PS The Triangle Zone of the Argentine Precordillera: Insights From the Integration of Geological and Geophysical Data*

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Abstract

This paper reports the results of the combination of multiple geological and geophysical exploration techniques in both pre-drill and post-drill exploration stages. Detailed geological mapping and regional gravimetric and magnetoteluric surveys have been integrated with existing poor quality seismic data in order to search for buried traps at the northern triangle zone of the Argentine Precordillera. The model was tested by a 10,000 feet study well whose lithological and structural data helped to calibrate the pre-drill interpretation. Outcropping foreland basin deposits delineates a NNE- oriented upright fold located at the downthrown block of a major east-verging thrust sheet. The fold has a fault near its crest and is dissected by a NE-SW trending left-lateral strike-slip fault. Near the edge of the triangle zone, high dipping beds of conglomerates are related to a series of NNW- striking backthrusts. The Bouguer anomaly map shows a clear tectonic boundary between basement-involved structures to the east and a lower density sedimentary fill of variable thickness to the west. Roughly E-W and N-S oriented magnetoteluric sections allowed the recognition of lateral variations on the resistivity response of the sedimentary cover that can be related to reverse fault juxtaposition. A deep high resistivity zone delineates a positive feature with a NW-SE strike that could be related to a west-verging fault-related fold. The analysis of the well path deviation, drilled lithology and beds and fractures orientation from image logs allowed the recognition of structural domains, fault zones and stratigraphic repetitions. Those features were successfully correlated with the outcropping geology resulting in a better understanding of the subsurface structural geometry. Post-drill data acquisition and reprocessing along a key magnetoteluric section improved the resolution of the model and recognized lateral variations that can be related to opposing vergence structures. The integration of surface and subsurface data helped to reduce the model uncertainty and provided methodological insights for future exploration at the triangle zone of the Argentine Precordillera and other fold and thrust belts.

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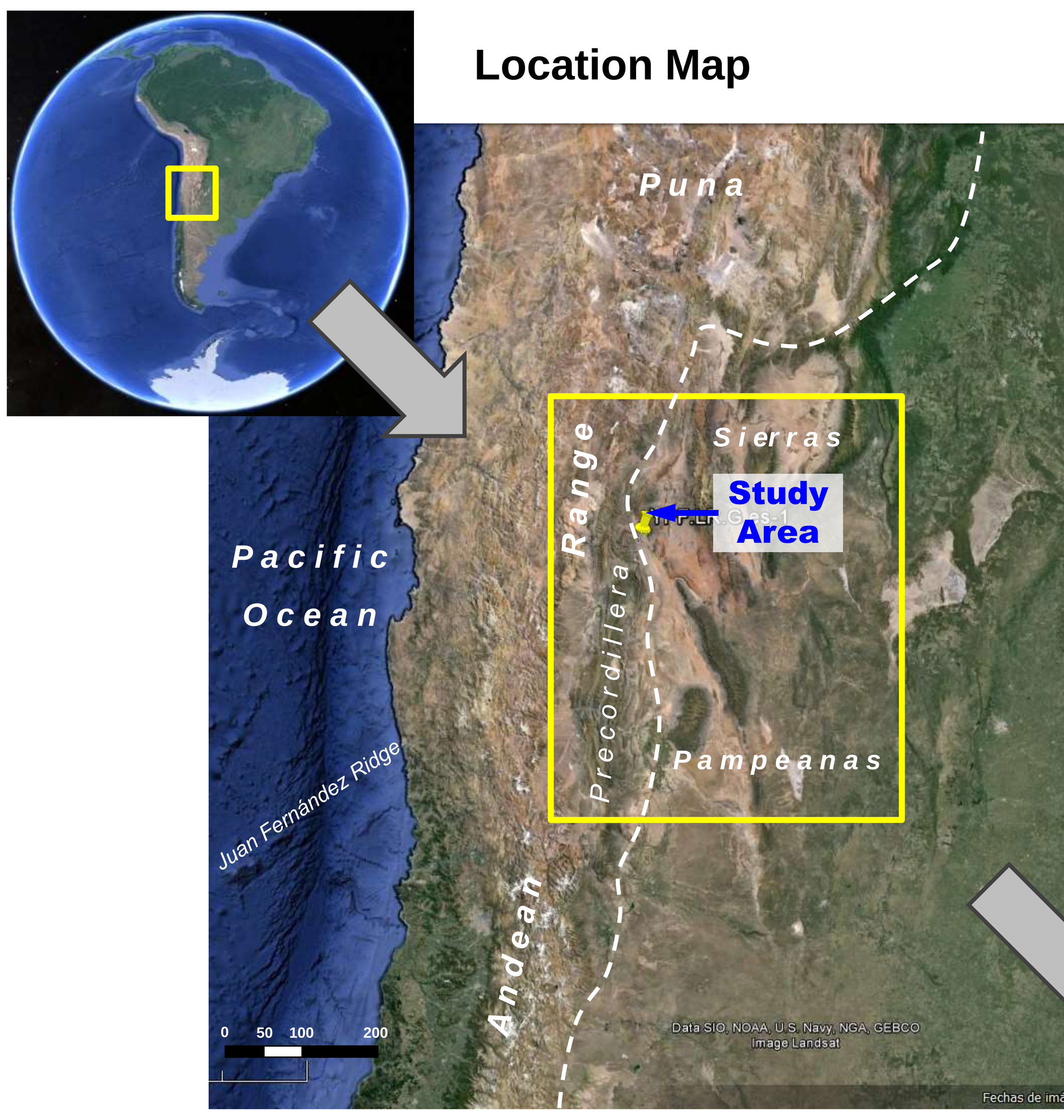
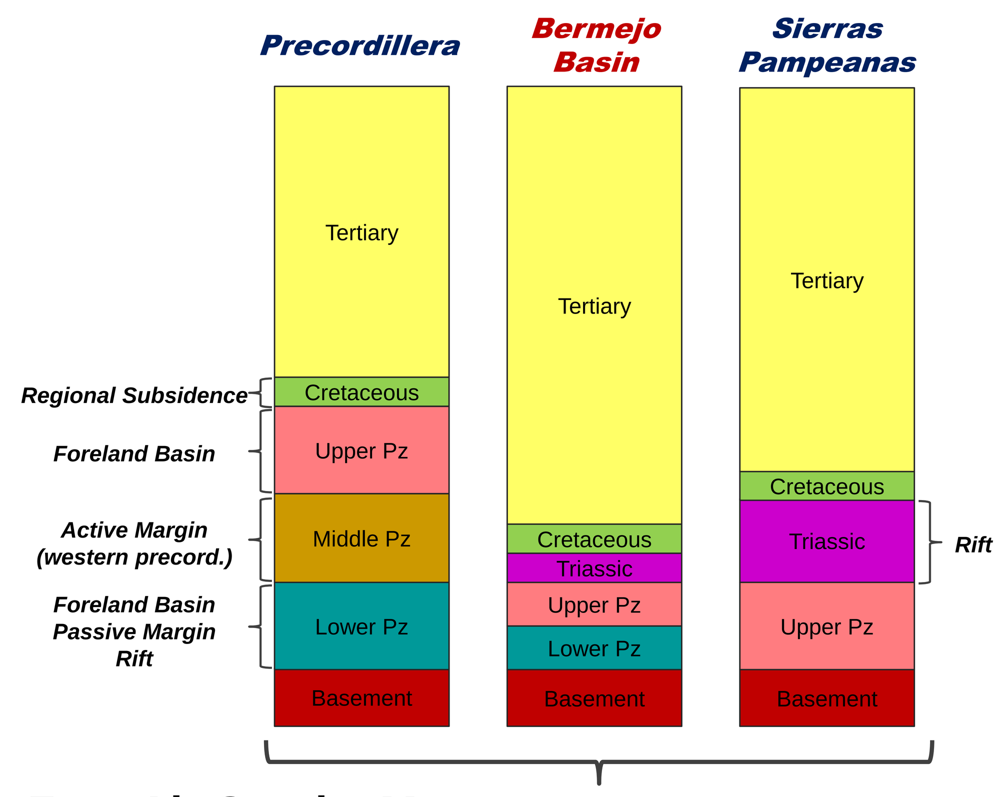
1) INTRODUCTION

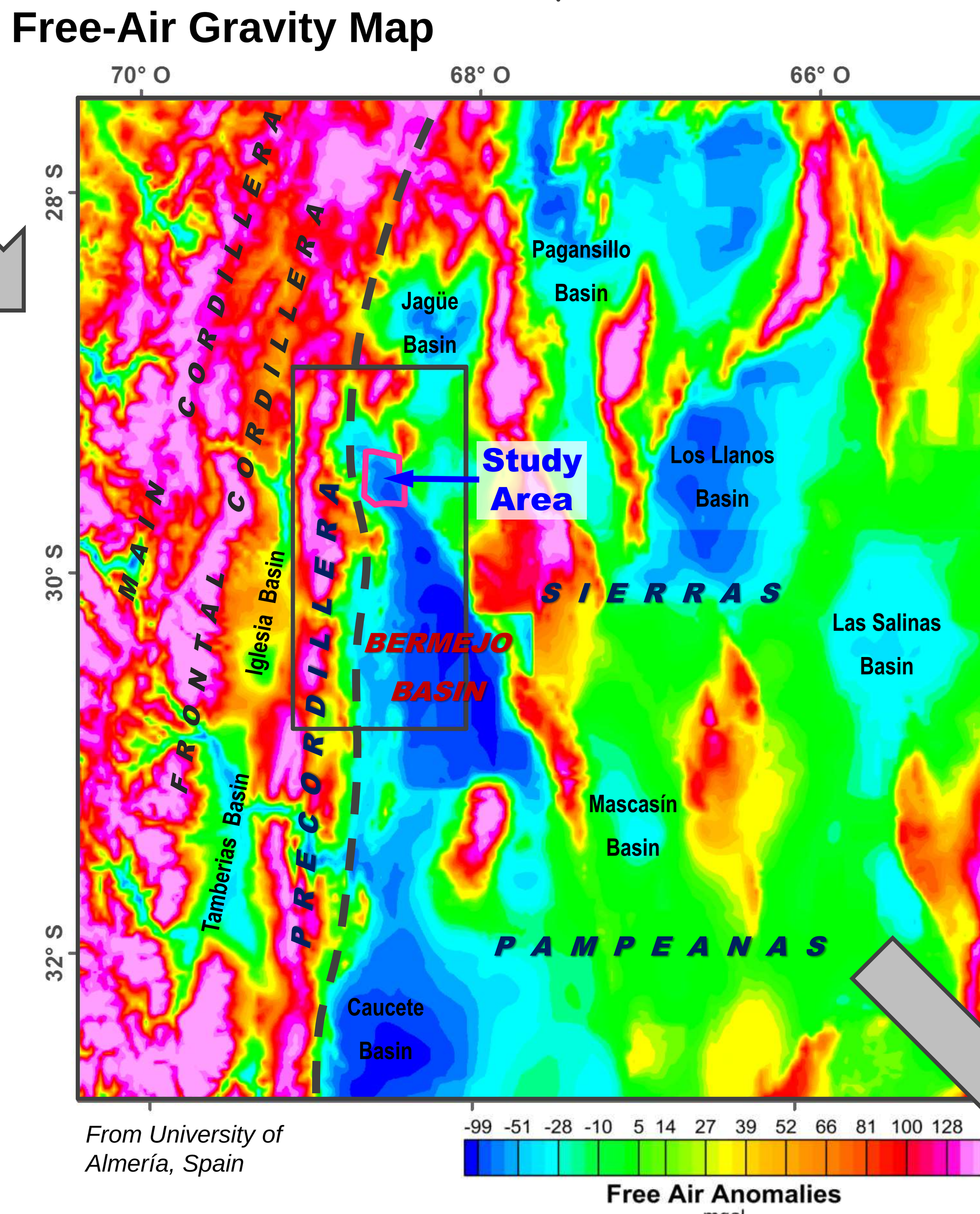
Location Map



Schematic Stratigraphic Columns



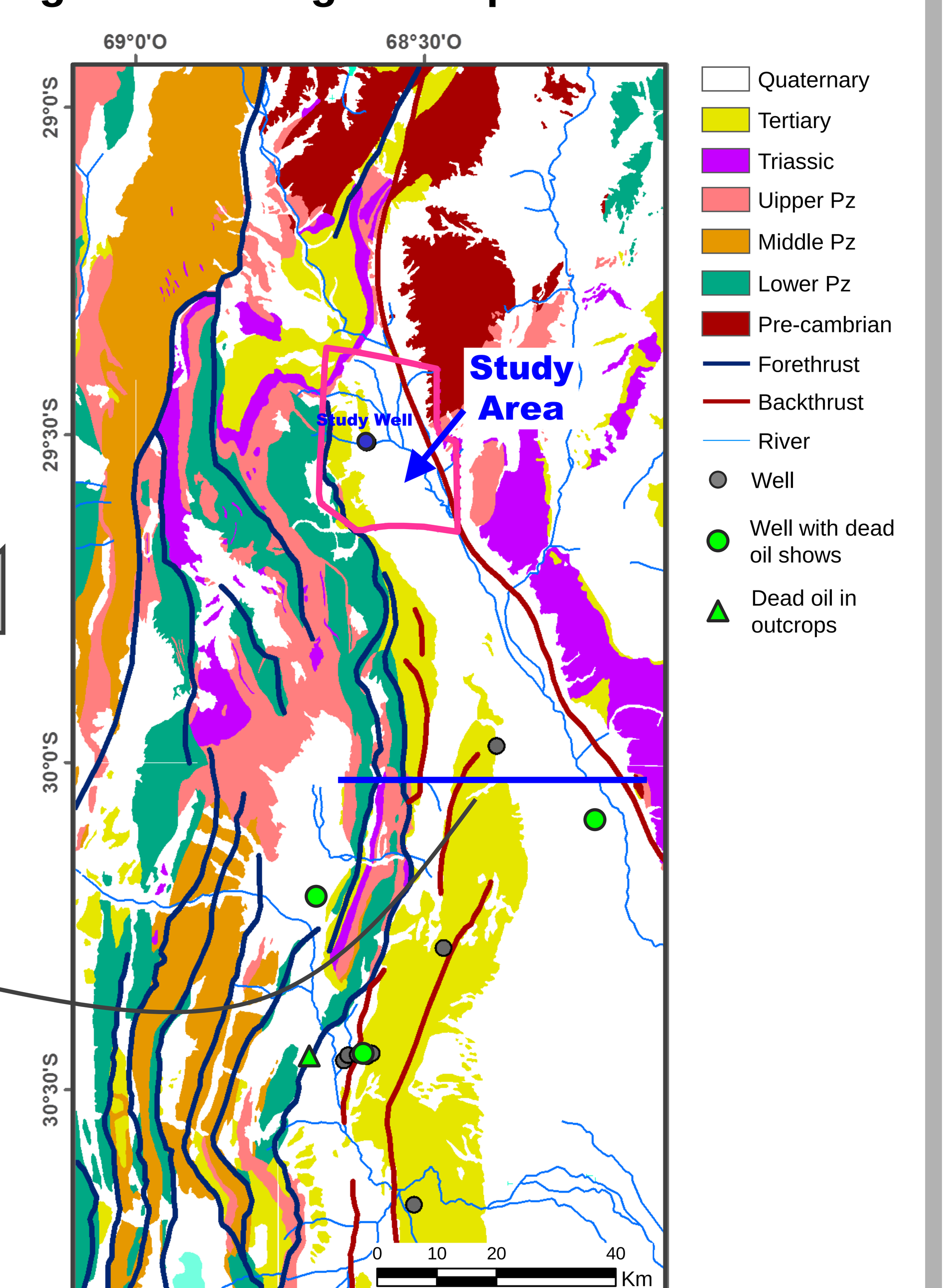
Free-Air Gravity Map



HYDROCARBON EXPLORATION

- The tertiary Bermejo basin and related paleozoic sedimentary sequences of the Precordillera have been drilled by 14 wells ranging from 500 to nearly 6000 meters of total depth. None of them reached the crystalline basement but some oil shows have been recorded on both tertiary and paleozoic rocks.
- The basin has 2334 km of regular to bad quality 2D seismic data and a number of gravimetric, magnetometric and magnetotelluric surveys of varying extent and resolution.
- No petroleum system has been proven to date but potential source rocks have been detected on outcrops of lower paleozoic marine shales (0,3 to 5%TOC and highly mature) and in upper paleozoic marine and lacustrine shales (less than 0,5% TOC).
- Potential reservoir facies includes lower paleozoic marine dolomites and fractured limestones, upper paleozoic marine and glaci-marine sandstones, and eolian and fluvial tertiary sandstones.

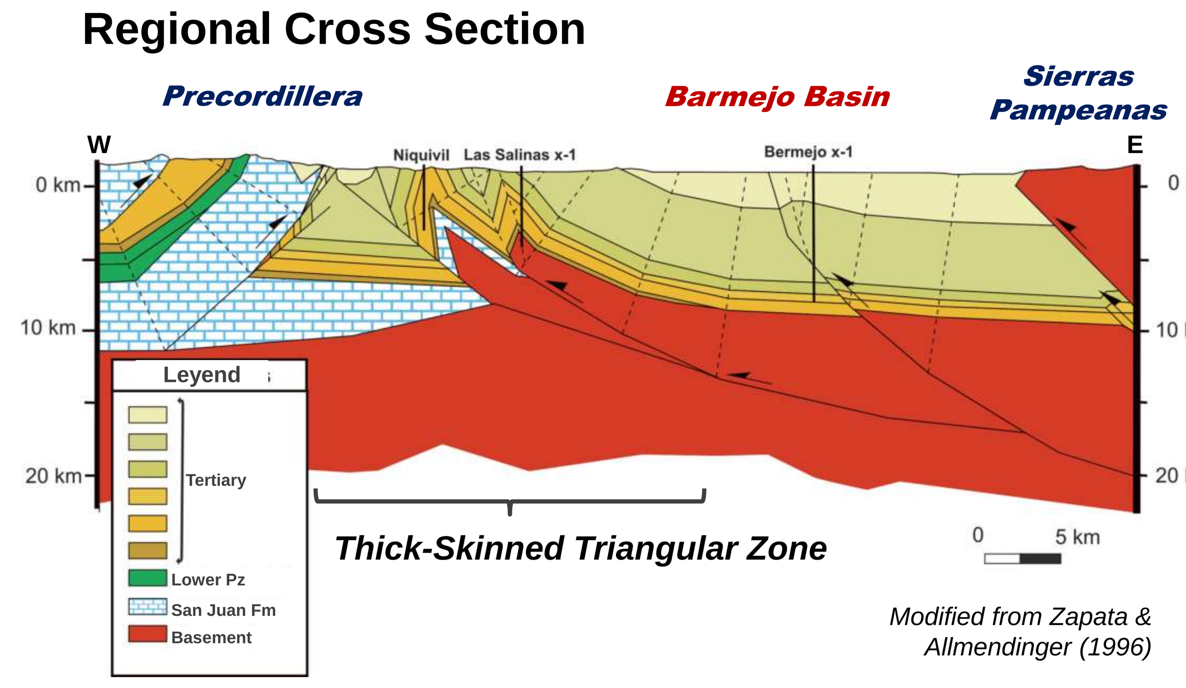
Regional Geological Map



LOCATION AND REGIONAL SETTING

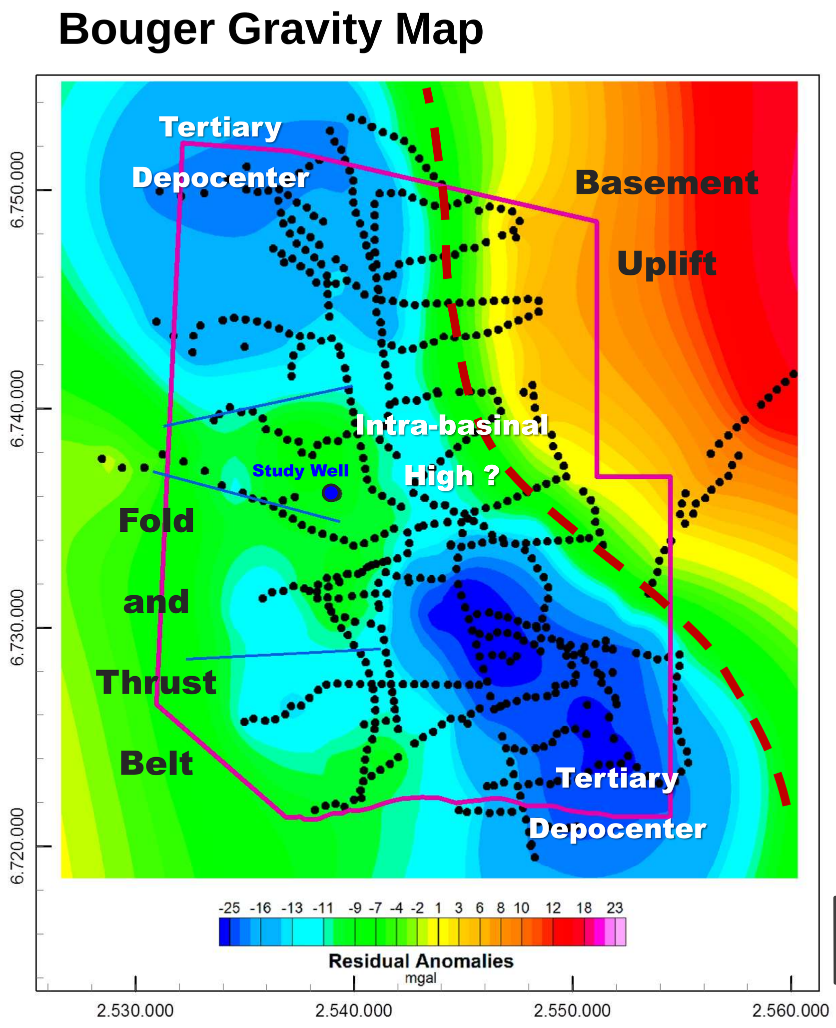
- The region under analysis is located in west-central Argentina where several tertiary Inter-mountain sedimentary basins are preserved in the downthrown block of Andean thrusts developed in the context of a broken foreland basin.
- From a morphological point of view, the study area belongs to the external part of the Argentina Precordillera and is bounded to the east by the Sierras Pampeanas ranges.
- The tertiary fill is part of the Bermejo basin and lies above a substratum made of Mesozoic and/or Paleozoic sedimentary units of variable thickness and areal distribution. The crystalline basement is composed of Precambrian metamorphic and igneous rocks.
- The structural style is a combination of east-verging thrust sheets detached on the sedimentary cover and west-directed basement blocks related to the reactivation of a preexistent structural fabric. The conjunction of both systems defines a thick-skinned triangular zone (Zapata and Allmendinger 1996).

Regional Cross Section



2) GRAVITY & SEISMIC SURVEYS

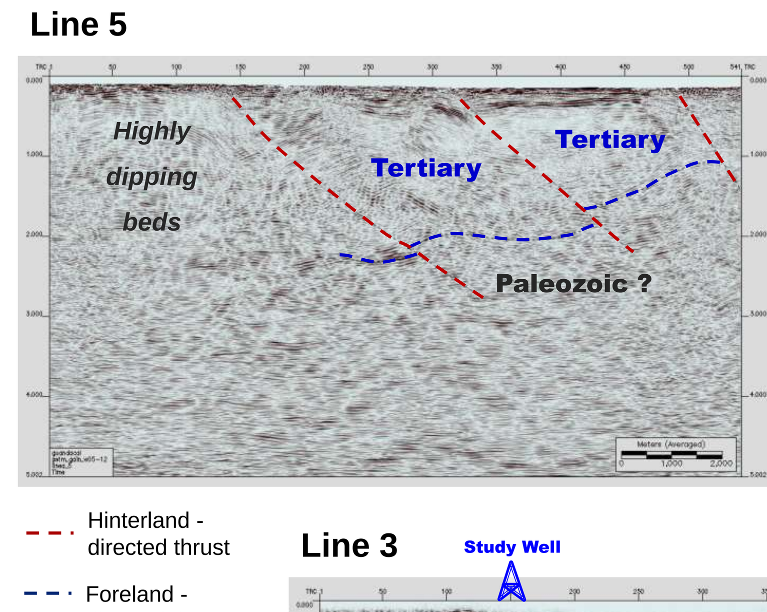
Bouger Gravity Map



SEISMIC SURVEY:

- 12 lines (220 km).
- Sources: vibroseis (4 elements linear array).
- Receivers: linear array, 12 elements.
- Shot points every 50 m.
- Receiver points every 50 m.

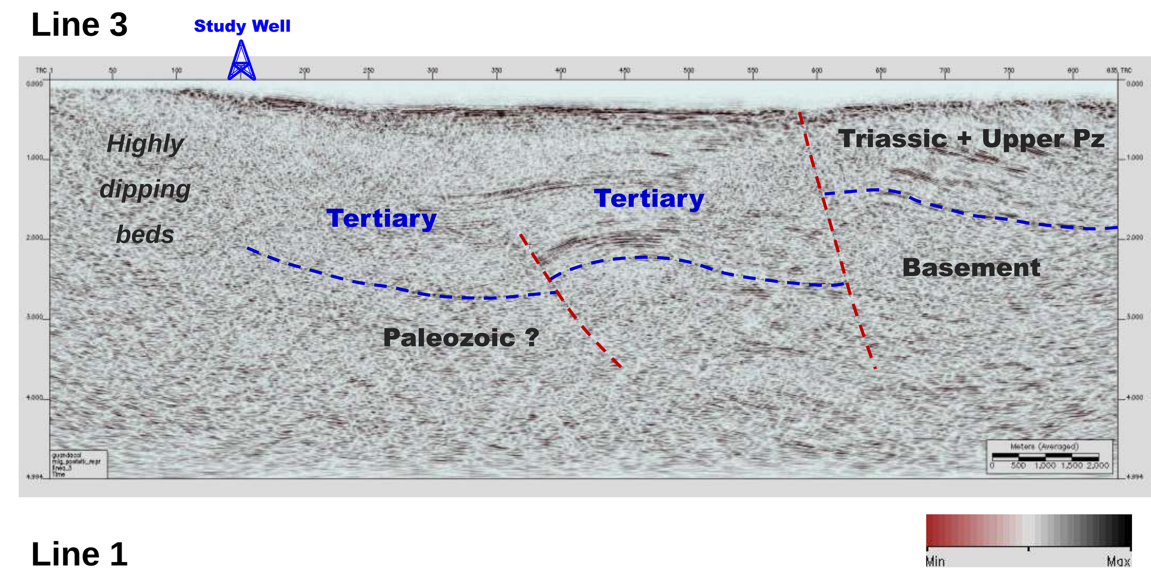
Line 5



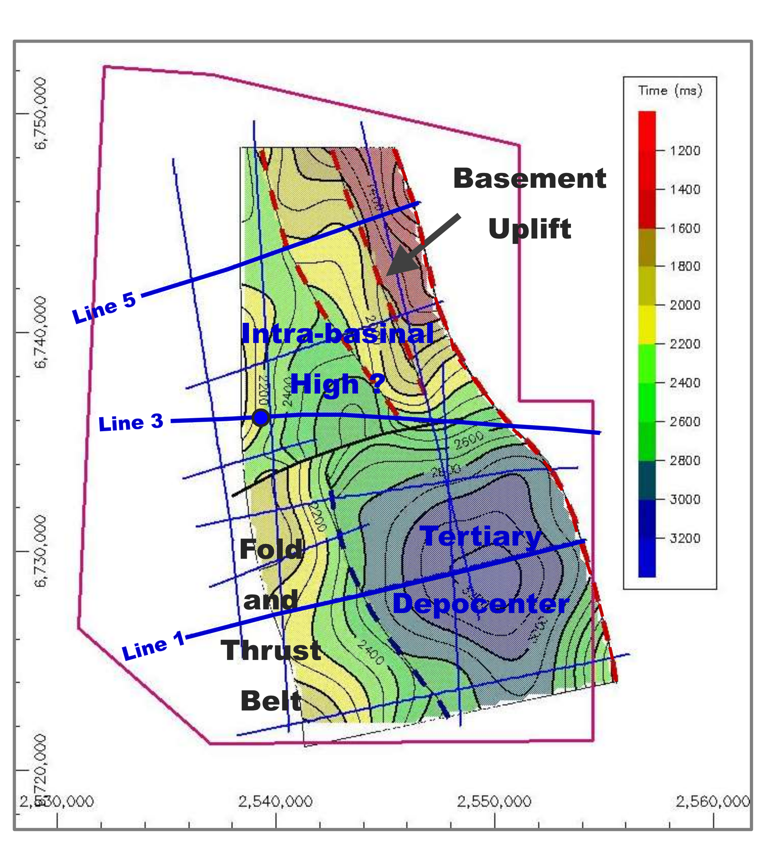
REMARKS:

- The Bouguer gravity map delineates the tectonic boundary between basement-involved structures to the east and a lower density sedimentary fill to the west.
- The structural geometry of the poorly defined base Tertiary seismic horizon broadly agrees with the Bouguer anomaly map.

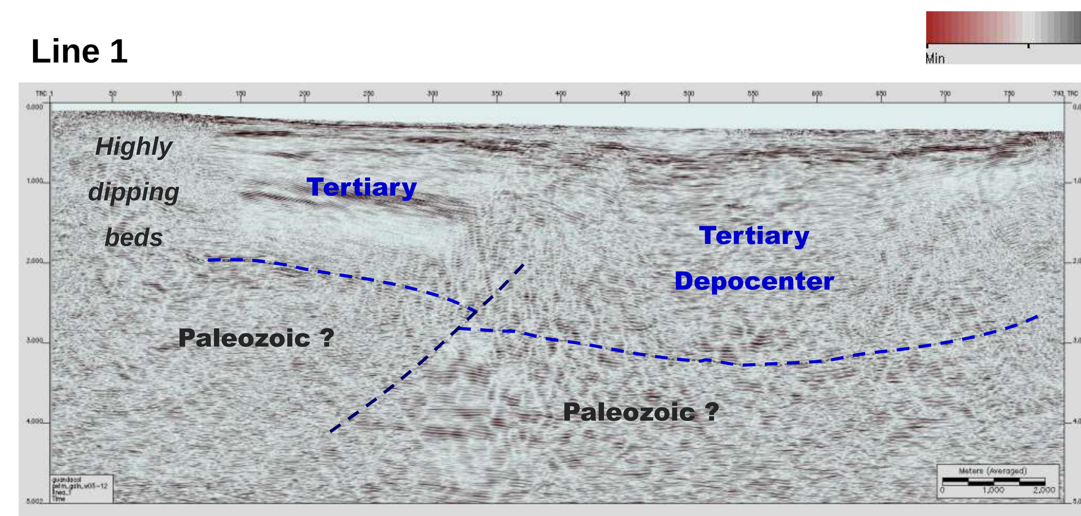
Line 3



Base Tertiary Time Structural Map



Line 1



BASIC PROCESSING SEQUENCE:

1. Change of format.
2. Geometry construction.
3. Noise attenuation.
4. Amplitude compensation.
5. Deconvolution.
6. Noise attenuation.
7. Refraction static correction.
8. Velocity picking.
9. Residual statics.
10. Velocity picking.
11. Amplitude compensation.
12. Stack.
13. Poststack filter and gain.
14. Migration velocity.
15. Poststack migration.
16. Poststack filter and gain.

GRAVIMETRIC SURVEY:

- 1450 land stations (precision: 0,5 mgal; spacing: 500 meters).
- Terrain correction calculated with SRTM90 (values from 0.3 up to 6 mgal).
- Free-air and complete Bouguer anomalies computed with new standards.

Reflection seismic data with low signal to noise ratio due to bad coupling of seismic sources to the terrain, high attenuation and scattering in weathering layer, and steep dips of geological structures.

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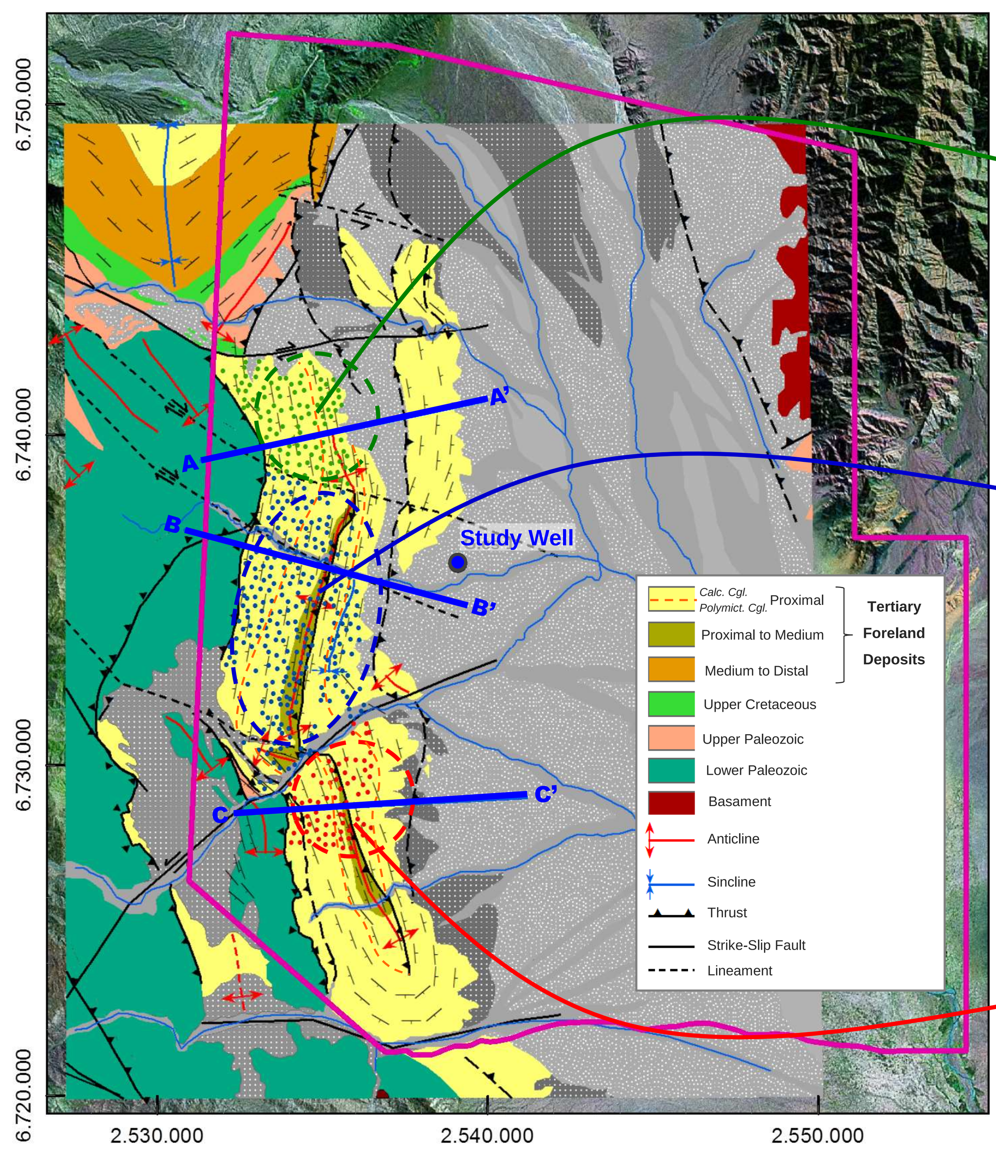
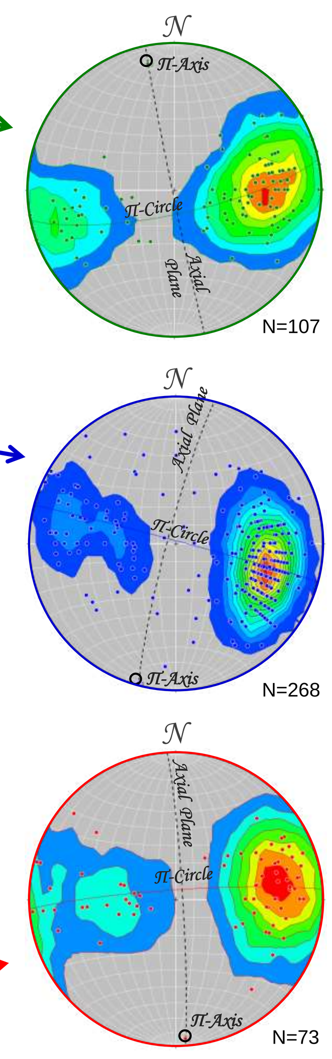
3) SURFACE GEOLOGY AND GEOCHEMESTRY

Geological Map

Modified from MAPaS (2012)



Stereographic Analysis

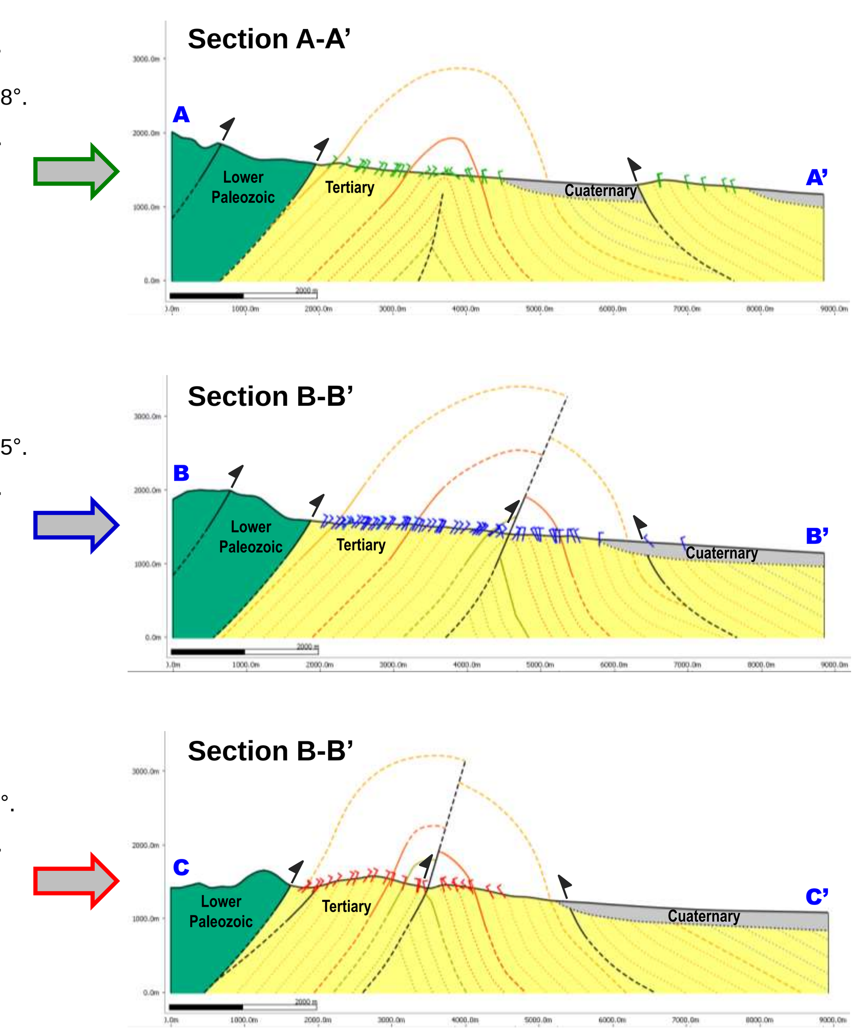


Fold Axis: 14°→348°
Axial Plane: 89°→258°.
Interlimb Angle: 60°.
Description: gently plunging, slightly closed, asymmetric upright fold.

Fold Axis: 1°→195°
Axial Plane: 85°→285°.
Interlimb Angle: 59°.
Description: faulted, non-plunging, slightly closed, asymmetric upright fold.

Fold Axis: 5°→176°
Axial Plane: 87°→87°.
Interlimb Angle: 68°.
Description: faulted, non-plunging, slightly closed, asymmetric upright fold.

Structural Profiles



STRUCTURAL FEATURES:

- **Frontal thrust**: E-verging regional thrust that brought lower paleozoic limestones to the surface.
- **Frontal anticline**: mainly N-S oriented fold, faulted at its core and slightly verging to the east. A geometrically well defined backlimb and a high angle, more diffuse, forelimb suggest an origin related to the propagation of a west-dipping fault at depth. Near the surface, the presence of less competent red beds at the faulted core of the anticline could be indicative of a local detachment component that amplifies the fold and generates a more symmetrical profile.
- **Oblique lineaments**: regional pervasive structural fabric that cut and displace the larger structural trains.

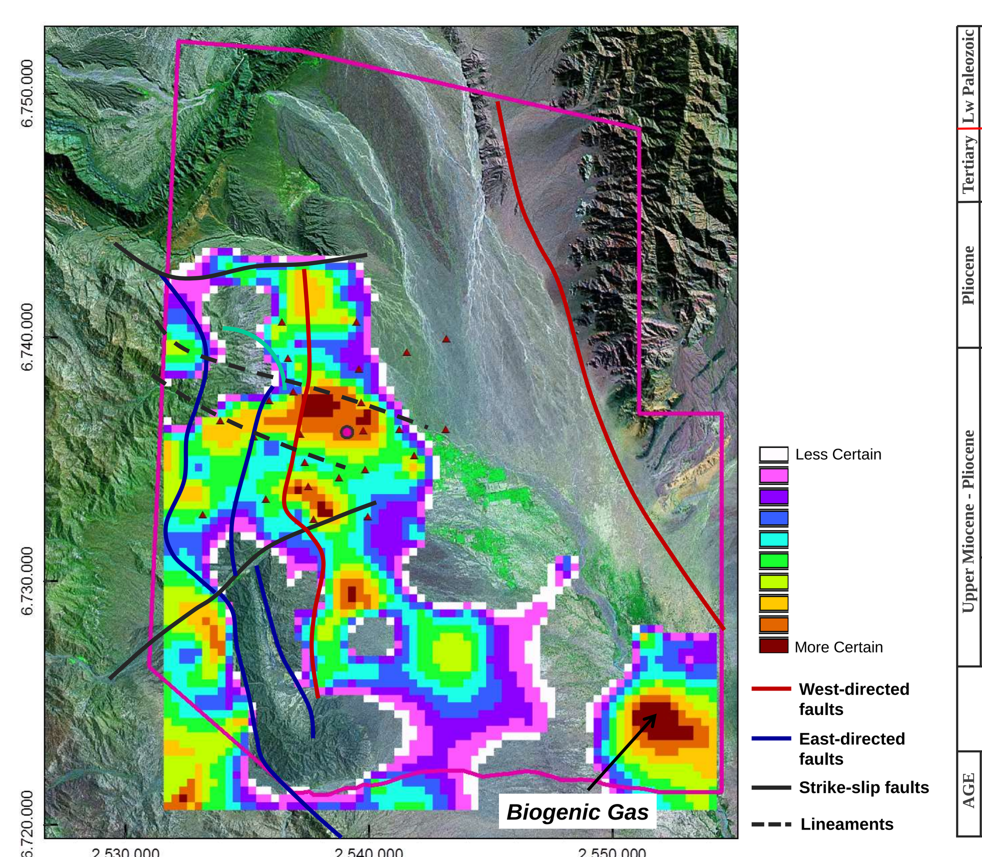
FORELAND BASIN FILL:

- Mainly Neogene continental deposits up to 9 km thick at the main depocenter.
- The clast composition reflects the changes in provenance related to the uplift of the mountain ranges.

SURFACE GEOCHEMESTRY:

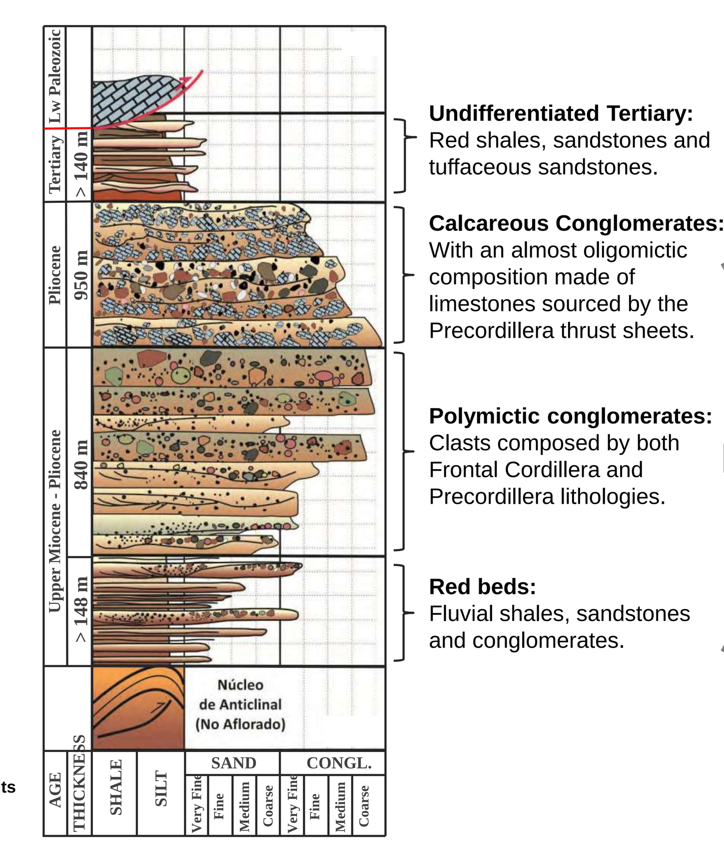
- **Survey**: 413 samples of soil adsorbed gas over a regular 1 km grid.
- **Results**: High methane anomalies are related to migrated dry gas through fault zones.

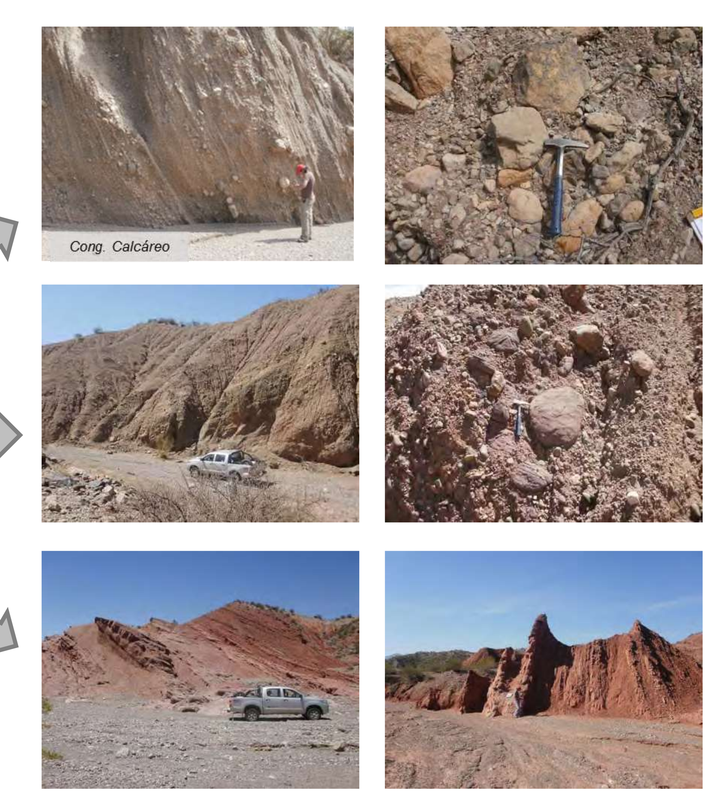
Methane Anomaly Probability Map



Modified from Fasola et al. (2012)

Sedimentological Profile





Modified from MAPaS (2012)

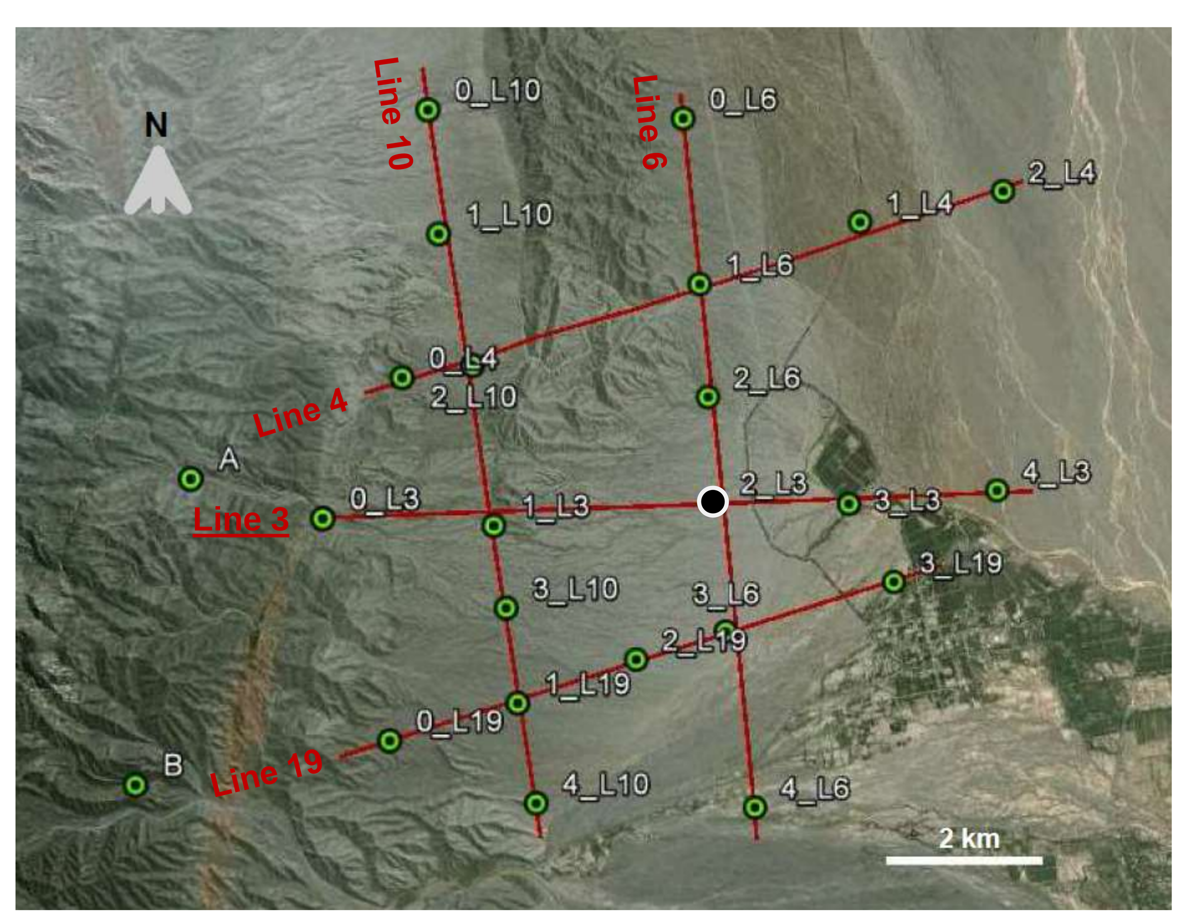
4) PRE-DRILL MT SURVEY

Why MT?

- ✓ Reflection seismic with low signal to noise ratio.
- ✓ Gravity anomalies indicate a possible depocenter.
- ✓ Need of complementary data to delineate structures.

1. FEASIBILITY & DESIGN:

- Target depth and dimensions estimated from complementary data.
- Formation resistivity values obtained from tables of typical values.
- Identification of noise sources.
- Computation of *skin depth* to understand depth of penetration for different frequencies and resistivity models: $SD_m \approx 500\sqrt{\rho_{\Omega m}/f_{Hz}}$



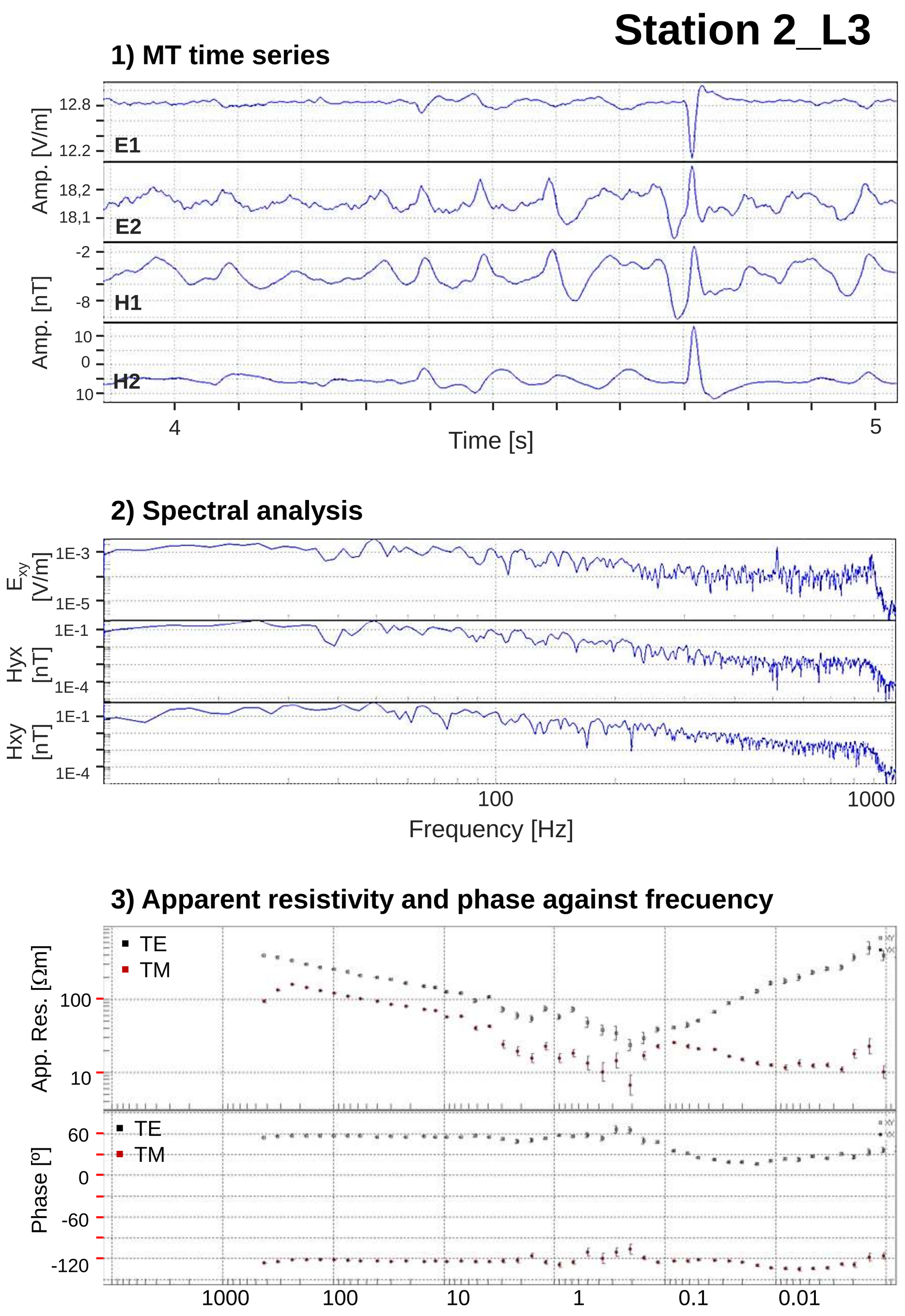
2. ACQUISITION

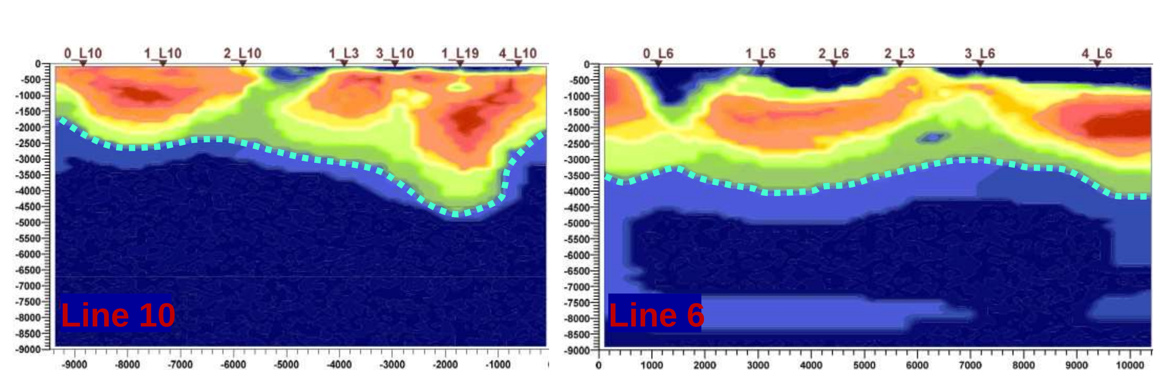
- Hardware: Metronix ADU07e.
- 24 stations and 5 lines overlapping 2D seismic sections.
- 5 channels per station: Ex, Ey, Hx, Hy and Hz (Hz was very noisy and was not processed).
- Station spacing: less than 2 km.
- Target depth: 3 km.
- Registration time: 8 hours.

3. PROCESSING:

1) Edition of temporal series.
2) Spectral analysis of temporal series with Fast Fourier Transform.
3) Computation of apparent resistivity and impedance phase curves with galvanic and static shift corrections.
4) Evaluation of skew, tipper, anisotropy and strike parameters to guide the interpretation.
5) 2D Inversion of apparent resistivity and phase curves of TE and TM modes.

Station 2_L3

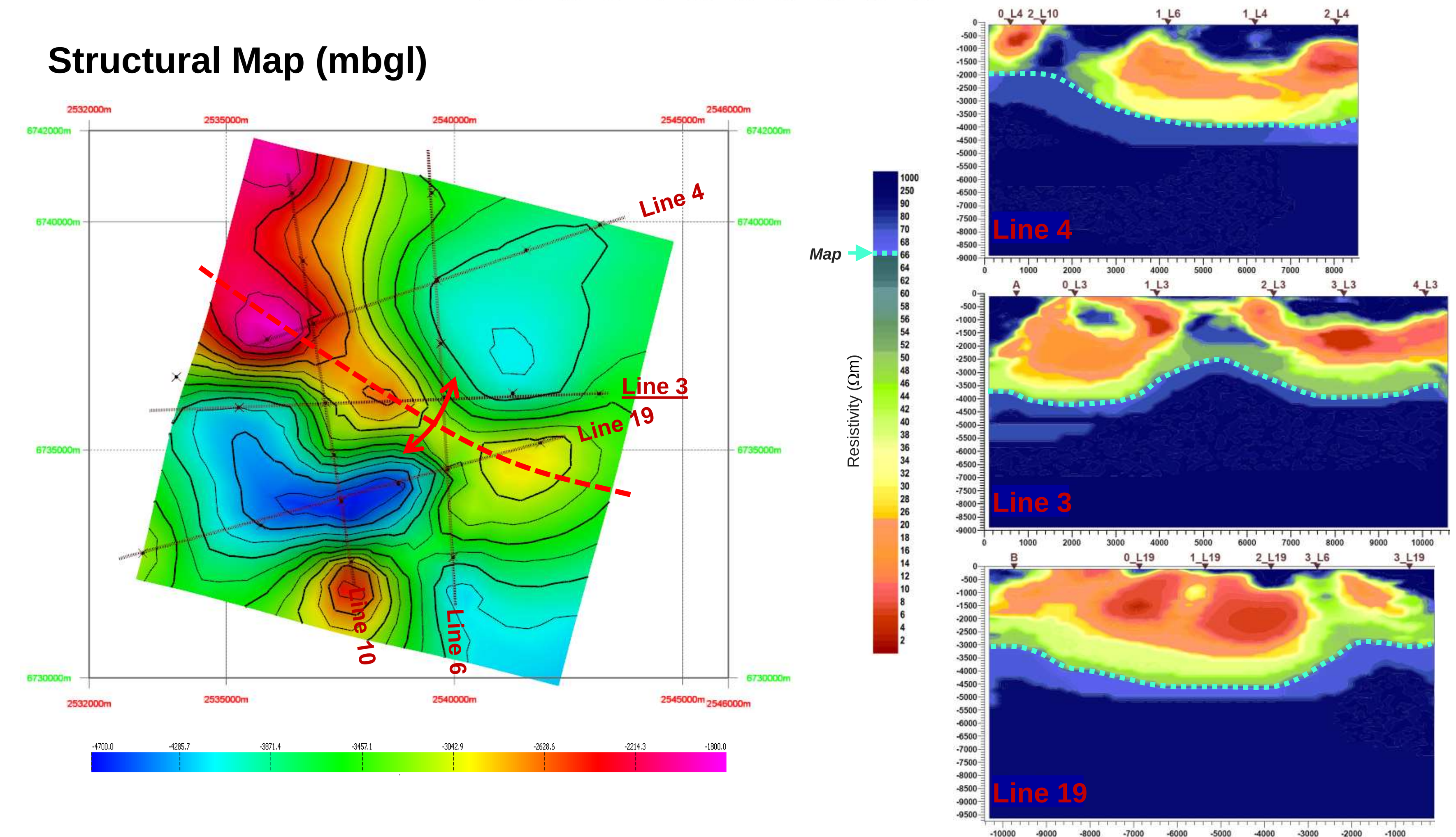




4. INTERPRETATION

- The structural map near the top of the high resistivity layer delineates a deep WNW oriented positive feature.

Structural Map (mbgl)



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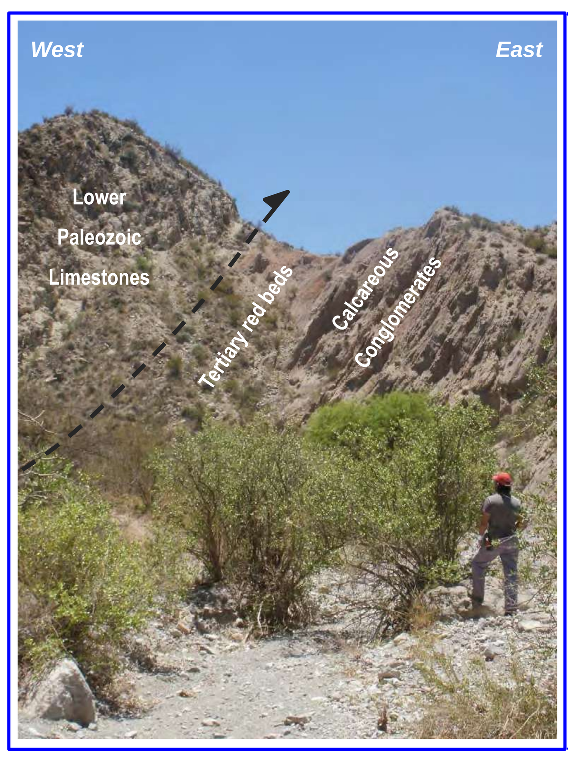
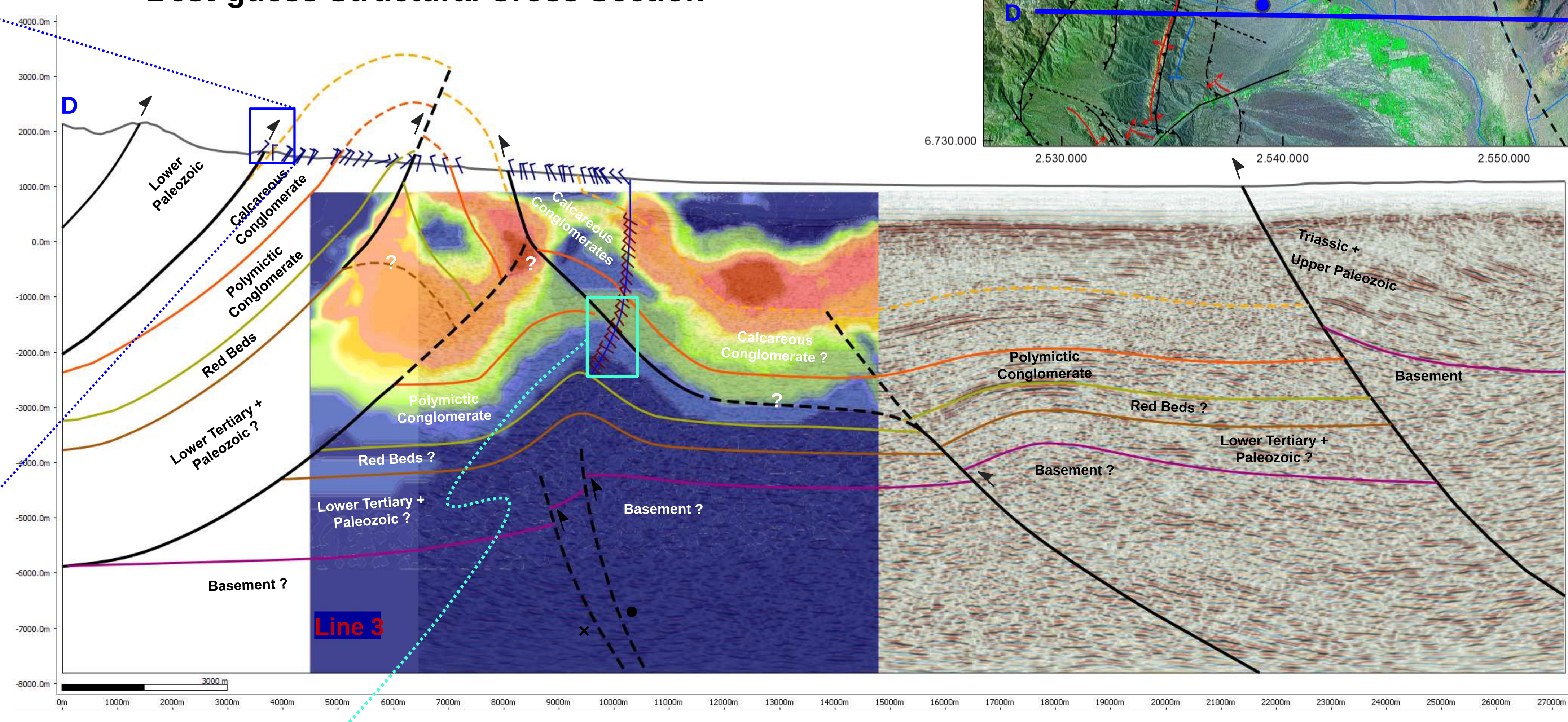
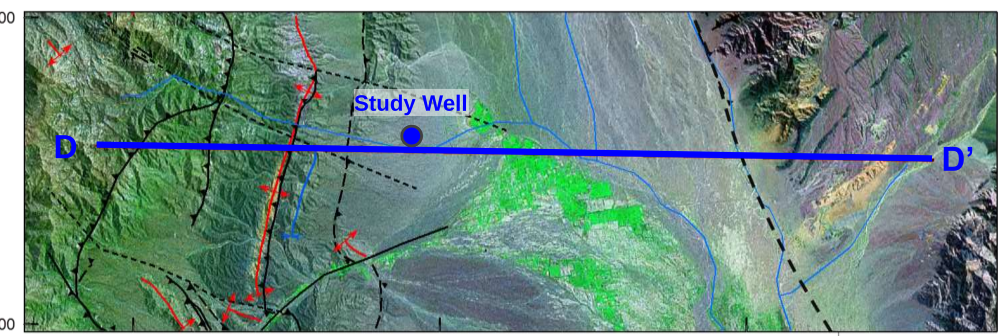
5) STRUCTURAL MODEL AND DRILLING RESULTS

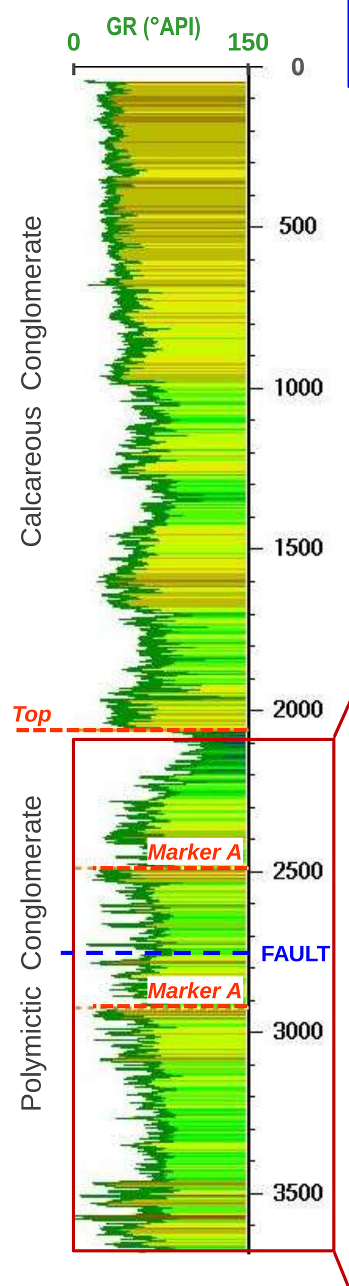
Best-guess Structural Cross Section



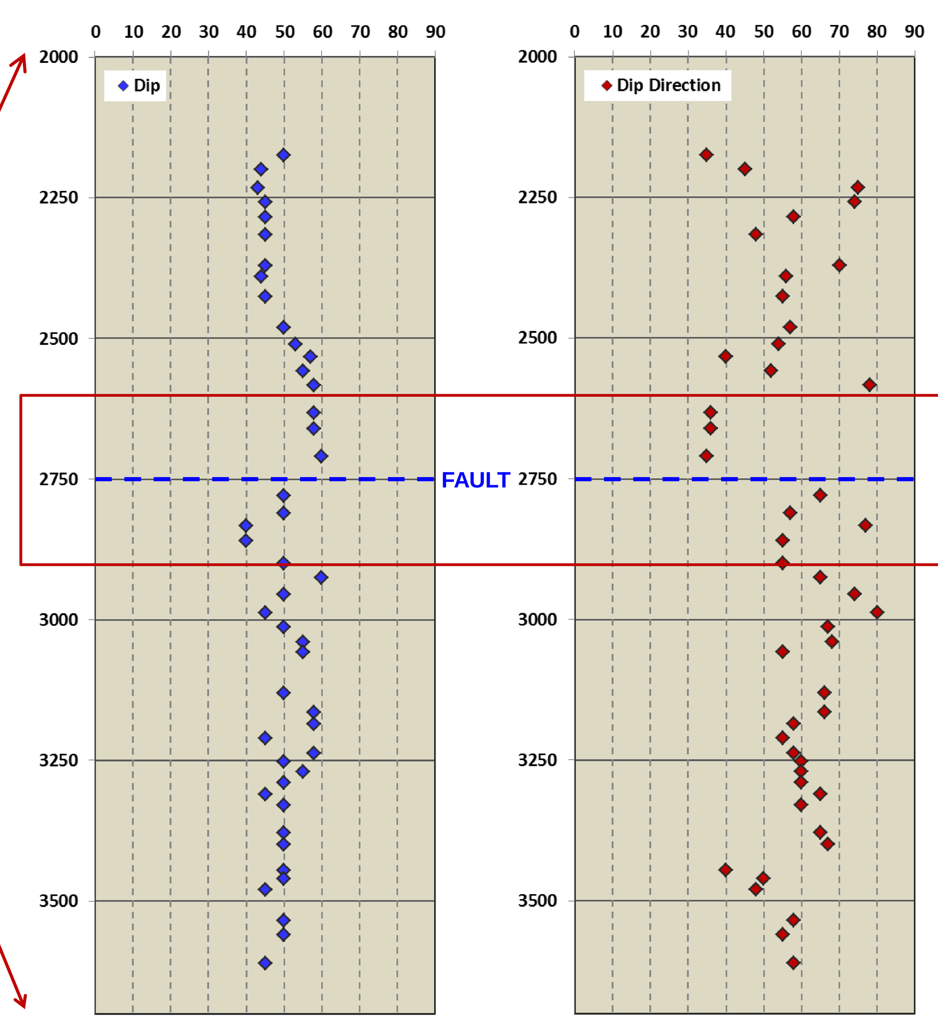


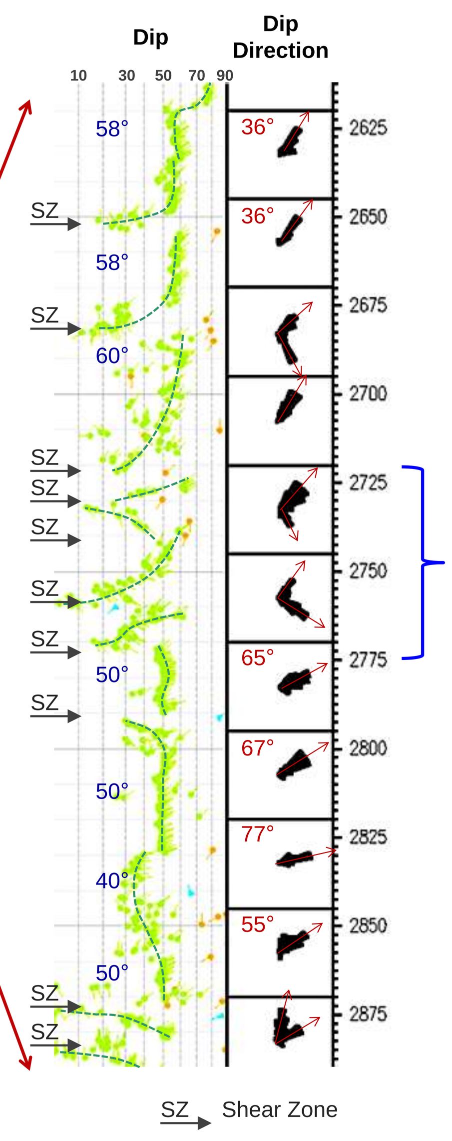


Gamma Ray Log

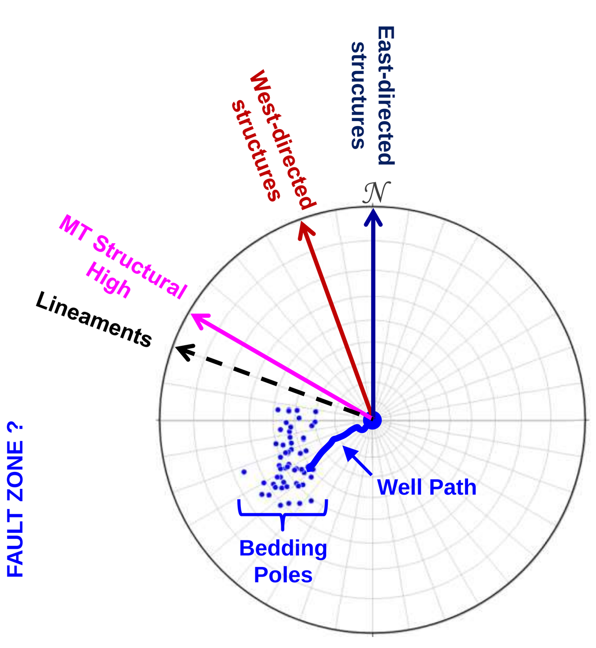


Bedding Attitude Anlysis





Natural Well Drift



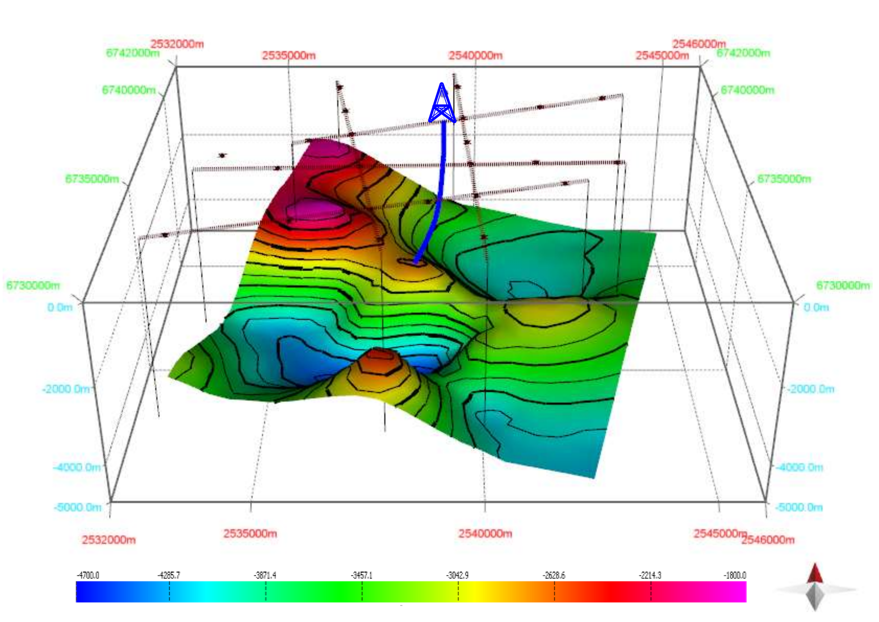
REMARKS:

- A best-guess structural cross section was constructed through the successful integration of surface and subsurface data.
- Bedding orientations derived from the interpretation of image log data helped to located a possible fault zone at depth.
- The non-controlled well path started more or less orthogonal to the outcropping backthrust but shifted to the SW for the most part of its length. This pattern suggests a geological control on the well trajectory that could be related to the presence at depth of a buried structure roughly parallel to the WNW-trending MT-derived high.

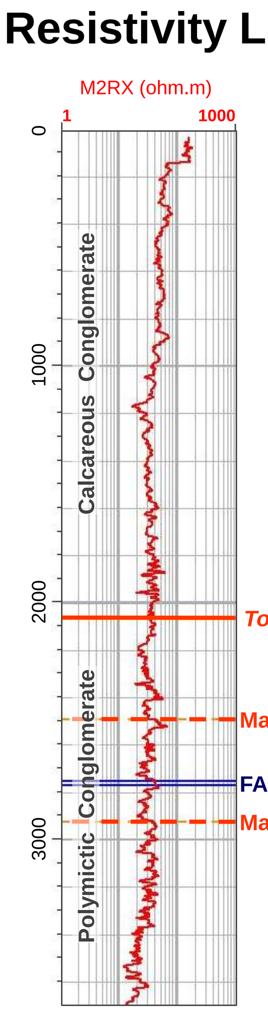
6) POST-DRILL MT SURVEY

1. MOTIVATION:

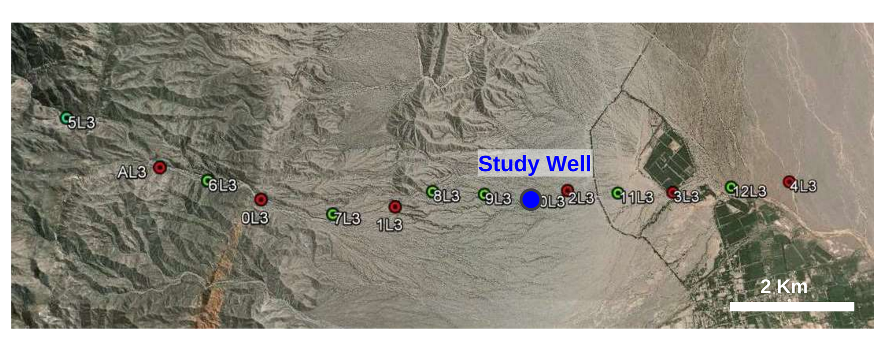
- Target depth was deeper than expected.
- Need to increase penetration depth and spatial resolution over the structure.
- MT resistivity values at the bottom well location are higher than observed on logs.

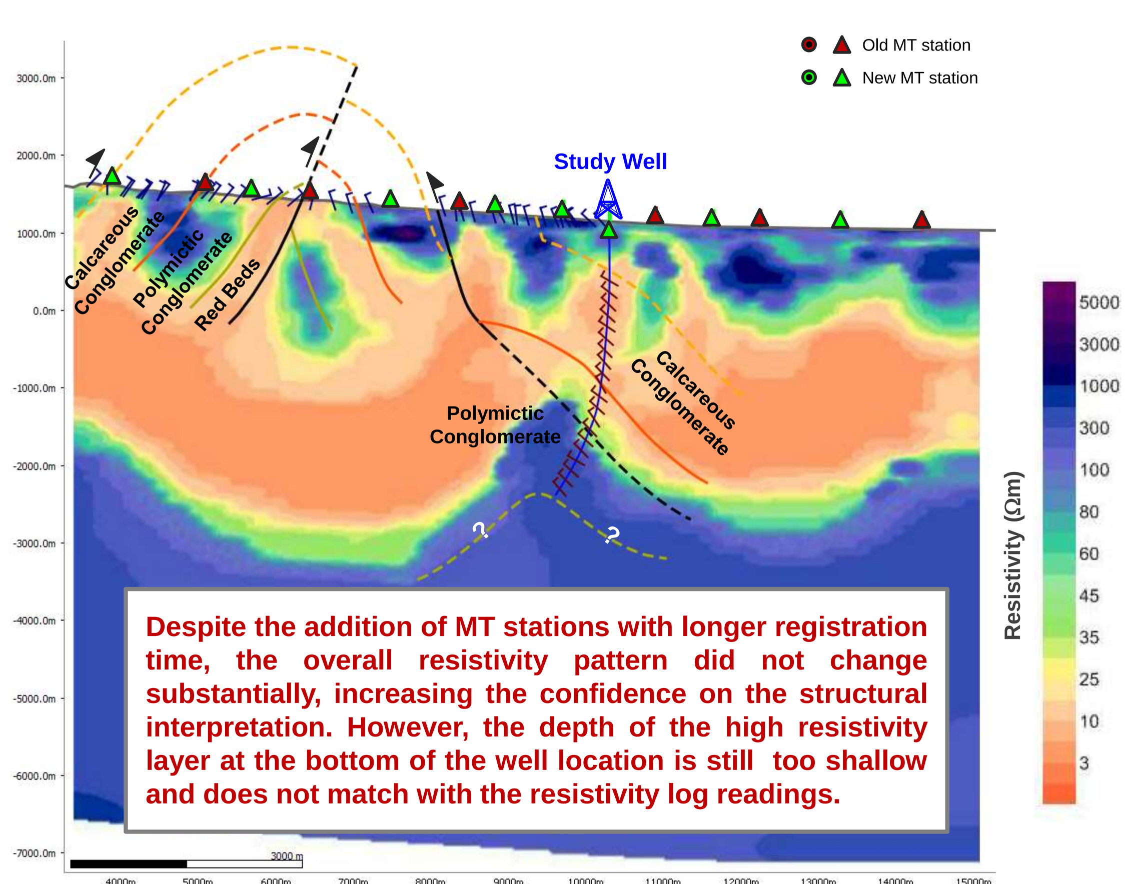


Resistivity Log



TD: 3700 m
(12140 ft)





2. ACQUISITION:

- Hardware: Metronix ADU07e
- 8 additional stations along Line 3.
- Station spacing around 700 m.
- 4 channels per station: Ex, Ey, Hx and Hy.
- Registration time: 21 hours.

3. PROCESSING:

- Same workflow as previous survey but a robust processing of temporal series.
- 2D Inversion of apparent resistivity and phase curves of TE and TM modes of 14 stations.

7) CONCLUSIONS

- **Fold and thrust belts are challenging to explore because the difficulty of predicting the subsurface structure. High dipping beds, the abundance of faults and strong lateral velocities variations causes seismic sections to show distorted images and become difficult to interpret. Natural field methods, such as gravimetry and magnetotelluric, can not produce an unique model of the subsurface geometry and have low resolution.**
- **On the other hand, the combination of multiple geophysical explorations tools coupled with high resolution data derived from geological maps can help to constrain the possible buried geological configurations and to built a best-guess structural model.**
- **The Argentine Precordillera triangle zone is the result of the convergence between N-S striking east-verging thin-skinned structures against west-directed backthrusts and NNW-trending basement blocks. In the subsurface of the study area this picture is complicated by the presence of oblique-oriented lineaments and uplifts that interfere with the overlying structures.**
- **Fault-controlled gas anomalies are indicative of the existence a potential petroleum system. However, the lack of good quality regional seals and the intense structural history of the area results in a low trap preservation potential. Further exploration efforts should be directed to search for less deformed locations capped by low permeability rocks.**