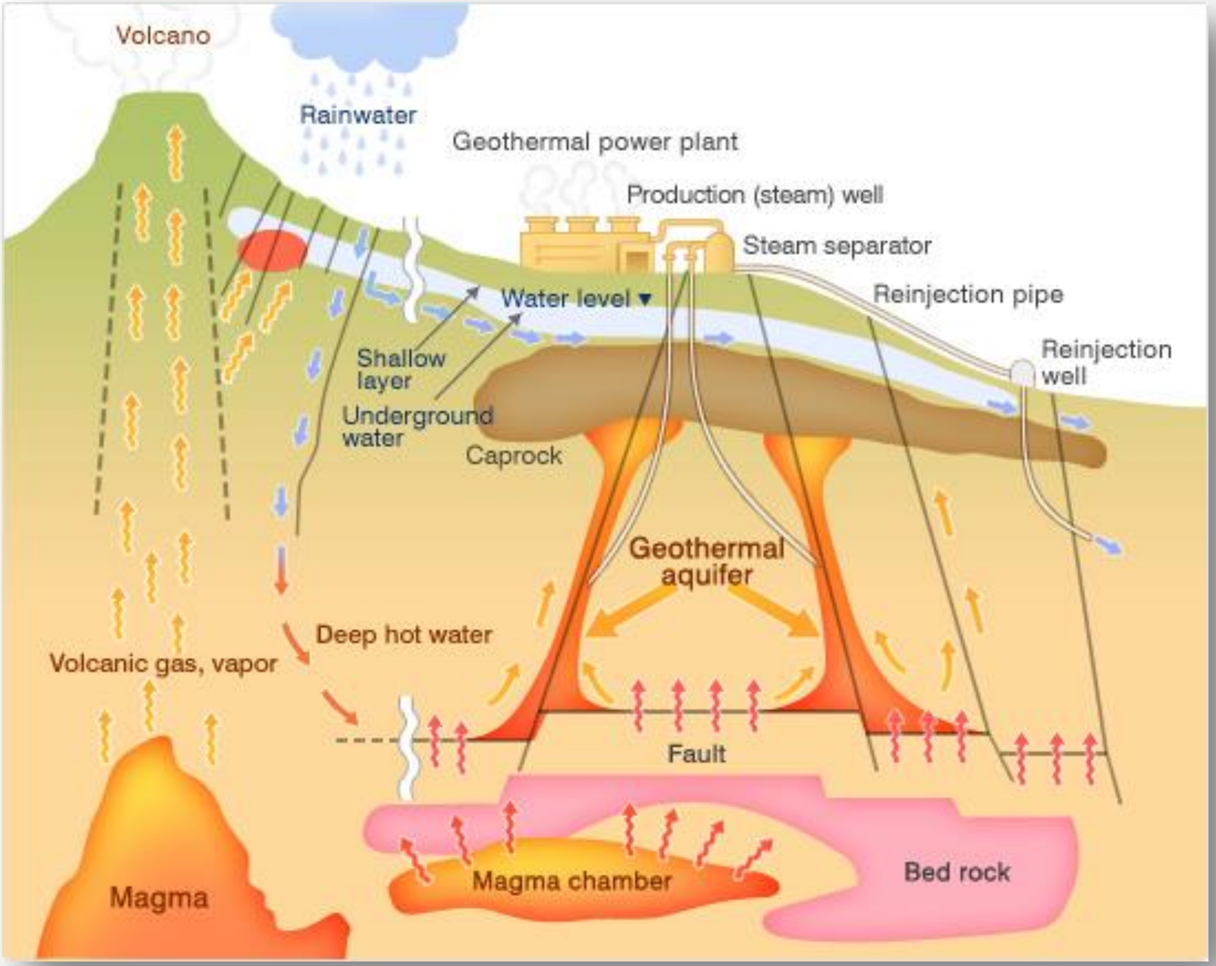
# RING OF FIRE - ALTERRA'S EXPLORATION TARGETS




- Exploration targets 2008 - 2013

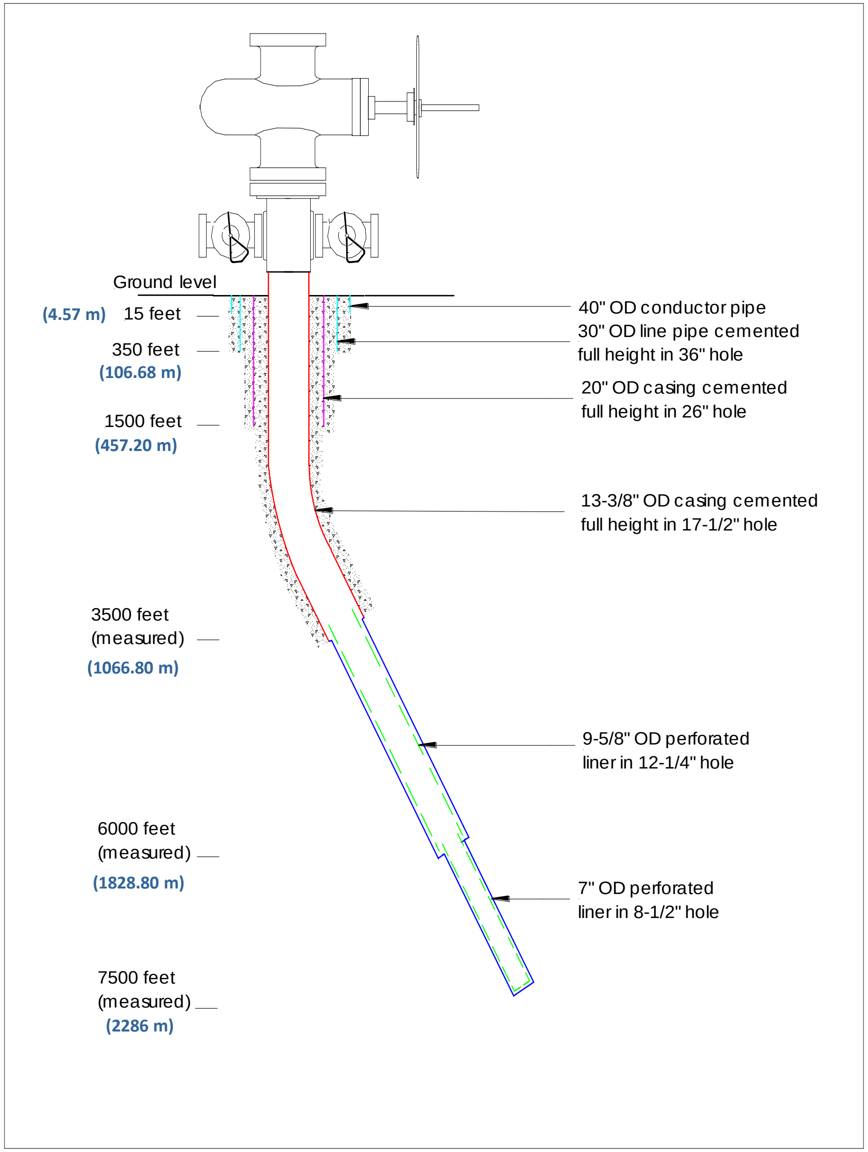
# GEOTHERMAL ENERGY – WHAT IS IT? ERUPTIONS TO ELECTRONS

- **Cartoon of a high temperature geothermal system.**
- **The interaction of magmatic fluids and ground water create a chemically complex mixture which over time creates extensive alteration zones including surface carbonate and/or silica deposits, a clay rich cap rock and eventual creation of near neutral fluids.**
- **Fluids are "produced" then reinjected to provide continued pressure support for the field leading to sustainable production on the order of many decades.**
- **Over time, geothermal systems deposit significant amounts of precious and base metals.**

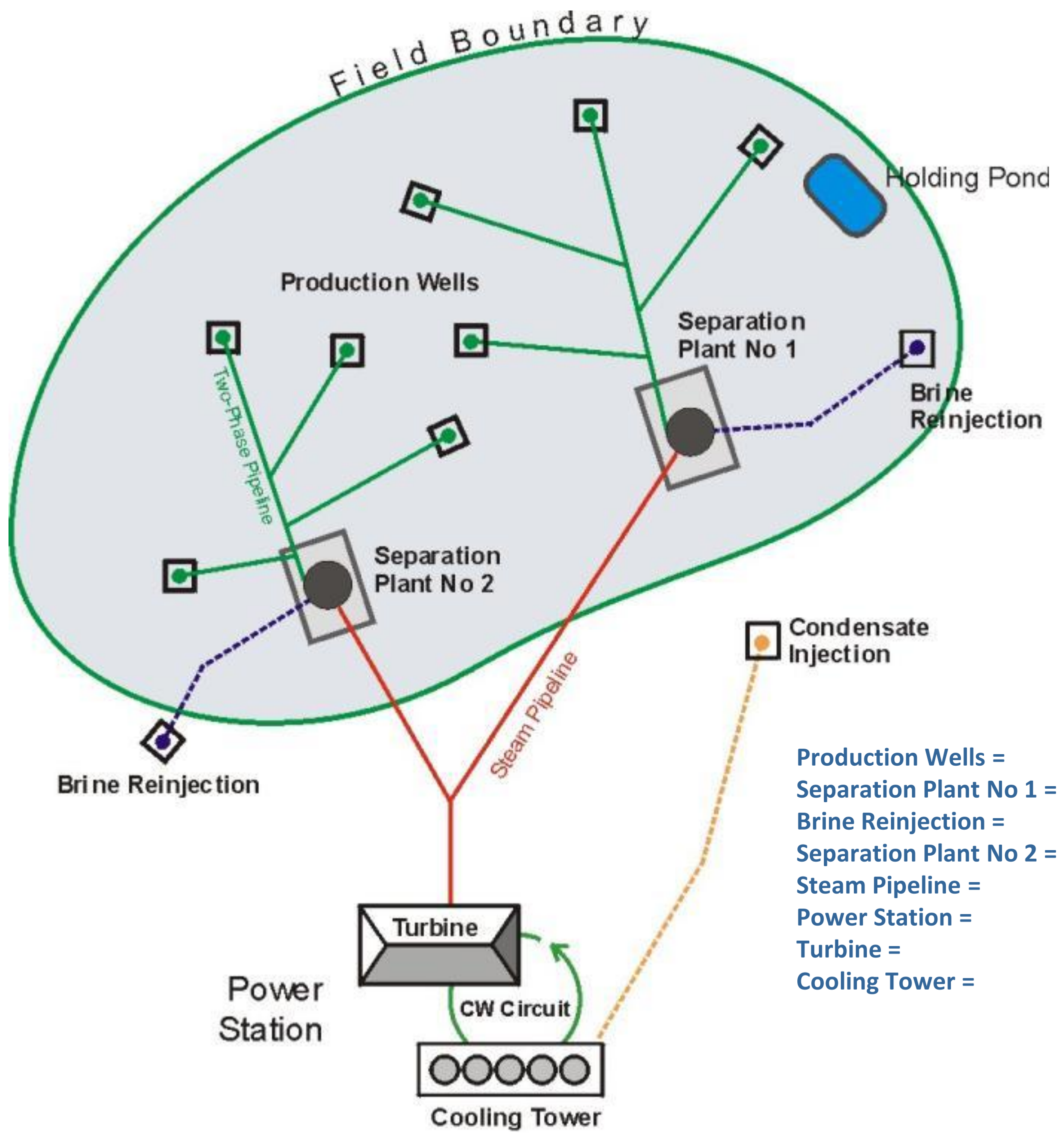


# ENERGY EXTRACTION – GEOTHERMAL WELLS

- Well depths typically 1,000 to 3,000 meters
- Can be deviated (do not need to be vertical)
- Many wells from one location
- Production and injection wells are similar



# ENERGY EXTRACTION – TYPICAL FLASH WELL FIELD LAYOUT




Production Wells =
Separation Plant No 1 =
Brine Reinjection =
Separation Plant No 2 =
Steam Pipeline =
Power Station =
Turbine =
Cooling Tower =

# GEOTHERMAL ENERGY – PLANTS

- In 1904 the first geothermal power was generated in Larderello, Italy, the field is still producing.
- Geothermal plants do not burn fossil fuel or produce smoke or toxic waste products.
- Geothermal plants generate all of their power from free and constantly replenished resources.
- **Geothermal plants usually operate at 90+% of their capacity vs typical usage rates of 32% for wind and 24% for solar.**
- Geothermal plants can operate successfully in sensitive environments.

Reykjanes Plant - Iceland

Svartsengi Plant - Iceland

# GEOTHERMAL RESOURCES :
# THE SEARCH FOR VERY YOUNG MINERAL DEPOSITS

White Island-andesitic volcano
aerosols from 850°C discharge (1988)

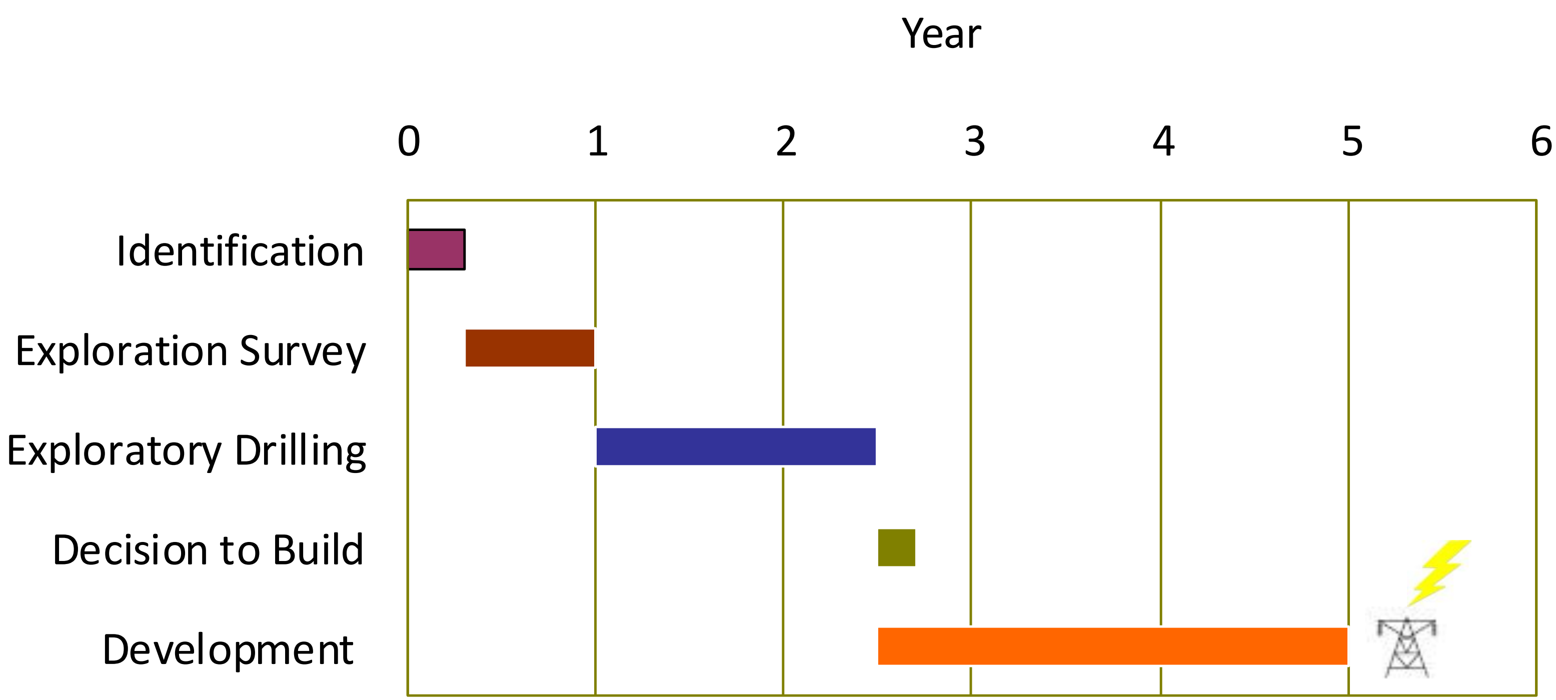
100 tonnes Cu/yr
.037 tonnes Au/yr

<1000 yrs to flux 1 million oz Au at White Island
>6000 yrs to flux 1 million oz Au at Broadlands-Ohaaki

(Hedenquist et al., 1993)

- The search for geothermal reservoirs is very similar to the search for mineral deposits.

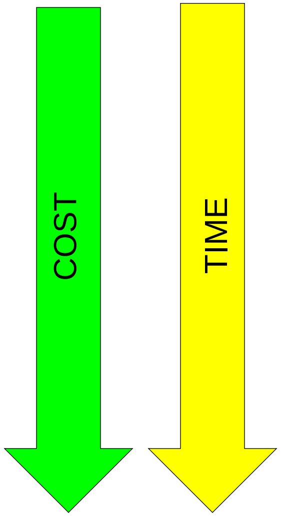
# TIMELINE OF A GEOTHERMAL POWER DEVELOPMENT







# GEOTHERMAL DEVELOPMENT METHODOLOGY - EXPLORATION




Geological data

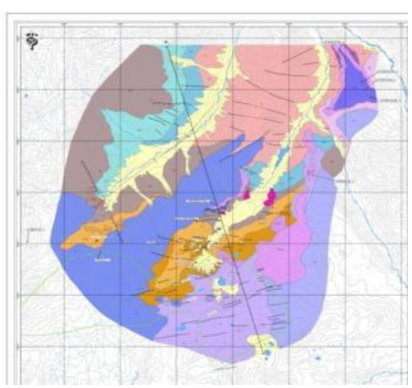
Geochemical data

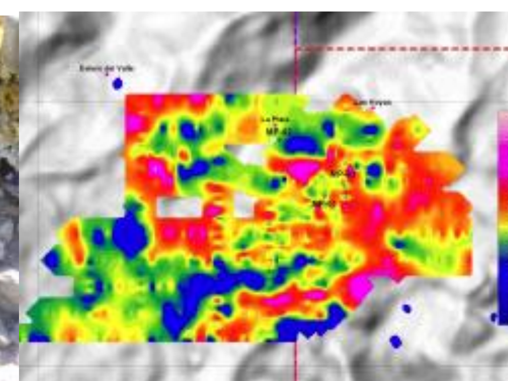
Geophysical data

Conceptual model
Size, depth, type of fluids and temperature

*Resource estimation

Exploration drilling

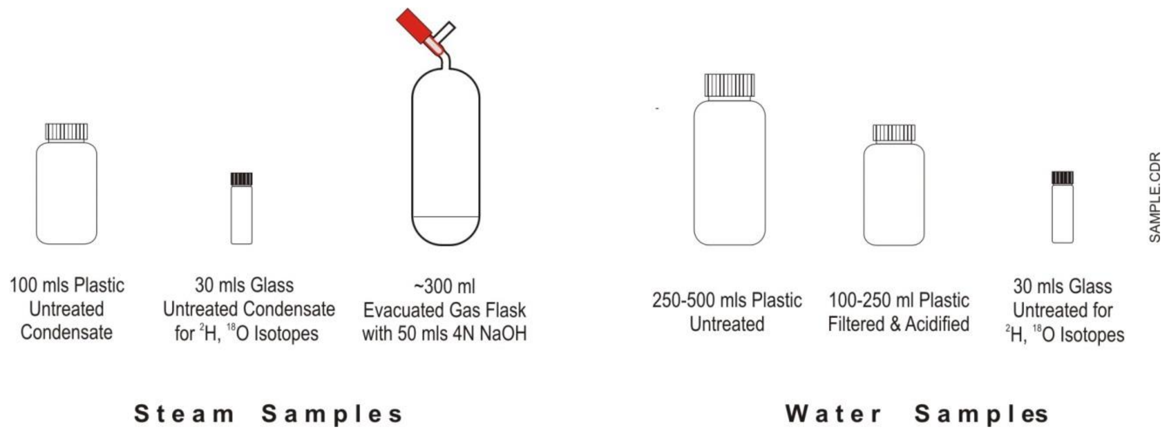




*** Inferred/Measured Resource Geothermal Reporting Code (similar to 43-101)**

# FLUID PROPERTIES AND COLLECTION

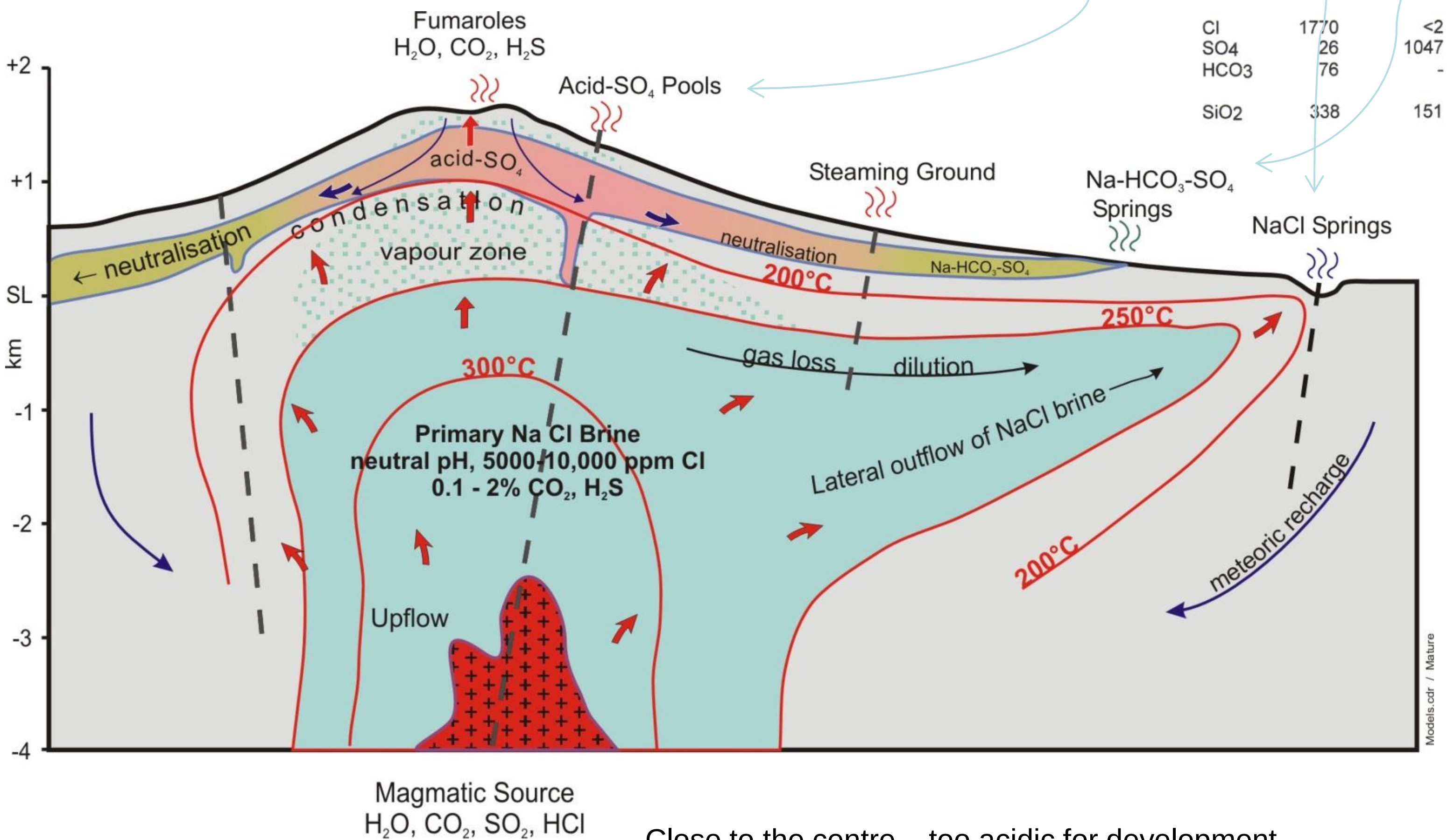
- **Phase (liquid or gas)**
- **Temperature (heat)**
- **Pressure**
- **Density**
- **Dissolved solids**
- **Dissolved gas**
- **Boiling**
- **pH, conductivity, TDS and salinity by multimeter in-situ**




# FLUID PROPERTIES AND COLLECTION

Geothermal Waters (mg/kg)

| | Chloride | Acid Sulfate | Bicarbonate |
|---|---|---|---|
| pH20°C | 8.0 | 1.8 | 7.0 |
| Na | 1070 | 4 | 398 |
| K | 102 | 6.2 | 31 |
| Cl | 1770 | <2 | 30 |
| SO4 | 26 | 1047 | 96 |
| HCO3 | 76 | - | 8492 |
| SiO2 | 338 | 151 | 190 |




Close to the centre – too acidic for development



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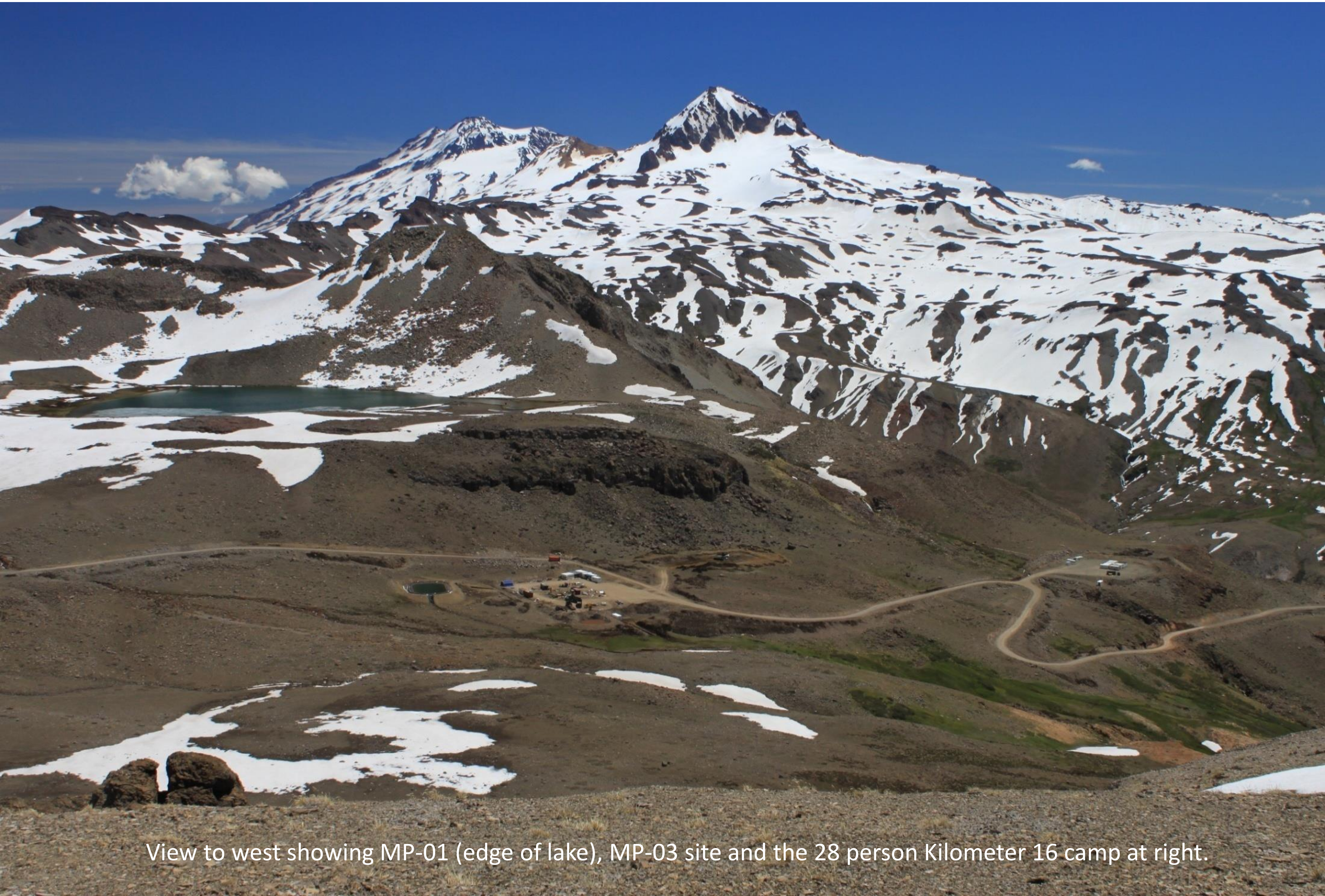
# EXPLORATION IN PRACTICE

## MARIPOSA CASE STUDY, CHILE

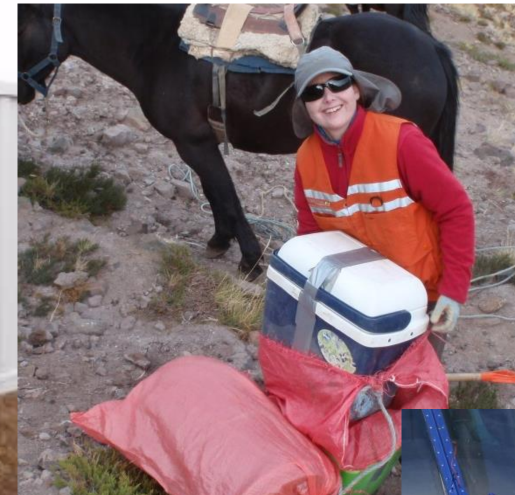
January 30, 2014

# MARIPOSA GEOTHERMAL PROJECT


View to west showing MP-01 (edge of lake), MP-03 site and the 28 person Kilometer 16 camp at right.

# SUCCESS THROUGH A MOTIVATED, HIGHLY TRAINED TEAM

- Dr. Carolina Rodriguez
- Fernando Ferraris
- Rene Henriquez (MSc student)
- Dr. Carlos Arevalo
- Dr. Andrea Brogi
- Dr. Moyra Gardeweg (ARUM)
- Gerd Sielfeld (PhD student)
- Augustine Perez
- Robert Ellsworth
- Dr. Phil White (SKM)
- Dr. Greg Ussher (SKM)
- Dr. Brian Clotworthy (SKM)
- Geophysical and drilling teams
- \+ others!!



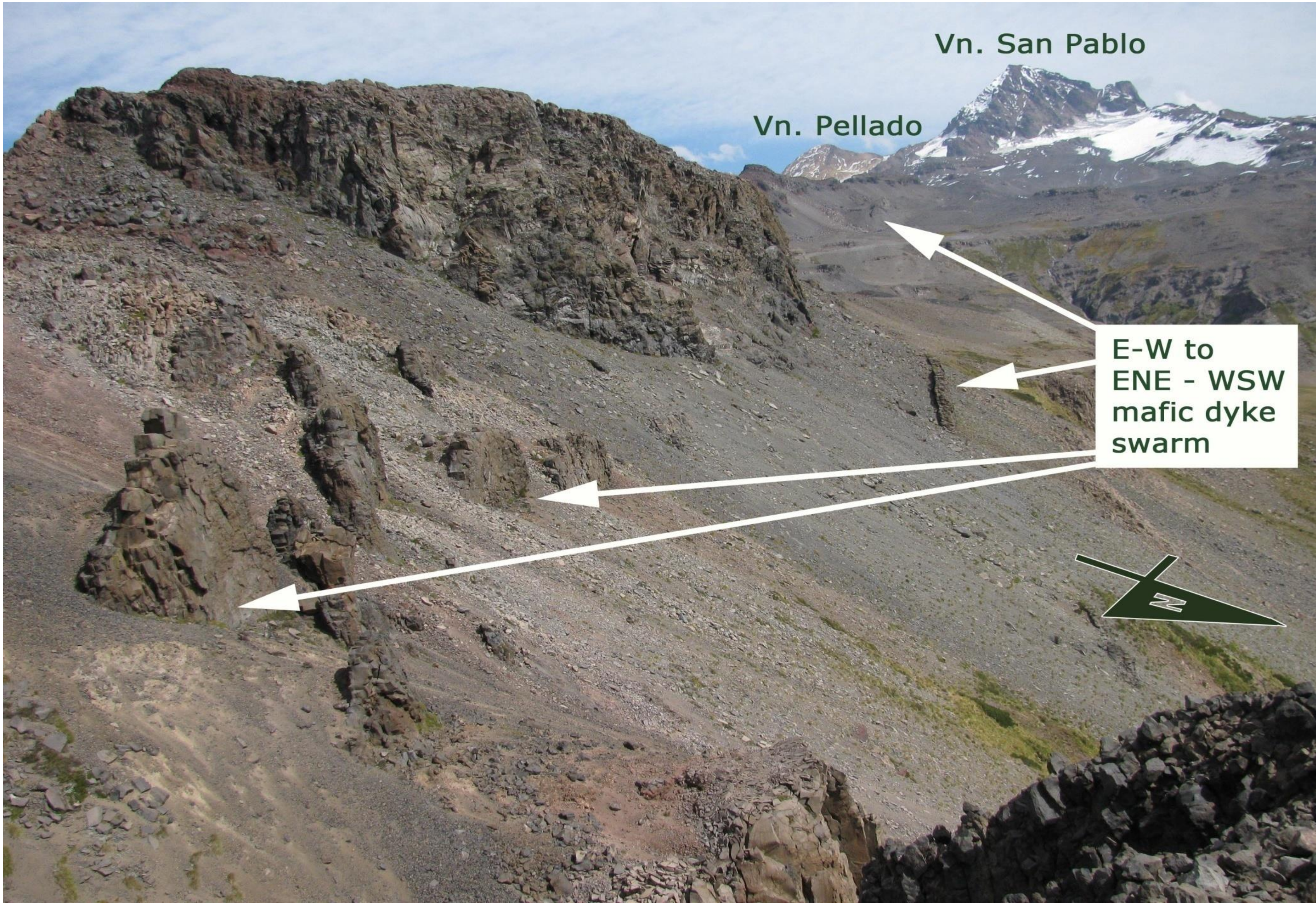

# MARIPOSA GEOTHERMAL PROJECT LOCATION

## REGIONAL LOCATION

- Located ~300 km south of Santiago
- 5.5 hours driving from central Santiago to the heart of the project
- ~1.5 hours helicopter from Santiago
- Talca (population 240,000) 1.5 hours driving time from project
- Access road leads from paved National highway #115 (International Pehuenche route to Argentina)
- Pellado Exploration lease 100,000 ha
- Laguna del Maule Exploitation lease 4,000 ha

# 1:50,000 SCALE MAPPING AND STRUCTURAL ANALYSIS

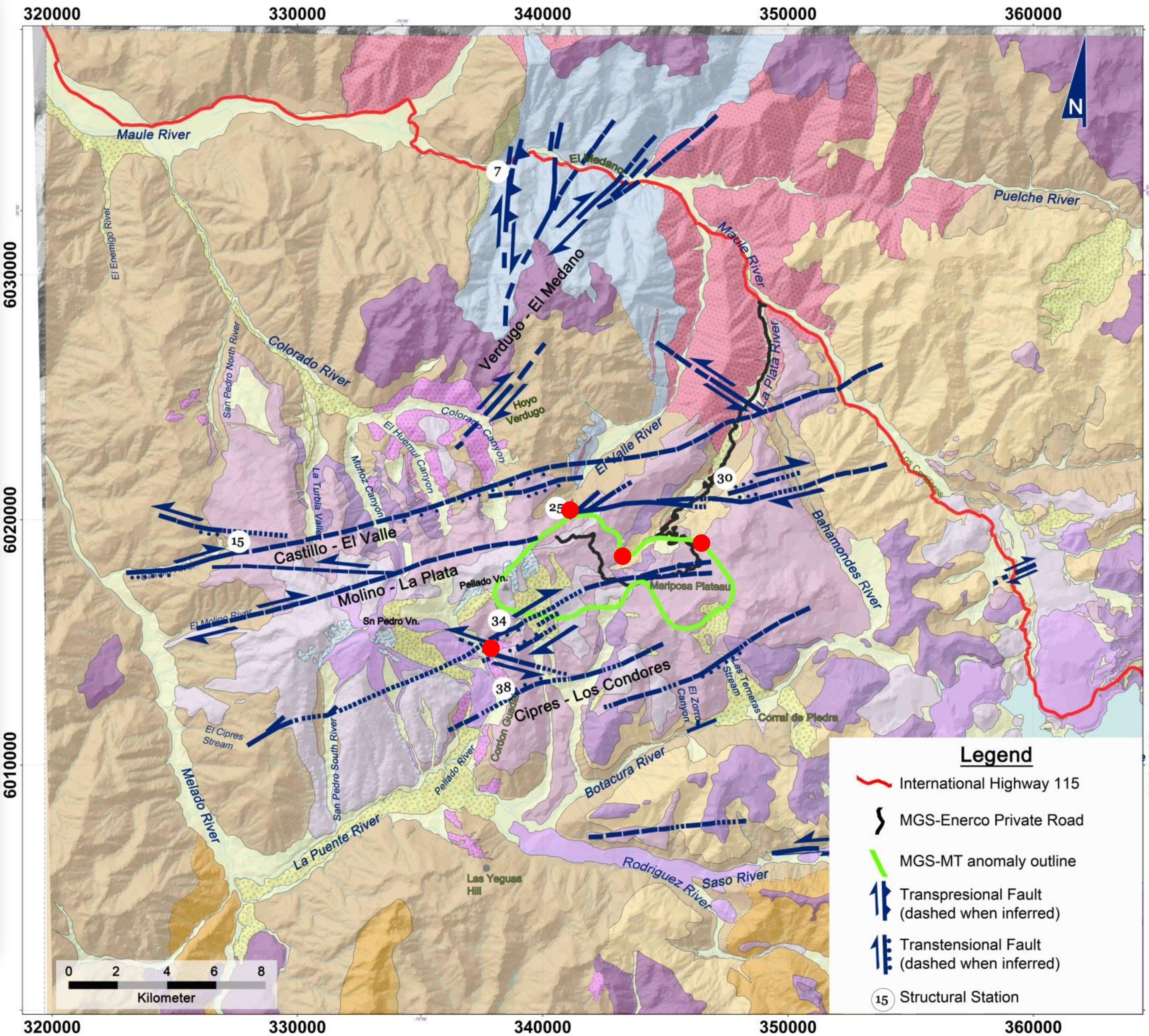
## ORIENTED DYKE SWARMS IN QUATERNARY VOLCANIC ROCKS



# 1:50,000 SCALE MAPPING AND STRUCTURAL ANALYSIS

**Stratigraphic time table**

| Eonothem Eon | Erathem Era | System Period | Series Epoch | Stage Age | Age Ma |
|---|---|---|---|---|---|
| Phanerozoic | Cenozoic | Quaternary | Holocene | | 0.0117 |
| | | | Pleistocene | Upper | 0.126 |
| | | | | "Ionian" | 0.781 |
| | | | | Calabrian | 1.806 |
| | | | | Gelasian | 2.588 |
| | | Neogene | Pliocene | Piacenzian | 3.600 |
| | | | | Zanclean | 5.332 |
| | | | Miocene | Messinian | 7.246 |
| | | | | Tortonian | 11.608 |
| | | | | Serravallian | 13.82 |
| | | | | Langhian | 15.97 |
| | | | | Burdigalian | 20.43 |
| | | | | Aquitanian | 23.03 |
| | | Paleogene | Oligocene | Chattian | 28.4 ±0.1 |
| | | | | Rupelian | 33.9 ±0.1 |
| | | | Eocene | Priabonian | 37.2 ±0.1 |
| | | | | Bartonian | 40.4 ±0.2 |
| | | | | Lutetian | 48.6 ±0.2 |
| | | | | Ypresian | 55.8 ±0.2 |
| | | | Paleocene | Thanetian | 58.7 ±0.2 |
| | | | | Selandian | ~ 61.1 |
| | | | | Danian | 65.5 ±0.3 |
| | Mesozoic | Cretaceous | Upper | Maastrichtian | 70.6 ±0.6 |
| | | | | Campanian | 83.5 ±0.7 |
| | | | | Santonian | 85.8 ±0.7 |
| | | | | Coniacian | ~ 88.6 |
| | | | | Turonian | 93.6 ±0.8 |
| | | | | Cenomanian | 99.6 ±0.9 |
| | | | Lower | Albian | 112.0 ±1.0 |
| | | | | Aptian | 125.0 ±1.0 |
| | | | | Barremian | 130.0 ±1.5 |
| | | | | Hauterivian | ~ 133.9 |
| | | | | Valanginian | 140.2 ±3.0 |
| | | | | Berriasian | 145.5 ±4.0 |
| | | Jurassic | Upper | Tithonian | 150.8 ±4.0 |
| | | | | Kimmeridgian | ~ 155.6 |
| | | | | Oxfordian | 161.2 ±4.0 |
| | | | Middle | Callovian | 164.7 ±4.0 |
| | | | | Bathonian | 167.7 ±3.5 |
| | | | | Bajocian | 171.6 ±3.0 |
| | | | | Aalenian | |




Surface thermal feature

# Local Geology

QUATERNARY VOLCANIC UNITS

- TSPP & Maule Volcanic Complexes

LATE MIOCENE-PLEISTOCENE VOLCANIC UNITS

- Cola de Zorro Fm
- Campanario Fm

*LATE MIOCENE DEFORMATION*

EOCENE-MIOCENE VOLCANIC & INTRUSIVE UNITS

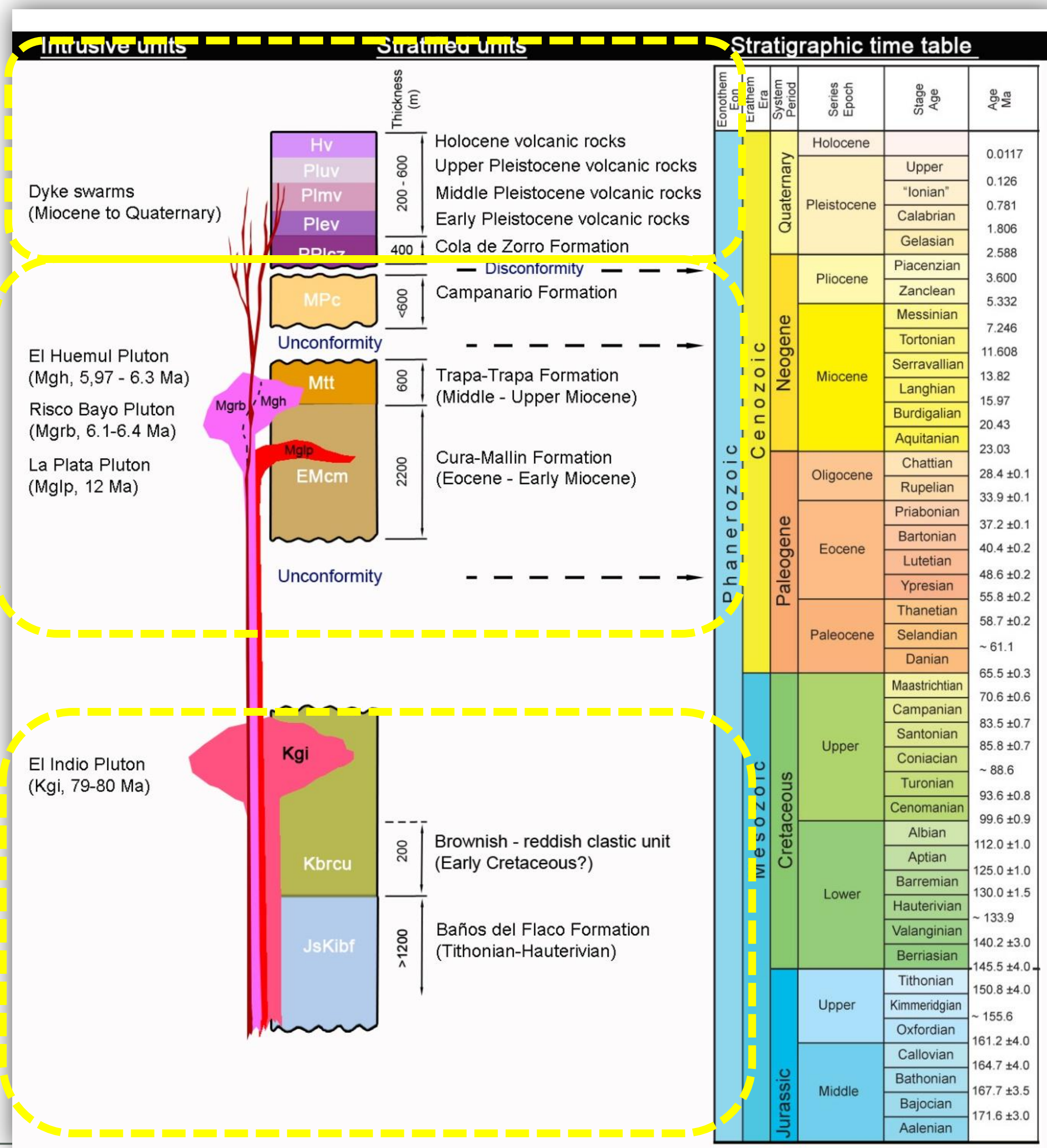
- La Plata, El Huemul, Risco Bayo and Vega Larga Plutons
- Trapa-Trapa Fm
- Cura-Mallín Fm

*LATE CRETACEOUS-PALEOGENE? DEFORMATION*

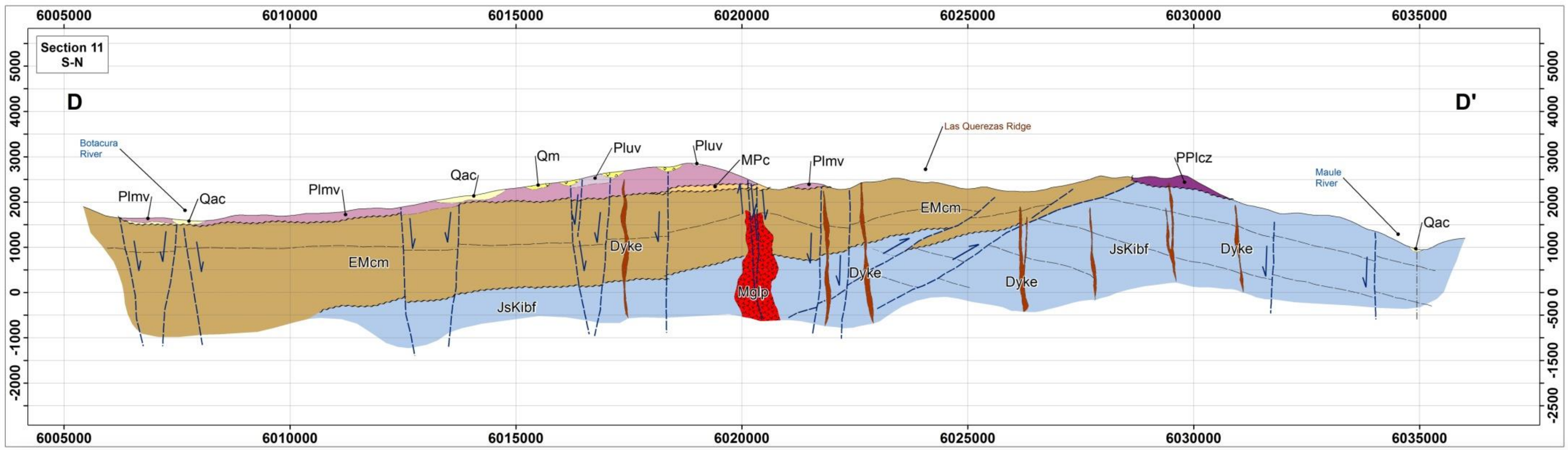
JURASSIC-CRETACEOUS BASEMENT

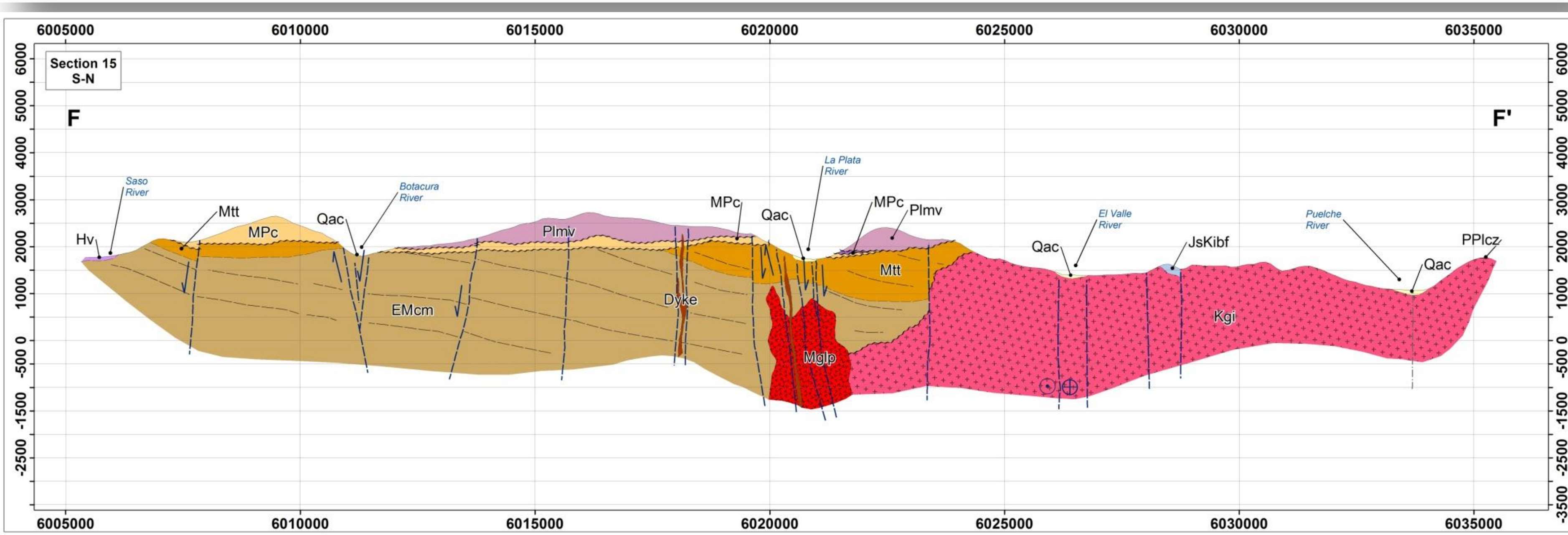
Marine and continental back-arc sedimentary rocks and granodiorites

- El Indio Pluton
- BRCU
- Baños del Flaco Fm



## N-S Cross Sections



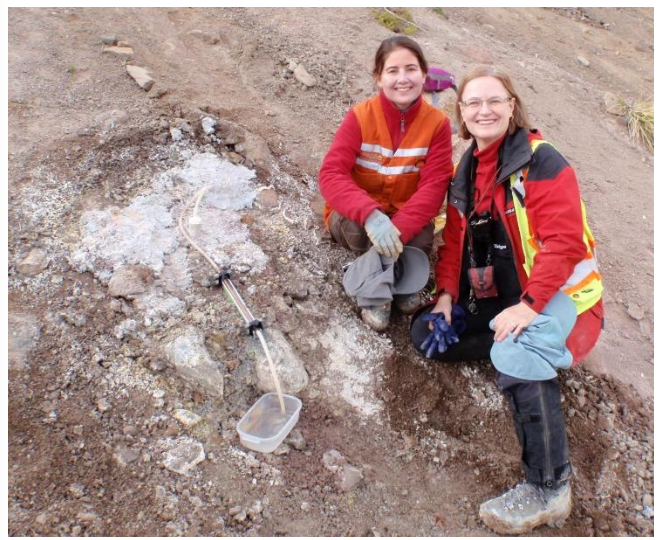



# MARIPOSA GEOCHEMISTRY



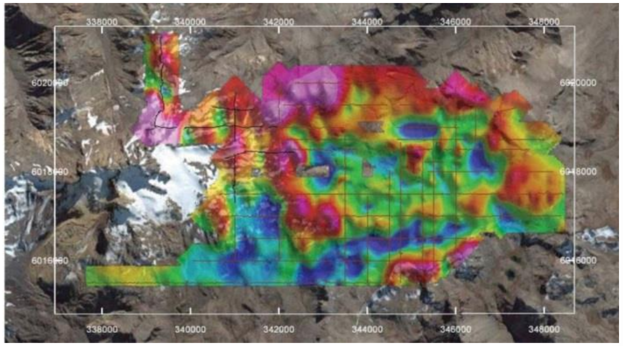
## GAS GEOCHEMISTRY SUMMARY

- There is no indication of acid-magmatic conditions
- The gas proportions of $CO_2$, $H_2S$, $H_2$, $CH_4$ are typical of those from other high temperature systems
- Reservoir temperatures ~240-290

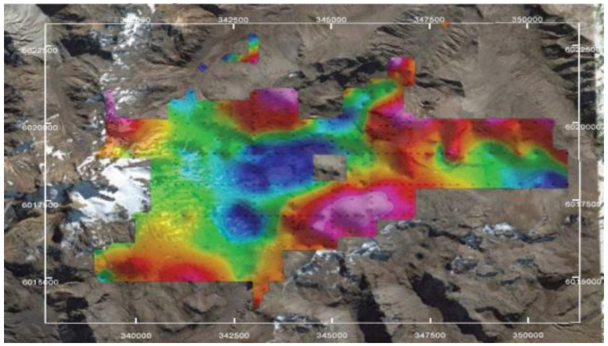


# MARIPOSA GEOPHYSICS: MT, GRAVITY & MAGNETICS

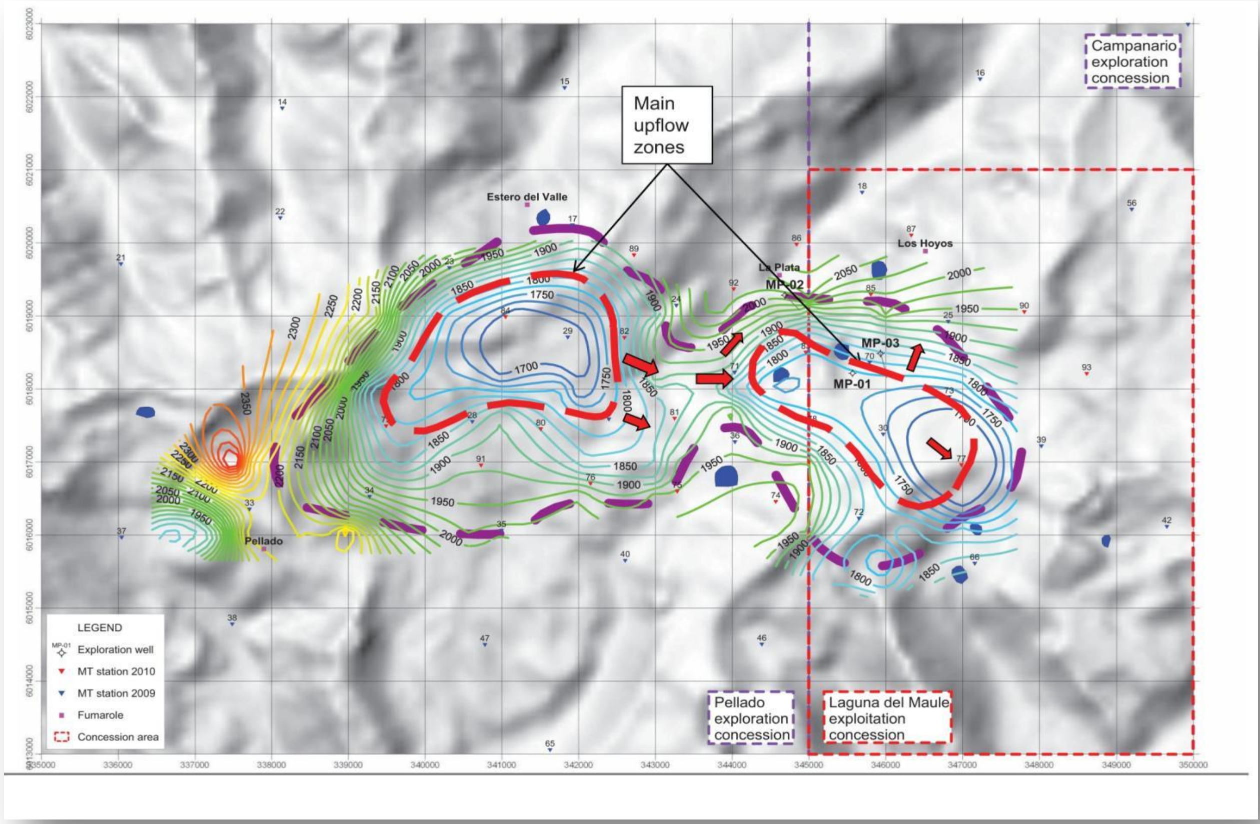
## GROUND MAGNETIC SURVEY



## GRAVITY SURVEY



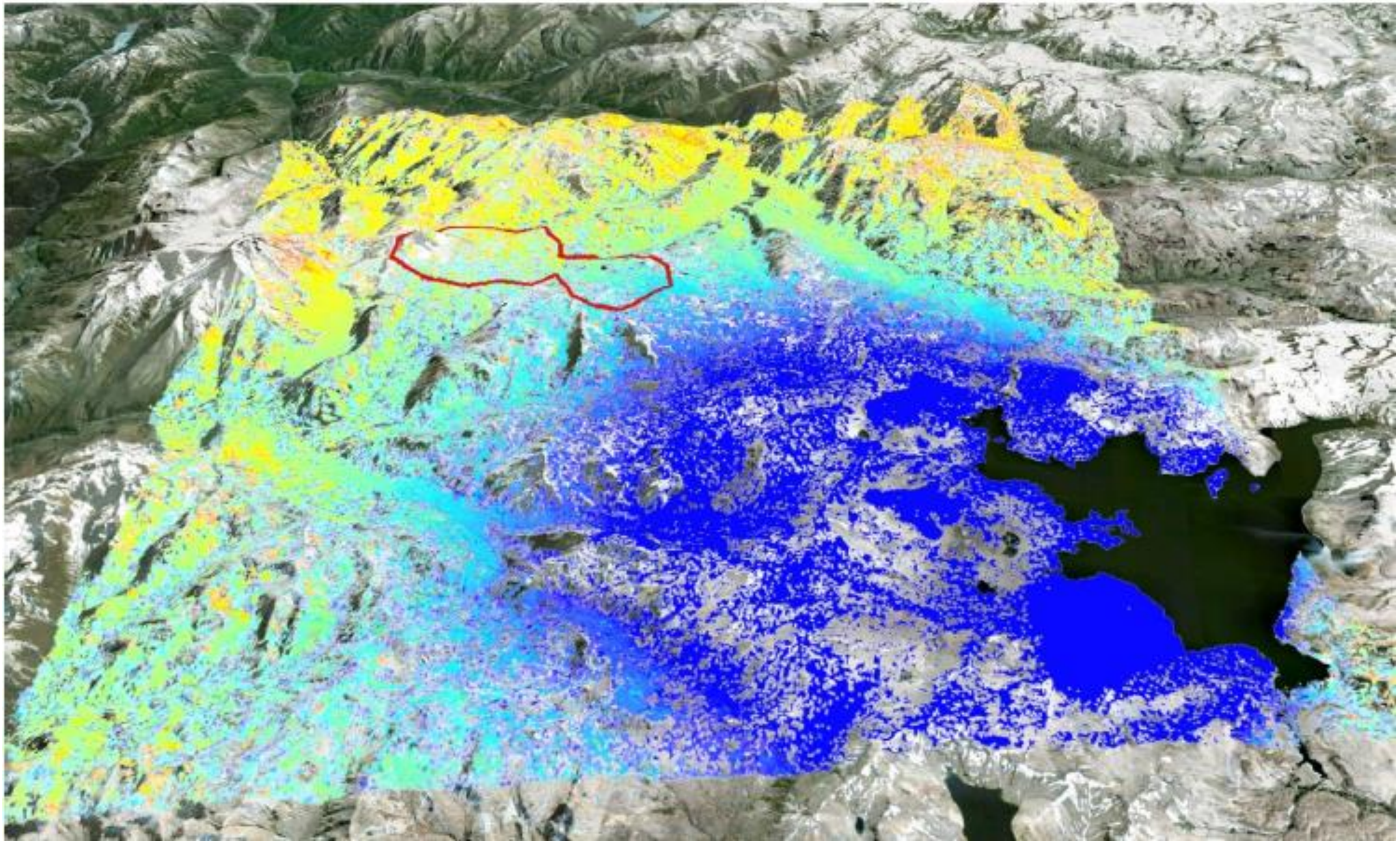
## MAGNETOTELLURICS (MT)




ELEVATION OF BASE OF SHALLOW MT CONDUCTOR AND SLIMHOLE LOCATIONS

# MARIPOSA GEOPHYSICS: INSAR

## INSAR: TRE (VANCOUVER) “SqueeSar” ANALYSIS



- Movement trends are dominated by a large area of uplift in the southeast. Measurement points identified over this feature exhibit uplift occurring at rates up to 260 mm/year. Many smaller pockets of subsidence and uplift are also located throughout the remainder of the area processed.

# MARIPOSA SLIM-HOLE DRILLING

## THE DECISION TO DRILL A $3M WELL BASED ON THE BEST SCIENCE AVAILABLE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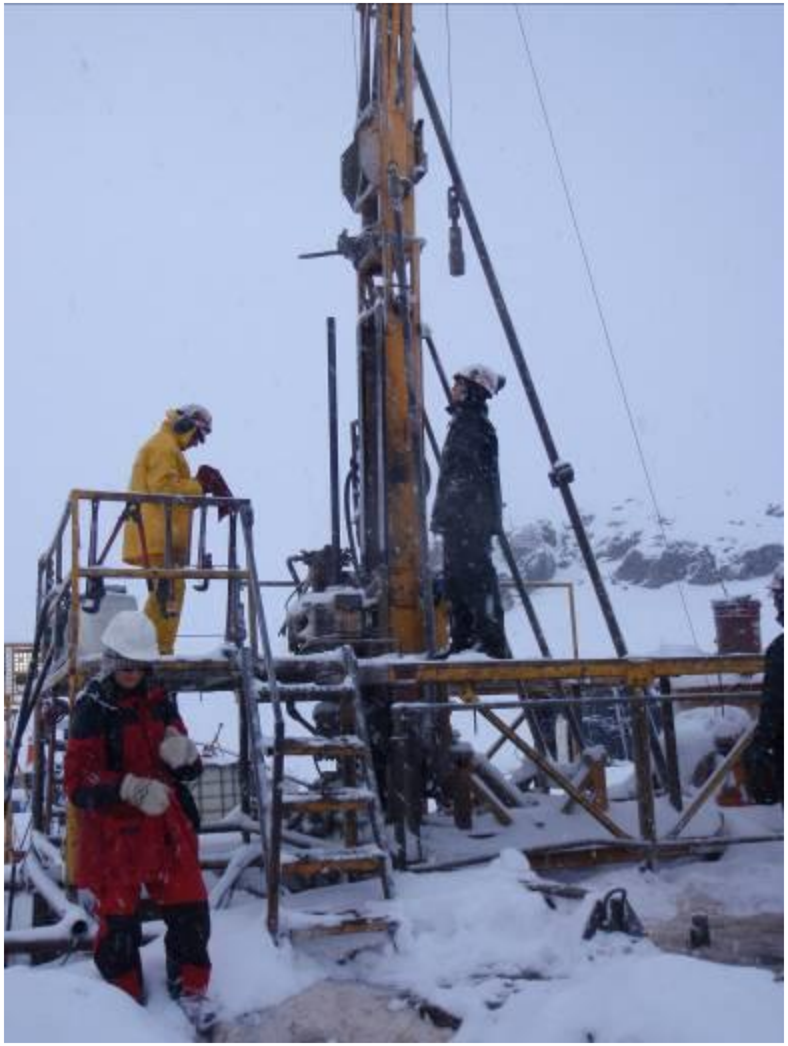
# MARIPOSA SLIM-HOLE DRILLING

## WELL WAS A “DO OR DIE” SCENARIO IN ORDER TO SAVE THE LEASE



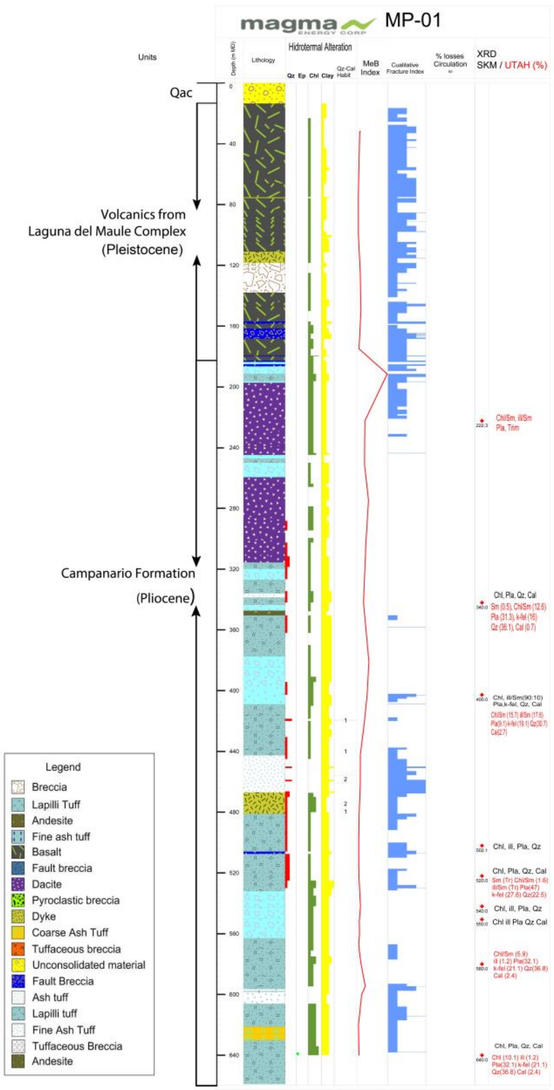

May – June 2009: An extremely strong storm early in the drilling operation created problems for the both the camp and hole. These were overcome and the camp secured against high winds. Snow, cold temperatures and strong winds hampered operations at times.

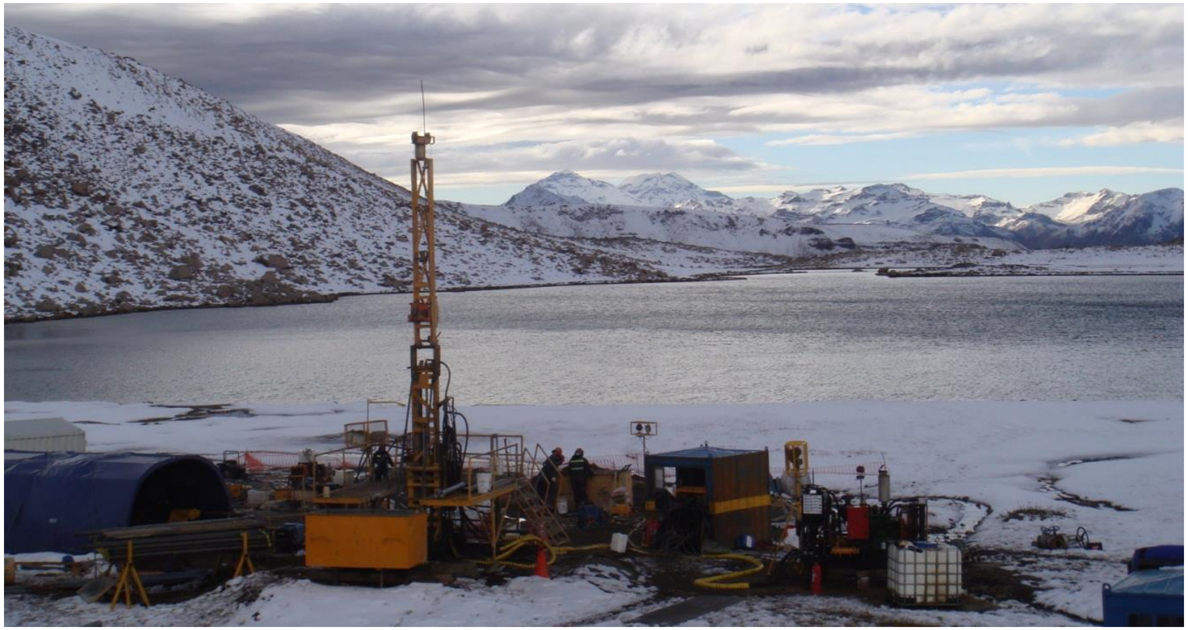
# MARIPOSA SLIM-HOLE DRILLING

A 2.5 m snow fall
Digging out!




## MP 01 DRILLING

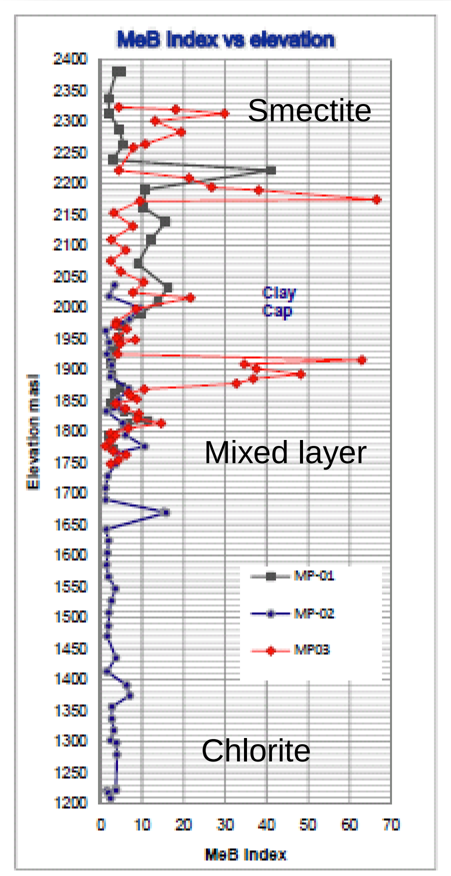


- The first slim hole MP01 was drilled in May-June 2009 to 659m
- Drilling was helicopter-supported due to lack of road access
- Drilling stopped in late June due to a 2.5m snowfall event.
- The well penetrated 300 m of Pleistocene Laguna del Maule volcanics overlying 359 m of the Pliocene volcanic Campanario Formation

# MARIPOSA SLIM-HOLE DRILLING

## MP 02 DRILLING




- Slimhole MP-02 was drilled in March-May 2010 on the northern margin of the system, inside the Pellado concession, to convert the exploration lease to an exploitation lease and learn more about the deep resource
- The hole was drilled as an angled core hole and was completed to a true vertical depth of 897 m
- The hole is located several hundred meters from the La Plata fumarole at a relatively low elevation; it therefore has abnormally high near-surface temperatures and produces a small and intermittent amount of steam

# MARIPOSA SLIM-HOLE DRILLING

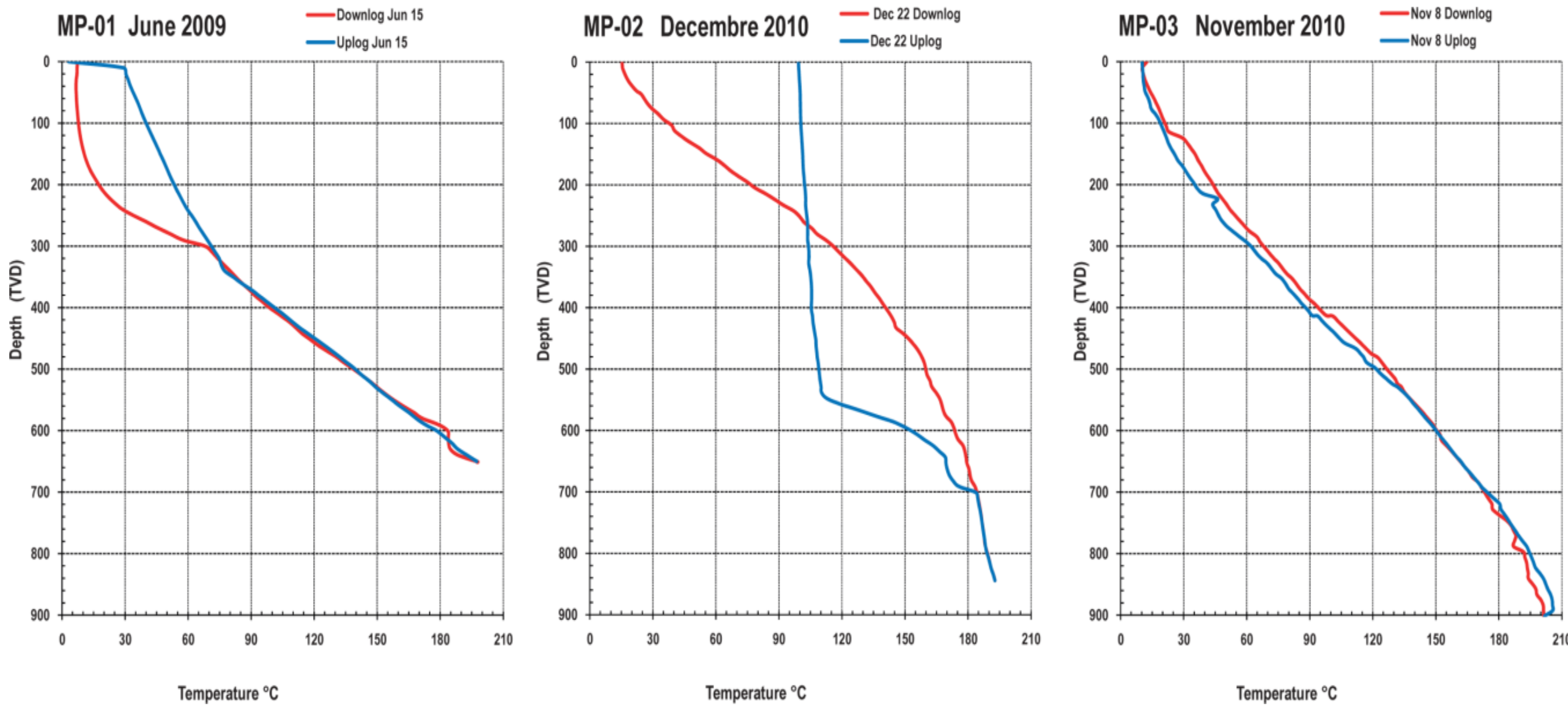
## MP 03 DRILLING

- MP-03 was drilled over the winter between June and October 2010
- It was drilled as an angled core hole to a true vertical depth of 911m
- Multiple fluid loss zones were encountered during drilling and it has the highest bottomhole temperature yet measure at Maule of 205ºC

- Extensive zones of vugs lined with bladed calcite, euhedral quartz, and disseminated epidote crystals in the matrix are present in the bottom section of MP03 indicating the an active geothermal reservoir is present below the clay cap recognized in the MT survey

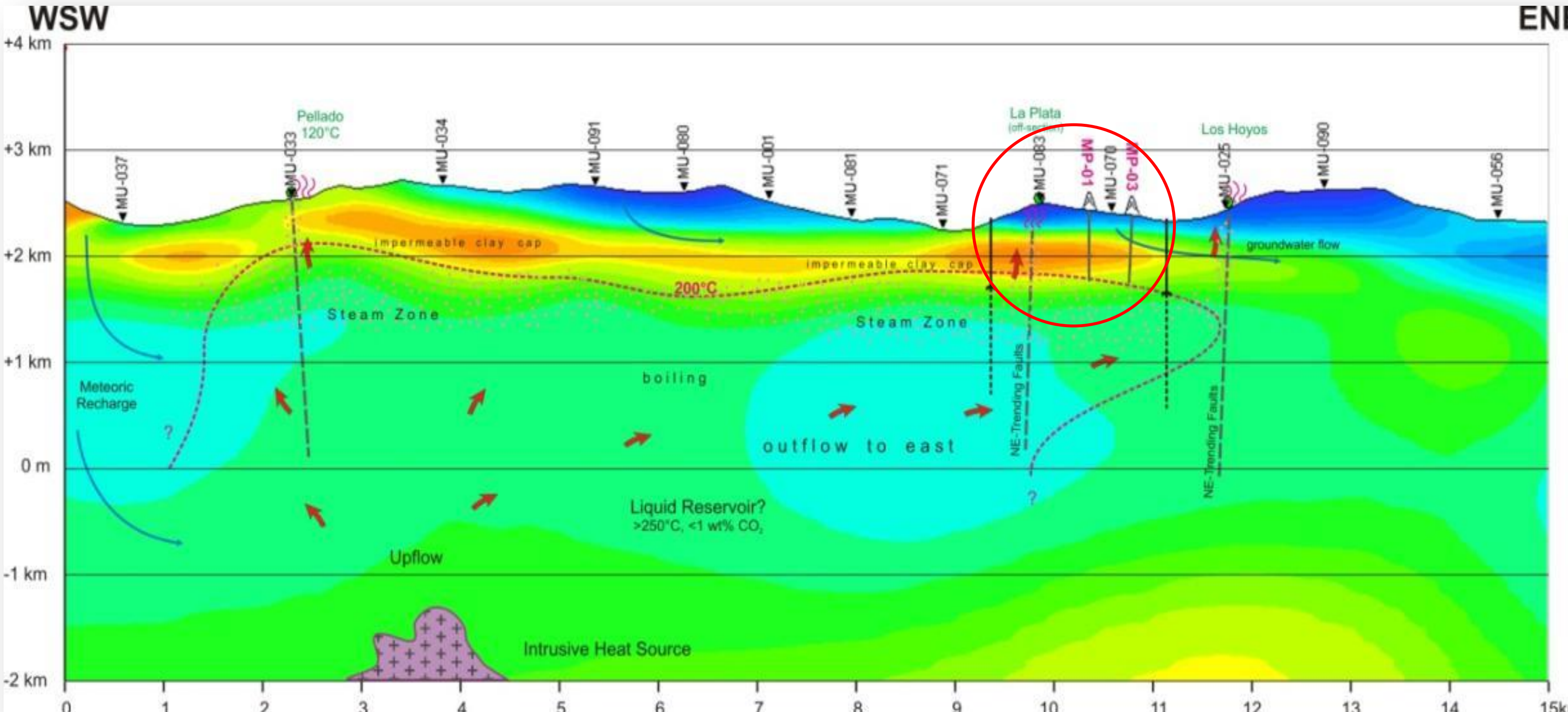
# MARIPOSA SLIM-HOLE DRILLING

## TEMPERATURE AND PRESSURE PROFILES




- Bottom hole temperatures reached as high as 205.6ºC (commercially viable resource is > 170ºC
- Wells penetrated through the clay cap (verifying conductive MT) and into the top of the reservoir
- Multiple fluid loss zones were encountered during drilling.

## MT CONCEPTUAL MODEL




- Two heat sources inferred from gas geochemistry, but the east side could be an outflow from the western side
- The western lobe is inferred to be hotter, with a higher steam content than the eastern lobe
- The geologic evidences would support a younger heat source close to the most recent volcanism (San Pedro volcano)
- Gas geothermometry suggests temperatures could be as high as 290ºC, but more likely in the 240ºC – 250ºC range



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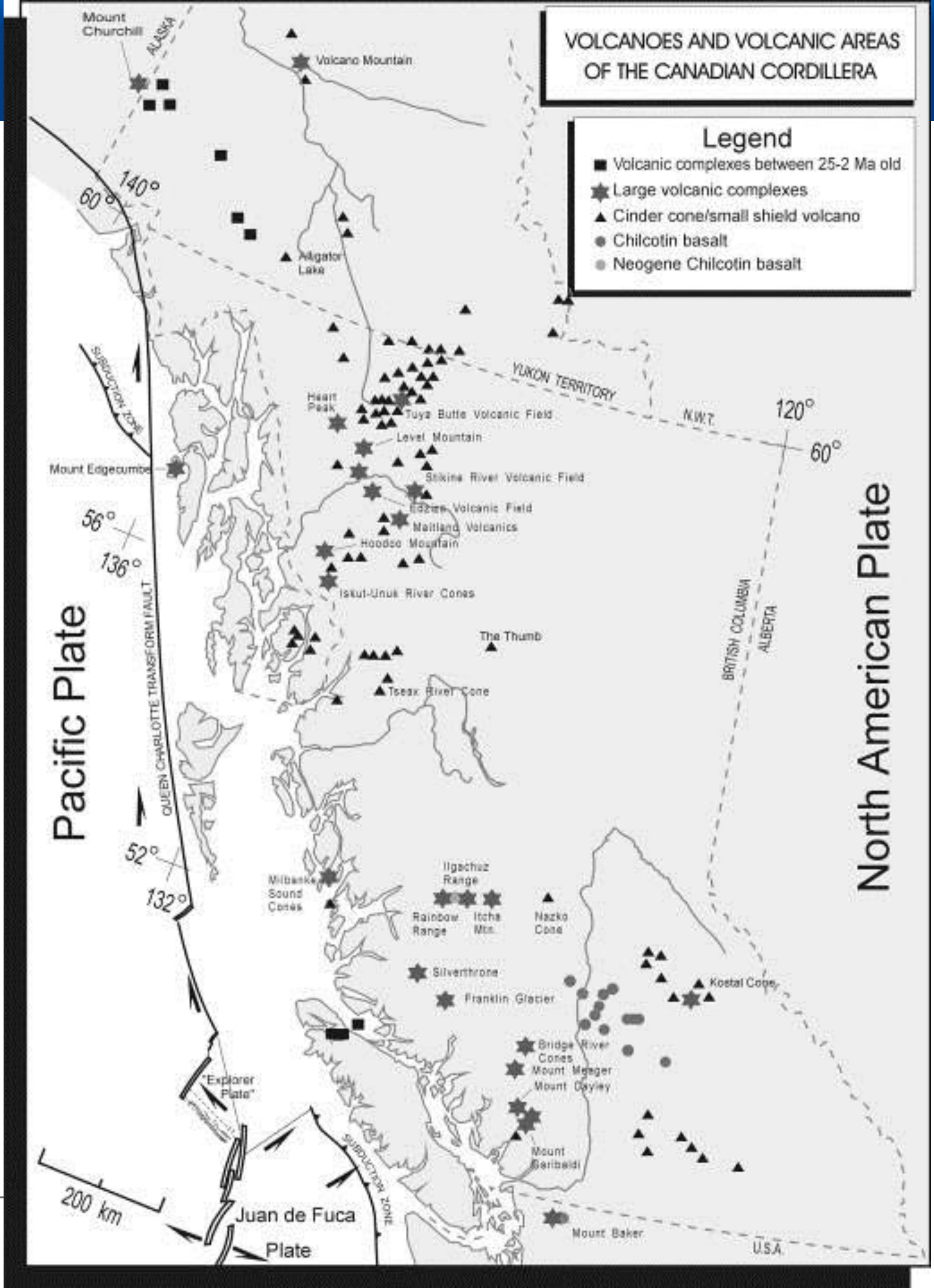
# GEOTHERMAL IN CANADA

## WHERE'S THE BEEF?

January 30, 2014

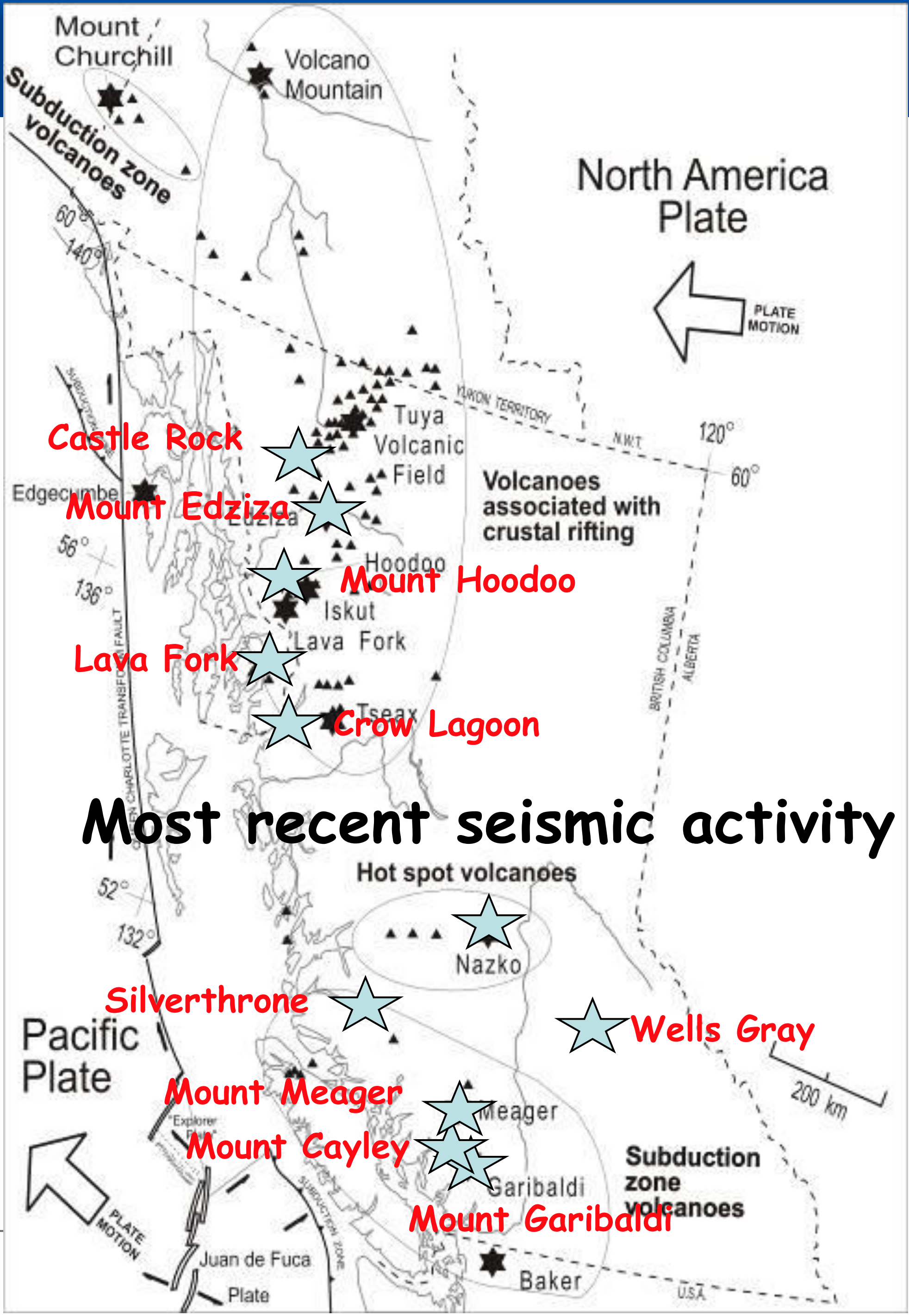
## Canadian Volcanic Regions

Over 200 volcanic centres exist in British Columbia and Yukon that have been active in the last two million years.

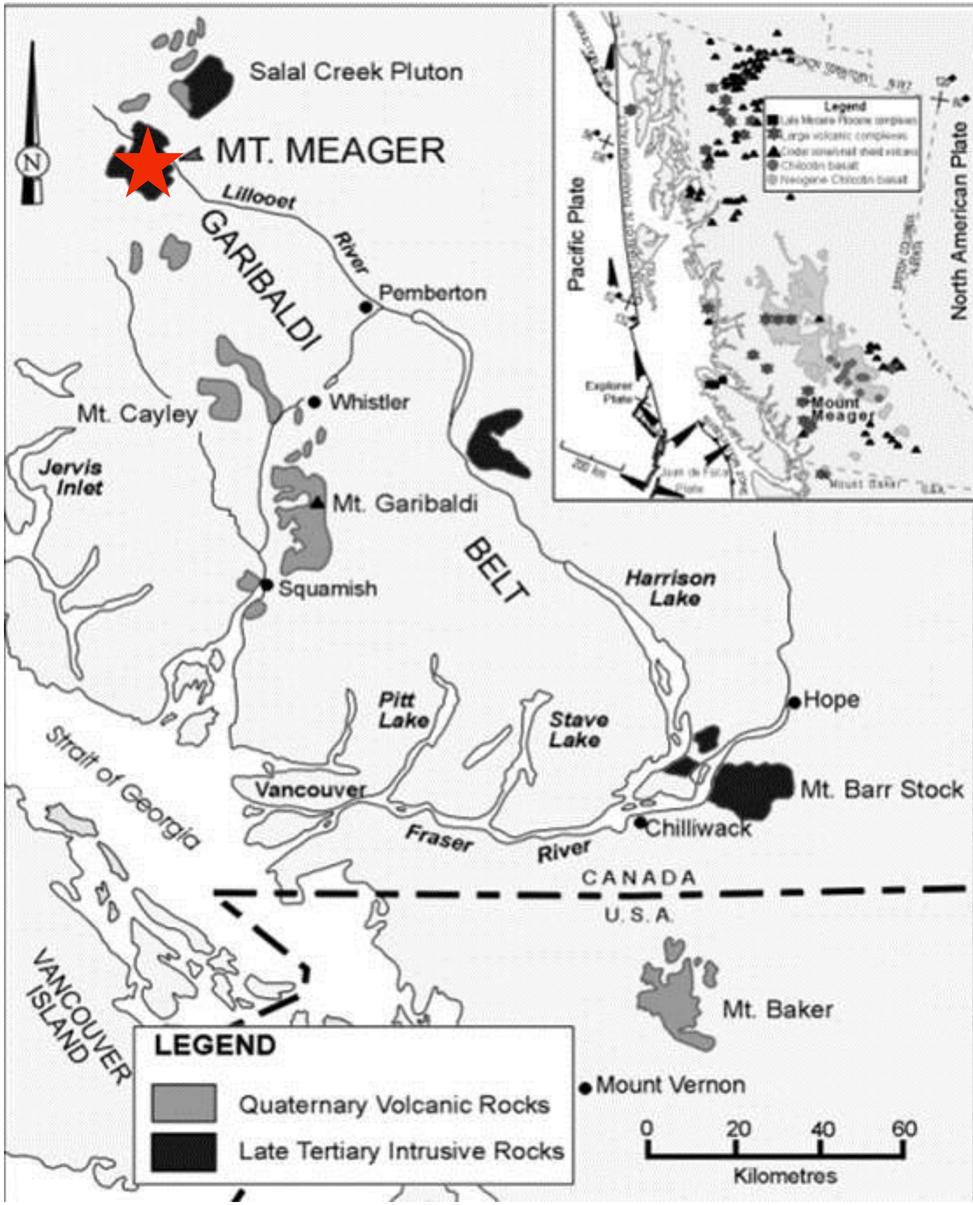


# CANADIAN VOLCANOES

- Castle Rock
- Mt. Edziza
- Mt. Hoodoo
- Lava Fork
- Crow Lagoon (basaltic field)
- Wells Gray – Clearwater (basaltic field)
- Silverthrone
- Mt. Meager
- Mt. Cayley
- Mt. Garibaldi



# CANADIAN VOLCANIC REGIONS

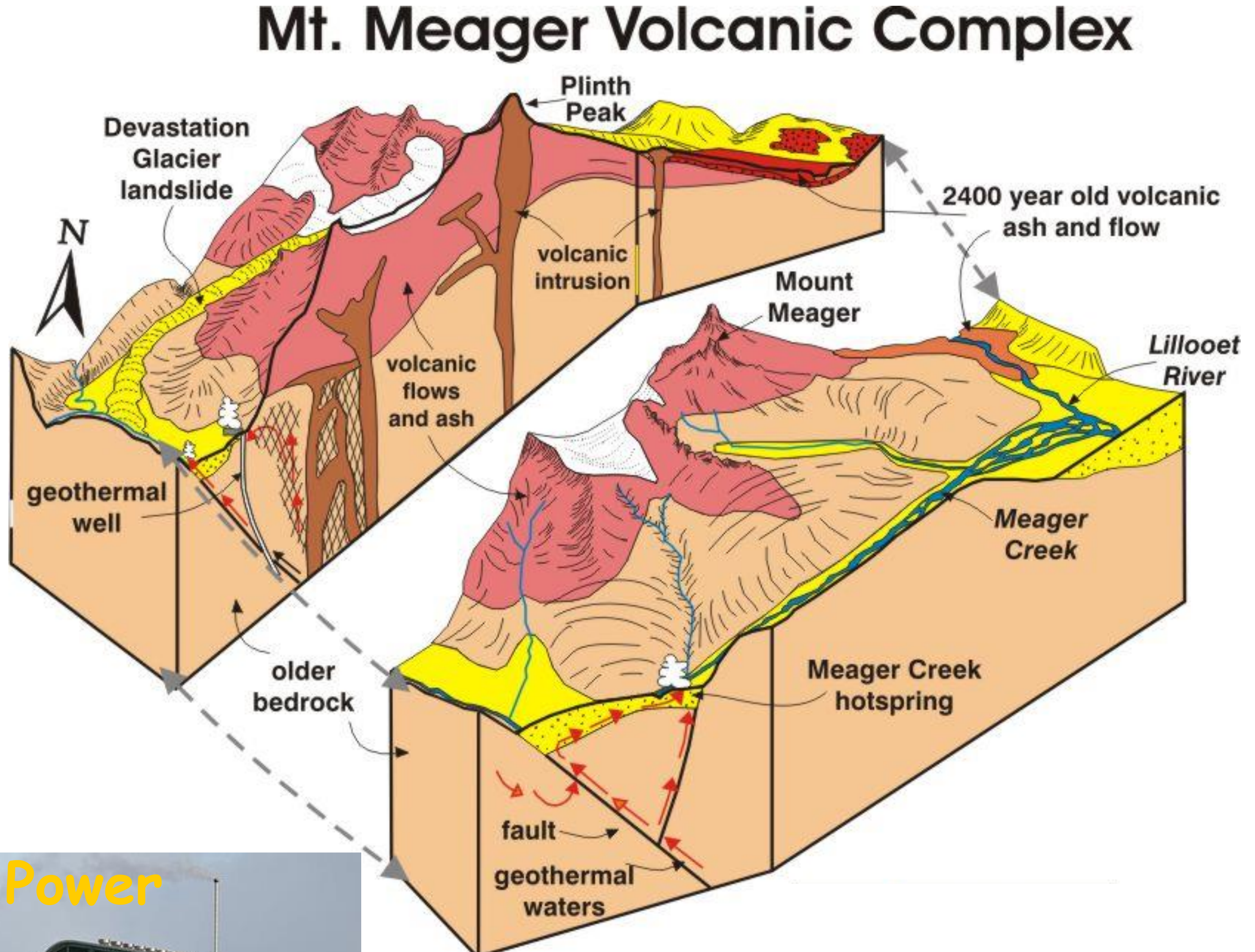



- 150 km north of Vancouver is the youngest of four overlapping stratovolcanoes. Recent volcanic activity started 2350 years ago from a vent on the northeast side of the mountain and consisted of a massive, dacitic, Plinian eruption.

Mt. Meager and Falls Creek, a nearby waterfall that cuts through the dacite columns formed by the lava.

# CANADIAN VOLCANIC REGIONS

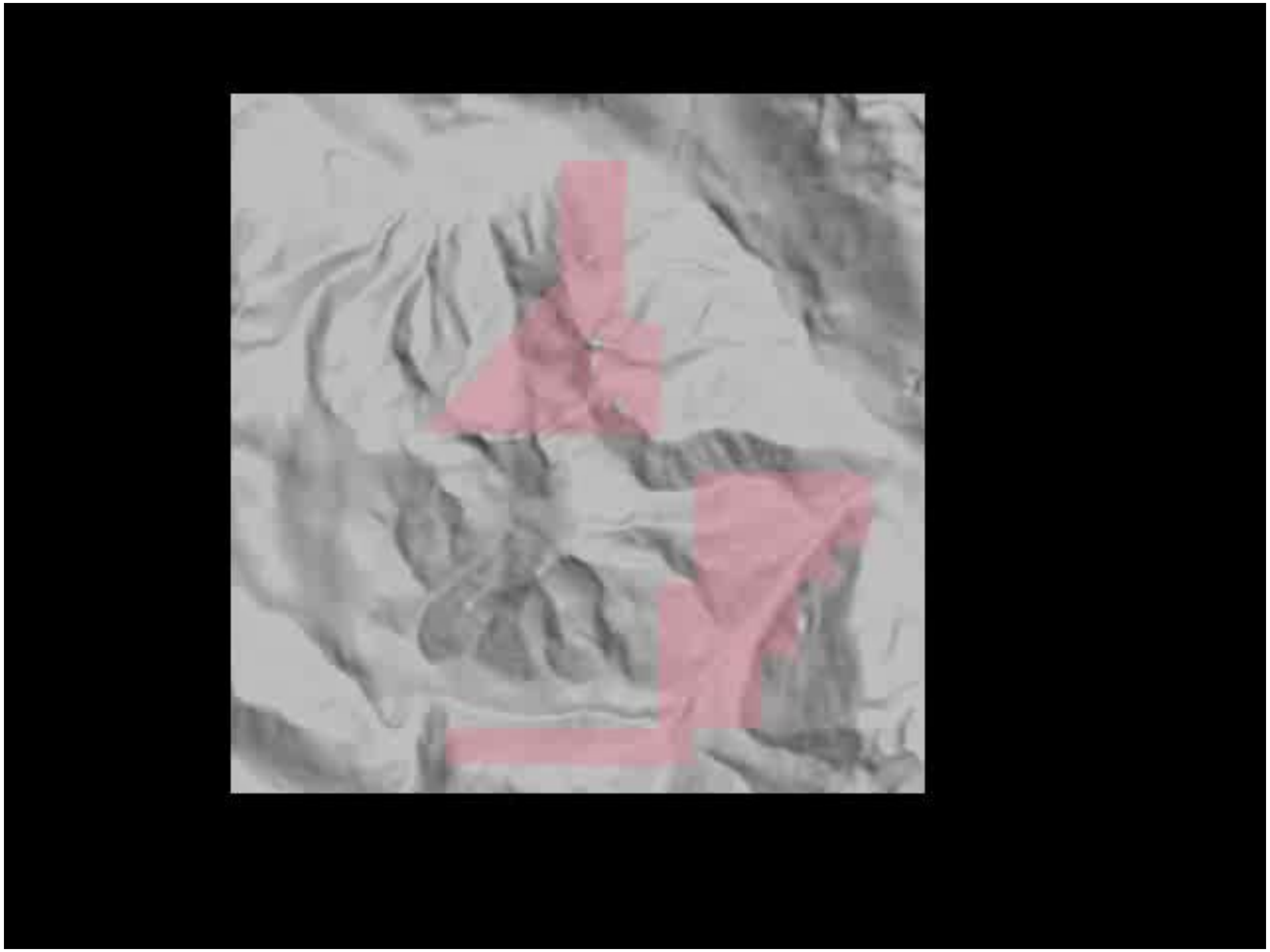
- The first geothermal power generated in Canada
- 5 production sized wells drilled.




# MEAGER 3D LEAPFROG CONCEPTUAL MODEL

**BC EXPLORATION TEAM**

- Ron Yehia
- Dr. Nathalie Vigouroux (Post Doc - Industry)
- Dick Benoit
- Dr. Peter Read
- Dr. Glenn Woodsworth
- Yuliana Proenza (MSc)
- Scott McTavish (student)



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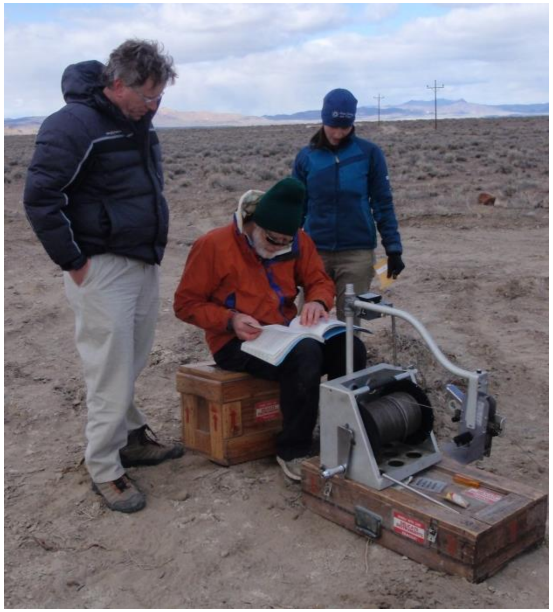
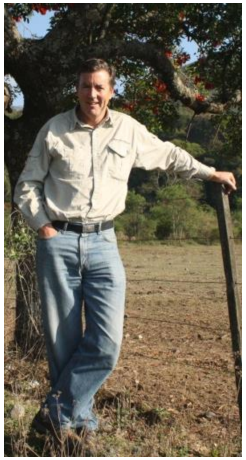
# EXPLORATION IN PRACTICE

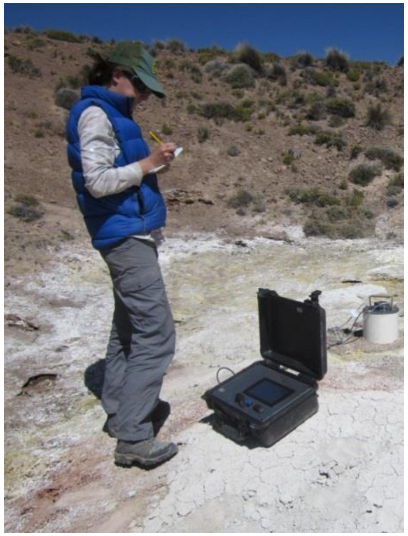
## GREENFIELD & INNOVATION

January 30, 2014

# IT TAKES TEAM WORK!







# GEOCHEMICAL FIELD TECHNIQUES: INNOVATIONS

## MULTIGAS: NSERC INDUSTRIAL PARTNERSHIP GRANT


- **INSTRUMENTATION ADVANCES**
  - GAS ANALYSIS ARE SLOW AND EXPENSIVE
  - FEW LABS PRODUCE HIGH QUALITY RESULTS SO NEED TO SHIP SAMPLES LONG DISTANCES (DANGEROUS GOODS)
- **RESEARCH WAS TO DEVELOP A FAST, FIELD FRIENDLY INSTRUMENT TO ASSIST EXPLORATION**
- **PUBLICATION IN PRESS**

# GEOCHEMICAL FIELD TECHNIQUES: INNOVATIONS

## USE OF A PORTABLE PHOTOMETER FOR ACCELERATED EXPLORATION: TESTING FOR GEOTHERMAL INDICATORS IN SURFACE WATERS



Set-up and equipment needed for Photometer analysis in the field. The Palintest Photometer 8000 is the blue and white device at the bottom right of the picture.

### NEW USE OF EXISTING TECHNOLOGY

- COVERING VERY LARGE AREAS
- REDUCE COSTS OF LABORATORY BASED ANALYSIS
- REAL TIME ANALYSIS SO FIELD PROGRAM CAN BE OPTIMIZED 'ON THE FLY'

### IN-HOUSE RESEARCH TO FIND A FASTER, CHEAPER WAY TO COVER LARGE TERRITORY RAPIDLY AND EFFICIENTLY (I.E. BRITISH COLUMBIA)

# EXPLORATION GEOCHEMISTRY INITIATIVE: THE FUTURE

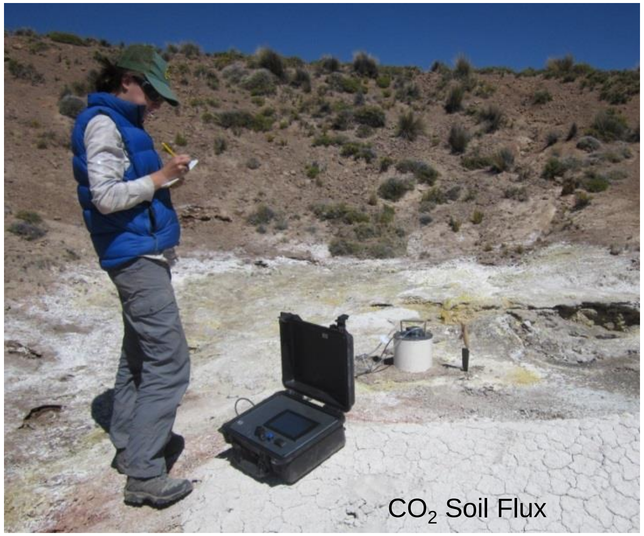
## NEW TECHNOLOGIES

- **MINIATURIZATION OF SENSORS, CONTROLS AND ELECTRONICS**
  - MINI MASS SPECS AND OTHER SENSORS
  - SMALL ENOUGH TO MOUNT ON DRONES AND REMOTE VEHICLES
- **ULTRASENSITIVTY OF NEW INSTRUMENTS**
- **REMOTE CONTROLLED VEHICLES**
- **HIGH POWERED COMPUTING**
- **ADVANCED SOFTWARE FOR 3D ANALYSIS**
- **NEW AND MORE SENSITIVE SATELLITES**
- **HYPERSPECTRAL IMAGING**



Low slow flight


multigas


$CO_2$ Soil Flux



mineralsed
Mineral Resources Education Program of BC

# Thank you!