Geological Structure of the Subandean Fold Belt of Bolivia Using Magnetotelluric Data*

Nikolay Palshin[1,3], Raul E. Giraudo[2], Denis Yakovlev[1], Roman Zaltsman[1], and Sergey Korbutiak[1]

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[1]Nord West-BOLPEGAS Association, Moscow, Russia (palshin@ocean.ru)
[2]YPFB Corporación, Santa Cruz de la Sierra, Bolivia
[3]Shirshov Institute of Oceanology RAS, Moscow, Russia

Abstract

Results of the two largest MT surveys carried out in South America will be discussed with a special focus on joint geological interpretation using MT, seismic, and logging data in the Subandean Fold Belt of Bolivia.

Reference Cited

Baby, P., P. Rochat, G. Mascle, and G. Herail, 1997, Neogene Shorting Contribution to Crustal Thickening in the Back-Arc of the Central Andes: Geology, v. 25, p. 883-886.

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Geological structure of the Subandean fold belt of Bolivia using magnetotelluric data

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(1) Nord-West BOLPEGAS Association, (2) YPFB Corporación, (3) Shirshov Institute of Oceanology RAS

Motivation

- Magnetotelluric (MT) surveys aimed at hydrocarbon exploration have been carried out for more than 50 years.
- Recent advances in MT technology, considerable increase of quantity and quality of data and integrated interpretation of MT data along with other geological and geophysical data allows to increase the efficiency of magnetotellurics.
- However, there is still some skepticism about the method, especially related to hydrocarbon exploration. Recently results obtained in Bolivia in two large MT surveys can significantly improve the impression about the method among petroleum geologists.

Magnetotellurics as a passive electro-magnetic method

Magnetotellurics (MT) is a technique to probe **electrical conductivity structures** of the Earth. MT utilizes a **broad spectrum of naturally occurring geomagnetic variations** as a source for the electro-magnetic induction in the Earth.

MT measures fluctuations of **electric** (E) and **magnetic** **(**B) fields in **orthogonal directions at the surface of the Earth** (or seafloor) as a mean to determine the resistivity at depth, ranging from a few tens of meters to several hundreds of kilometers.

Electrical conductivity

Electric conductivity of sedimentary rocks as a multiphase system consisting of matrix and pores filled by fluids, depends on (1) porosity and (2) fluid conductivity (so called Archie's Law). For clayish sedimentary rocks, the dependence of conductivity on fluid conductivity (salinity) is practically absent because alternative conductivity mechanism is dominating. Thus, electrical conductivity of sedimentary rocks depends on:

- **Clay content**
- **Porosity (effective or connected)**
- **Fluid saturation**
- **Fluid resistivity (salinity and temperature)**

Constrained MT inversion

MT could be used separately at preliminary exploration stages, but the most effective approach is the application of the method as a supplement to the seismic method. Practically, a constrained inversion of MT data is one of such approaches. In most cases, it uses seismic and logging data as constraints.

Sub-horizontal sharp discontinuities in sediments, which correspond to reflectors, could correspond also to sharp changes in resistivity. Logging data (VSP, electrical logging, lithology) are used to check the existence of such interfaces.

Constrained inversion of MT data is based on the existence of sub-horizontal interfaces on which velocity and resistivity (and density) change significantly and could increase the reliability of the geological interpretation.

Advantages and shortcomings

Broad band span of depths

Sensitive to porosity and pore fluid salinity

Could be used for characterization of reservoirs and seals

Effective tool for outlining fault zones

Relatively low cost and environmentally friendly

Could not detect geological boundaries with accuracy compatible with seismic methods

Low spatial resolution, decreasing with depth

Vulnerable to industrial EM noises

Where the application of magnetotellurics is effective for hydrocarbon prospecting?

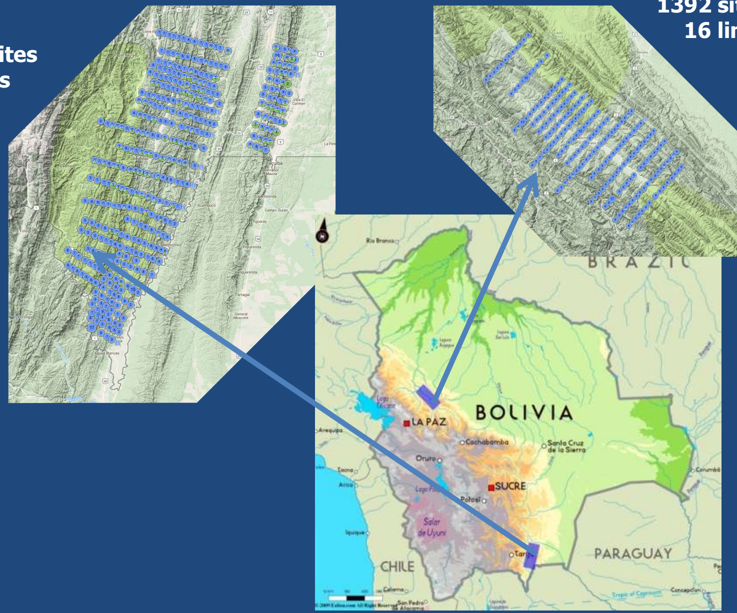
- Where seismic faces problems…
- 1. Geological provinces with rigid seismic boundaries or/and velocity inversion in the upper section (basalt traps: Eastern Siberia, Parana, Deccan).
- 2. Fold belts (e.g. Taimyr, Zagros, Bolivian Subandean, NW Colombia, etc).
- 3. Salt tectonics (e.g. Mexican Gulf, Precaspian depression, Central Iran, etc).
- 4. Sedimentary basins covered by thick permafrost (e.g. Eastern Siberia, Alaska, Northern Canada and Arctic Seas Shelf).

MT surveys in Bolivia

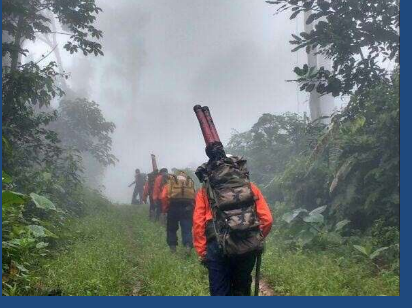
- **ADQUISICIÓN INTEGRAL MAGNETOTELÚRICA SUBANDINO NORTE (SAN)**
- **ADQUISICIÓN INTEGRAL MAGNETOTELÚRICA SUBANDINO SUR (SAS)**
- **The two largest MT surveys ever carried out in South (and North…) America!**

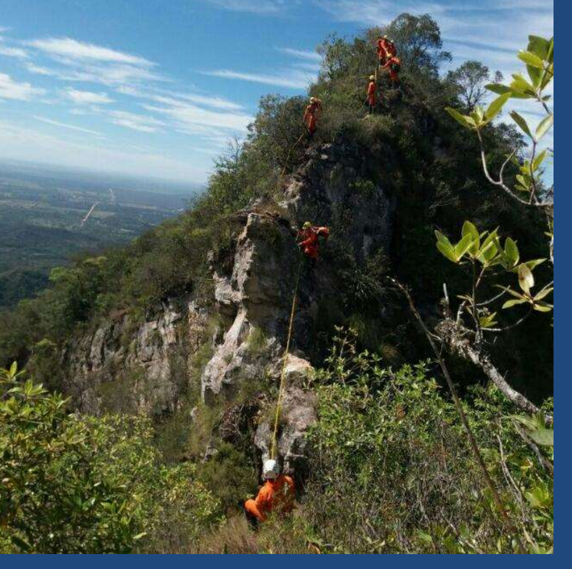
SAS
2265 sites
41 lines

SAN
1392 sites
16 lines



MT data acquisition

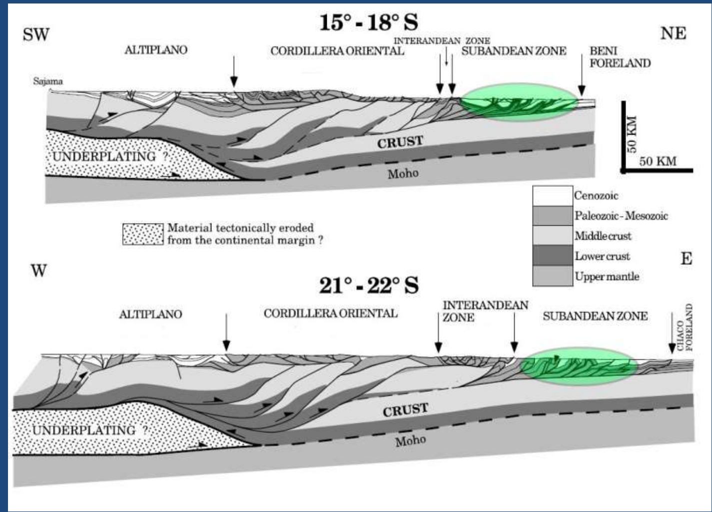




Tectonic background

In the Central Andes of Bolivia, thrusting started in the late Oligocene and is active nowadays. The sedimentary section involved in the deformation consists of Cambrian to Oligocene pre-orogenic strata and Oligocene to recent continental syn-orogenic infill. The back-arc system consists of several tectonic zones, including a narrow thrust-and-fold Subandean belt.

Both MT surveys areas are characterized by complicated geological structures (duplexes, pop-ups, out-of-sequence thrusting) with significant shortening and several decollement levels and believed thin-skinned folding.



Baby et al., 1997

SAN: Petrophysics and lithology

Silurian-Devonian
Tequeje and Carrasco fm – conglomerates, sandstones and black shales
Tomachi fm – sandstones with beds of clay, black shales

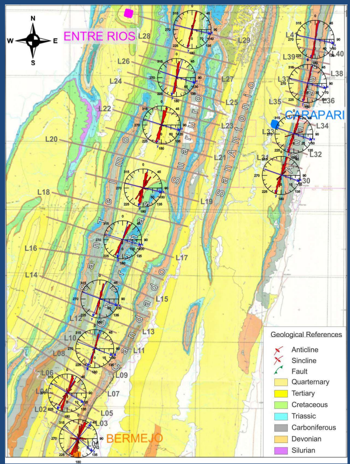
Carboniferous – Lower Permian - variable sedimentation conditions.
Kaka fm - sandstones
Toregua fm – sandstones with conglomerates and clays
Copacabana fm – limestones, sandstones, shales (brittle)

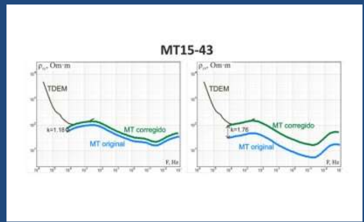
Jurassic – Cretaceous
Beu fm - sandstones with clay bands

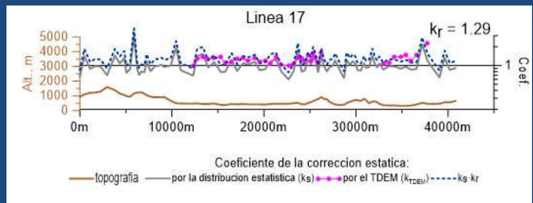
Cenozoic
Charqui, Quendeque, Bala fms - terrigenous mostly river sediments

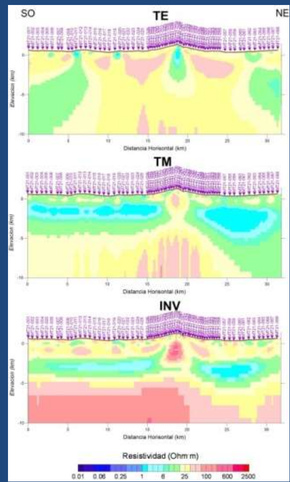
Well	Formation	Thickness, m	Porosity, %	Shale volume, %	Permeability, mD
LQM-C1	BEU	371.8	6	19	0.008
	COPACABANA-1	1180	6-14	12-19	0.01-0.06
	KAKA	224	6	6	0.07
	TOREGUA	236	3-5	4-11	0.06
	TOMACHI	187	7	5	1.5
	COPACABANA-2	889	no data	no data	no data
LQM-X1	BALA	385	14	6	6.83
	BEU	679.5	10	5	40.23
	COPACABANA	2477	9	10	4.49
TCR-X1	BEU-1	1222	14	6	9.11
	COPACABANA-1	106.5	7	24	0.31
	BEU-2	1077	13	13	9.65
	COPACABANA-2	662	5	6	0.09
TCR-X1D	COPACABANA	696.7	7	17	0.49
BYA-X1	BEU	480.6	16	10	139.08
	TOREGUA	188.2	13	6	3.17
	TOMACHI	2137.9	12	14	3.55
	RIO CARRASCO	68.1	6	20	0.08

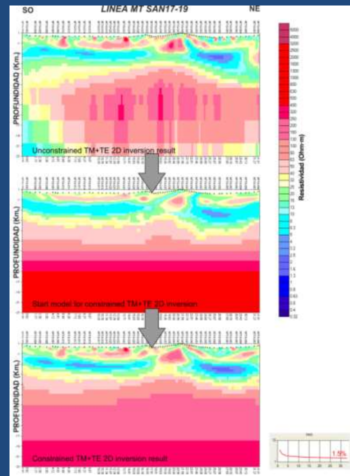
MT data analysis and 2D bimodal Occam inversion





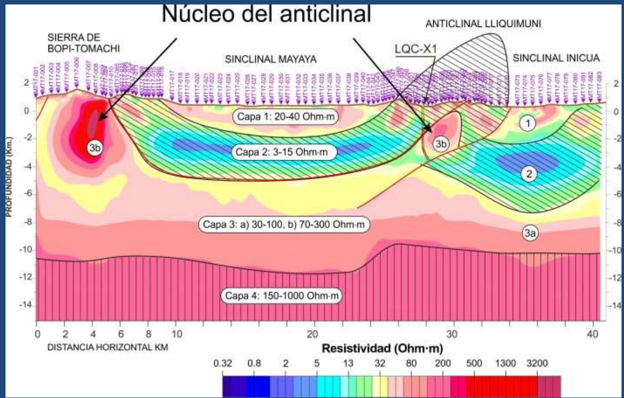


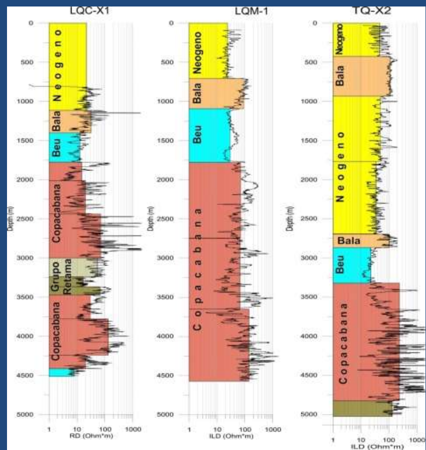




Geoelectric characterization of sedimentary layers

Subandino Norte

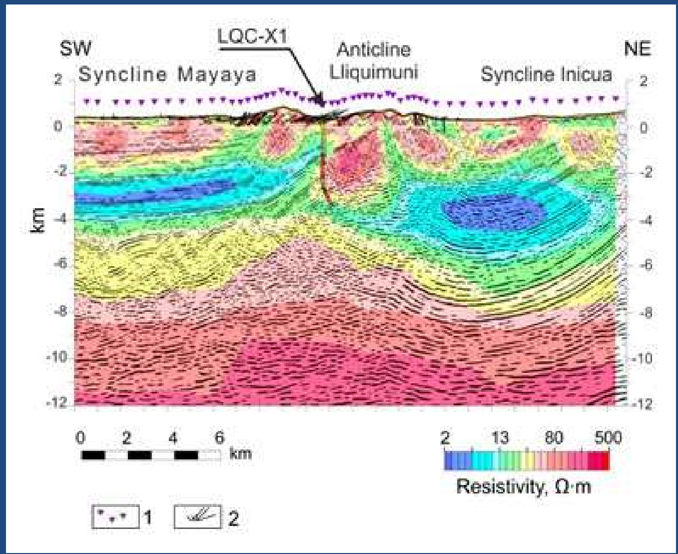


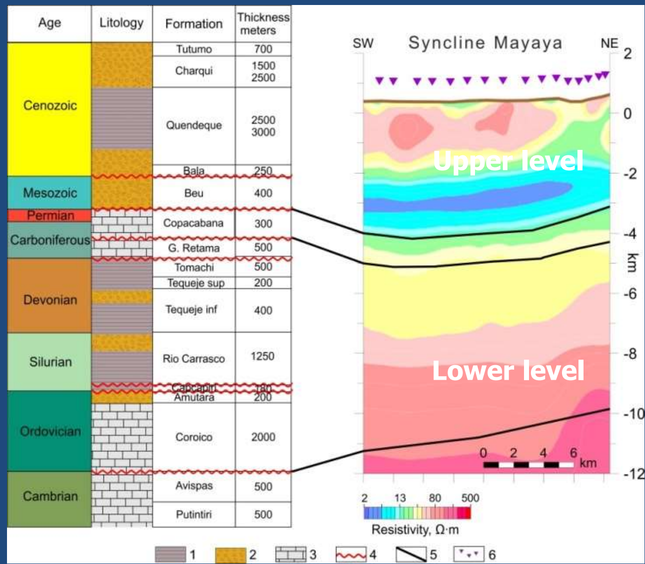


Edad	Capa Geoléctrica	Sinclinal	Anticlinal	
		Resistividad por MT	Resistividad por registros	Resistividad por MT
Terciario	1	20 - 40	-	30 - 60
Mezozoico	2	3 - 15	10 - 30	10 - 40
Pérmico	3	30 - 100	30 - 100	70 - 300
Carbonífero				
Devónico			-	
Silúrico				
Ordovícico	4	150 – 1.000	-	150 – 1.000
Cámbrico				

Geoelectric characterization

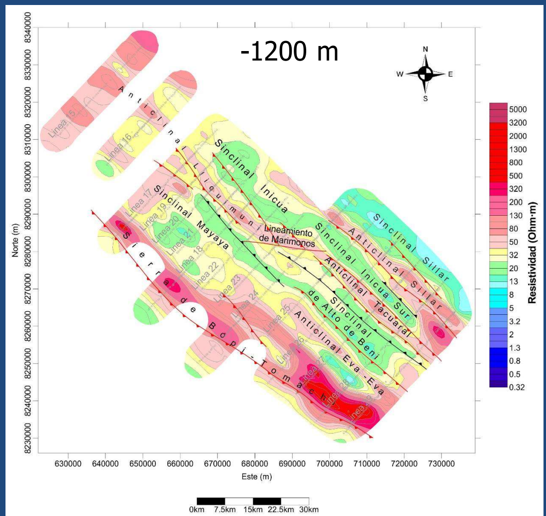
Subandino Norte

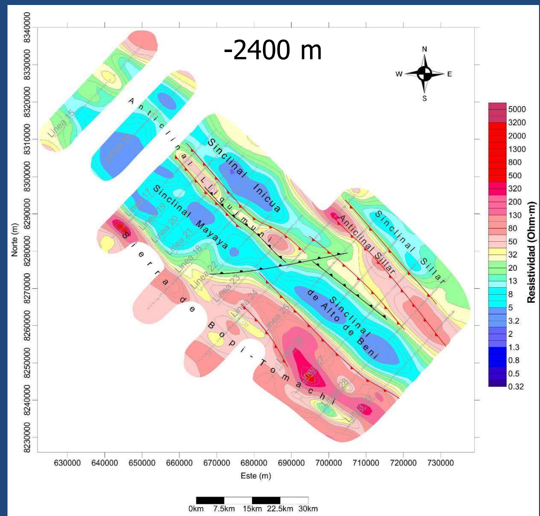


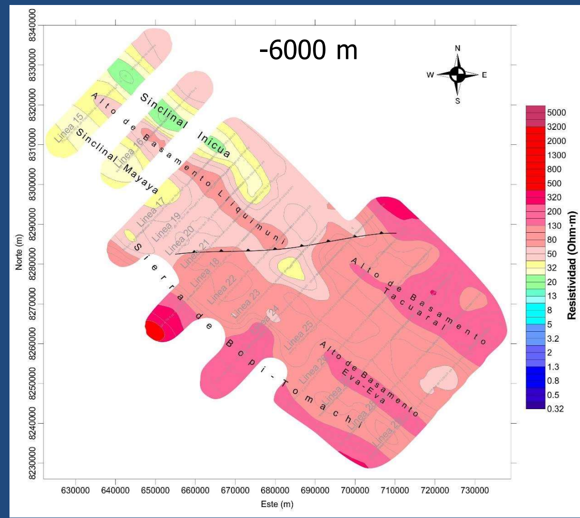


Resistivity images overview

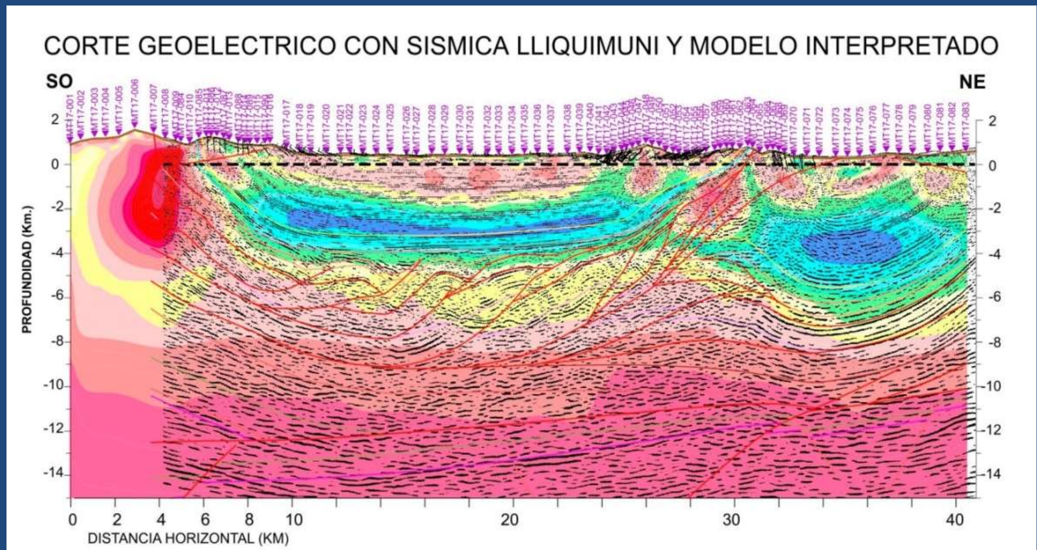
Subandino Norte





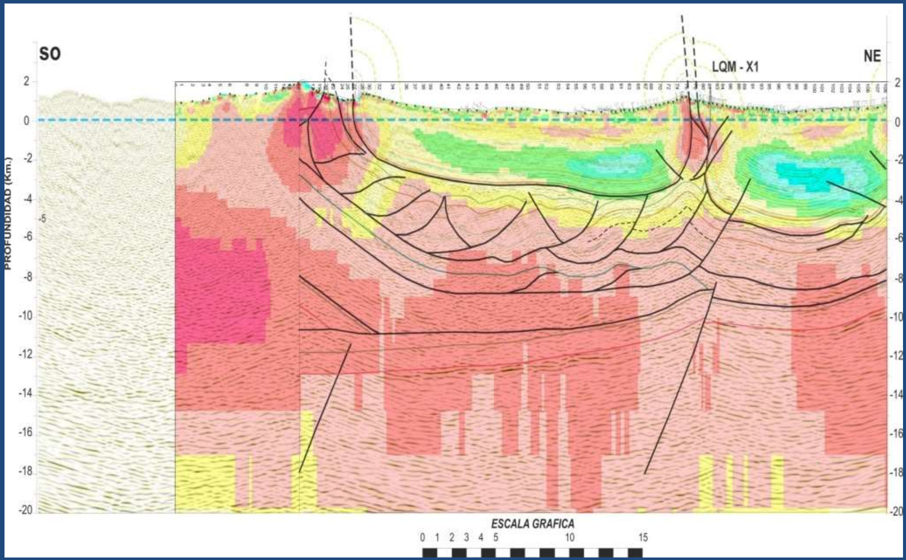


Resistivity image vs seismic section
Integrated interpretation
Subandino Norte



Resistivity images: lower level structure

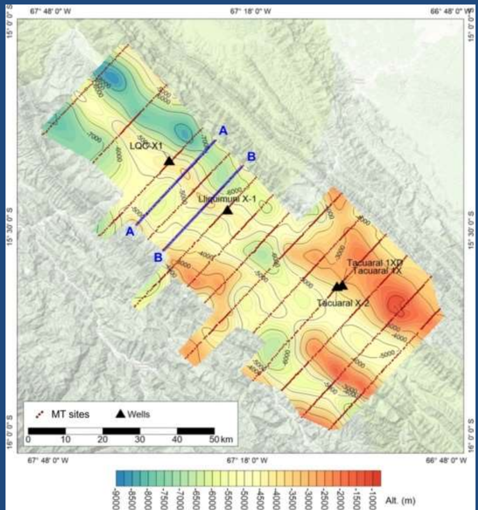
Subandino Norte

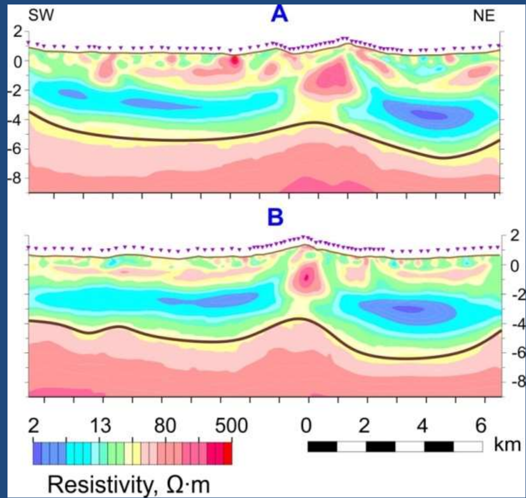


Interpretation is based on seismic (mainly), wells and surface data. Duplex structures correspond to layers with a gradual increase of resistivity with depth.

Resistivity images: two-level structures

Subandino Norte



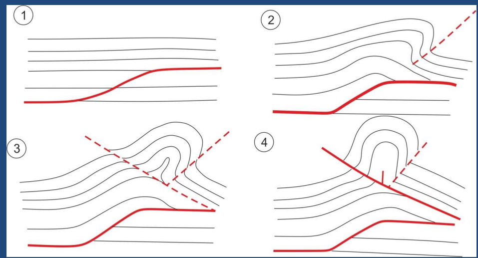


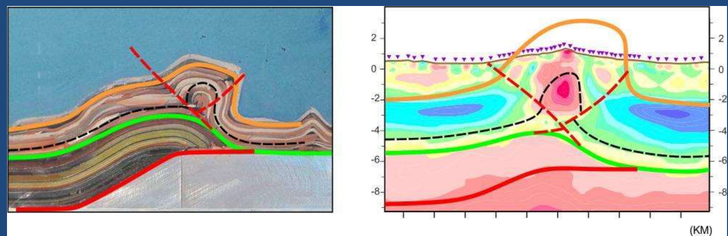
Top of lower structural level

Resistivity images: upper level structure
Subandino Norte

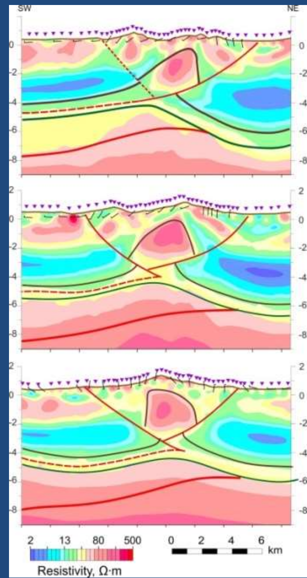
Pop-ups and palm tree structures are typical for Lliquimuni and Tacuaral anticlines.

MT data is characterized by enhanced resolution in the anticlines nuclei

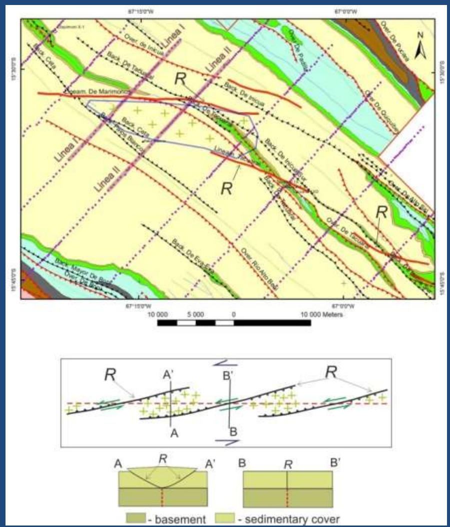


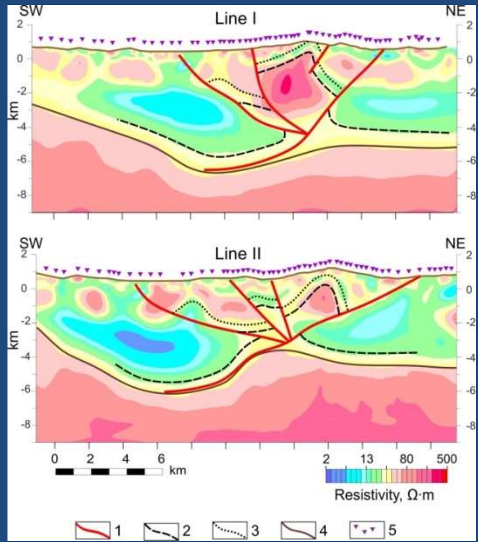


Formation of pop-up and palm structures



Palm structures
Subandino Norte



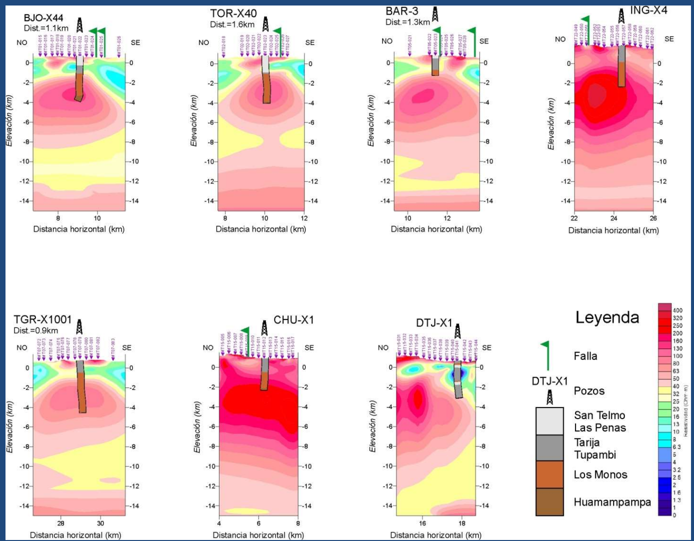


SAN: Two-level resistivity structure.
Structural levels are characterized by different mechanical properties and different type of folding.

The basin is separated by several oblique faults into two different parts.

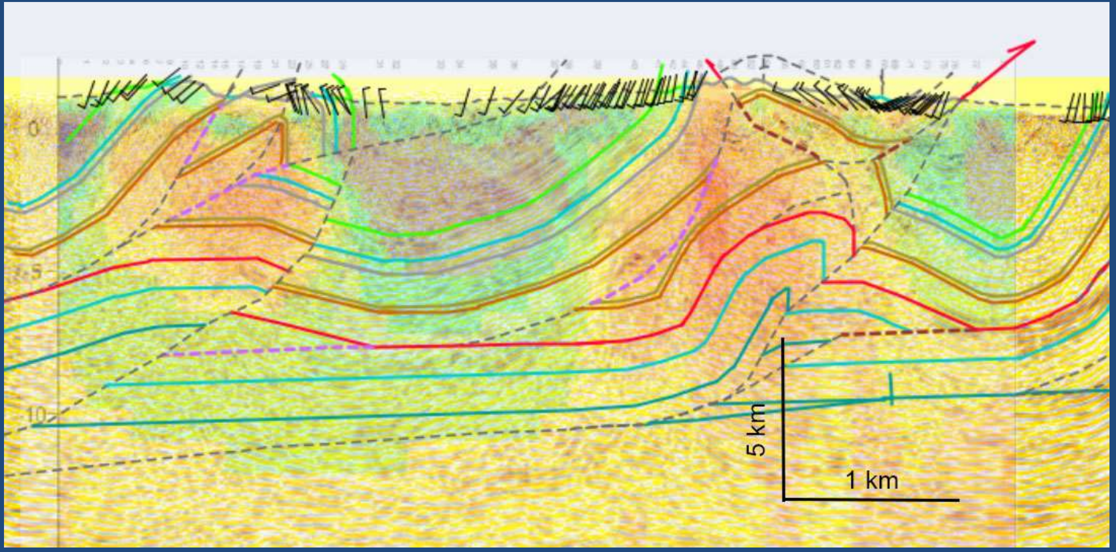
Electric logging vs resistivity

Subandino Sur



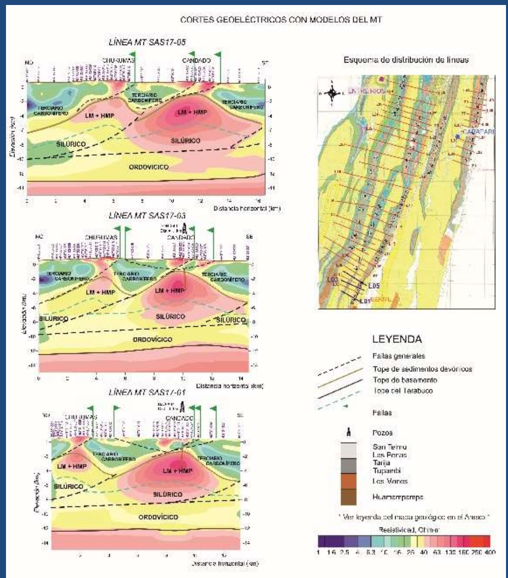
PERIODO	GRUPO	FORMACIÓN	POZOS							
			BJO-X44	TORO-40	BAR-X3	ING-X4	CHU-2	SAN-X2	DTJ-X1	TGR-X1001
CARBONÍFERO	MANDIYUTI	SAN TELMO				110 - 120				
		ESCARPMENT		30 - 50	40					
	MACHARETI	TAIQUATI								
		CHORRO								
		TARIJA	30 - 40	20	30 - 40	10 - 40	30 - 40	10 - 50	30 - 40	
		ITACUAMI		30		10 - 50	45 - 50	10 - 50		
		TUPAMBI	20 - 30	20	30	100 - 130		10 - 50		
		ITACUAMI								
DEVÓNICO		IQUIRI				100 - 110				
		LOS MONOS	50 - 80	30 - 80	30	50 - 100	70 - 80		60 - 70	10 - 100
		HUAMAMPAMPA	50 - 60	40		100	100 - 110			

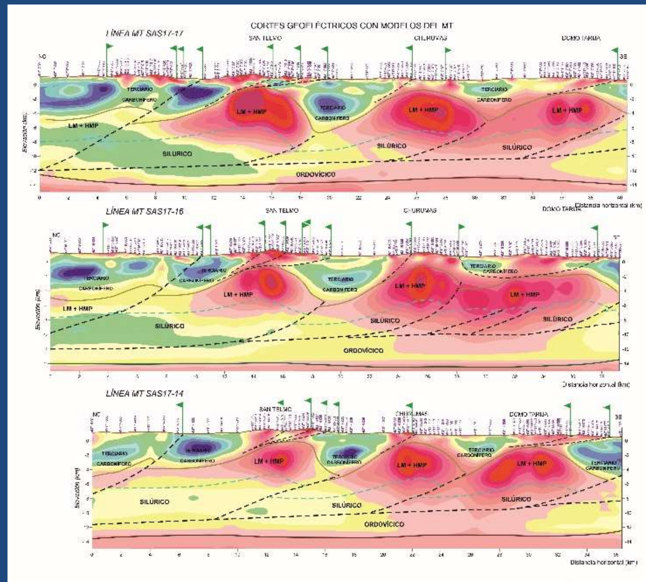
Resistivity image vs seismic section
Integrated interpretation
Subandino Sur



Resistivity images

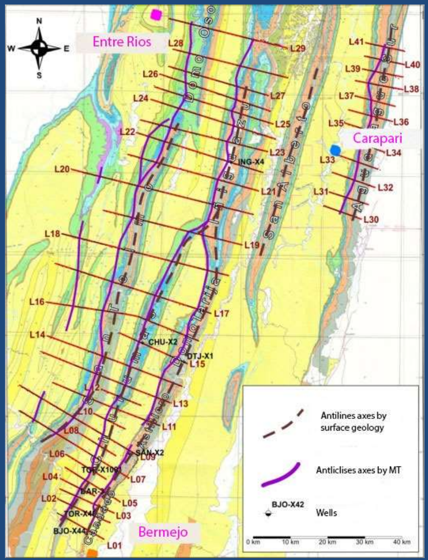
Subandino Sur

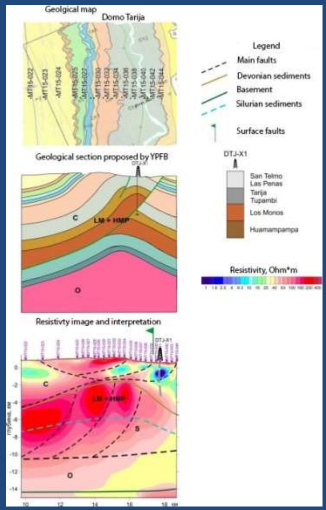




Important structural constraints:

Subandino Sur



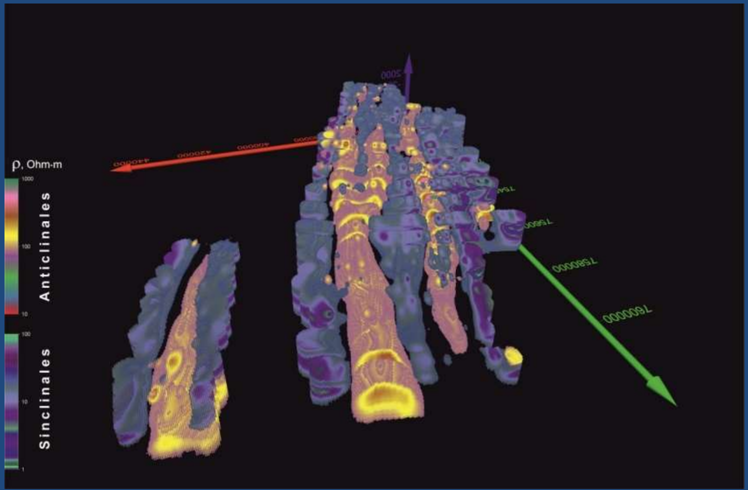


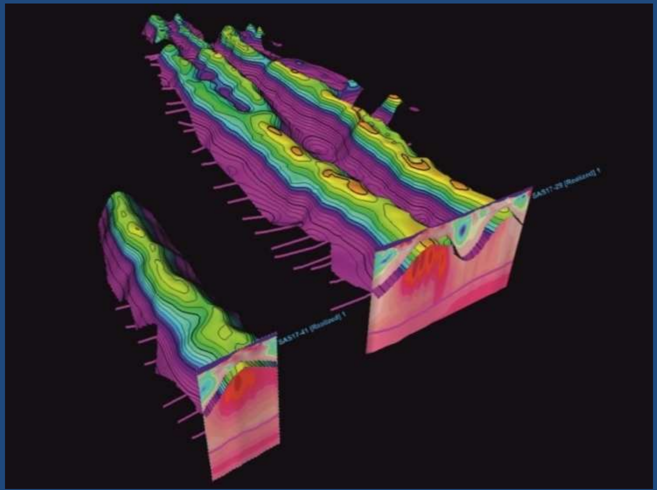
Real positions of Devonian were outlined in anticlines nuclei

Surface structures are systematically shifted southeast relative to Devonian structures

Anticlines and synclines: 3D view

Subandino Sur





Importance of a priori geological and geophysical data

Surface geology, tectonic schemes, stratigraphy, petroleum systems

Potential fields and airborne data

Borehole data: electric logging, VSP, thermometry, etc.

Rock properties: petrophysics and hydrophysics

Seismic data

Interpretation of any kind of geophysical data should be integrated !

Conclusions

The results of MT surveying carried out using advanced modern technology and integrated interpretation along with seismic and logging data give important structural constrains, especially at the core of anticlines

An importance of several decollement levels in Subandian fold belt for understanding geological evolution were confirmed.

New targets (already delineated with seismic) were outlined and confirmed by MT.

Magnetotellurics is an effective technology to delineate resistivity contrasts in areas where seismic faces problems, i.e. the Subandean fold belt