THE SILURIAN-DEVONIAN CHACO BASIN: A REVIEW FOR RESERVOIR CORRELATION IN ARGENTINA AND BOLIVIA

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ABSTRACT

An alternative model for the Silurian-Devonian Chaco Basin development has been created based on well and outcrop data, regional seismic interpretation, sequence stratigraphy, and structural restoration techniques.

The Ordov.-Early Silurian Cancañiri Fm. and its equivalents (100–2000m), which are tectonically inverted in the Altiplano region, were deposited in fault-controlled, narrow depocenters. Contrarily, the overlying units exhibit a remarkable eustatic control within an overall setting of regional subsidence.

An important sea level transgressive+highstand episode was responsible for the deposition of the Early-to-Late Silurian Kirusillas+Tarabuco sequence-set (SSt.). The basin received the highest volume of sand during an Early Devonian global lowstand episode (Santa Rosa SSt.). The Icla, Huamampampa, and Lower and Upper Los Monos SSts were deposited from the end of Early Devonian through the Late Devonian and represent an overall transgressive+highstand episode with several lesser order transgressive-regressive cycles. These cycles have been discussed in Montemurro (1994), Sempere (1995), and Stark (1995).

A huge volume of Huamampampa sands were constrained to a coastal ramp setting as “lowstand prograding shoreface” deposits along the SW border. These sandstones were subsequently folded and fractured, and are the reservoirs in the largest gas and condensate fields (i.e. Aguarague and Ramos fields). Overlapping the ramp to the west, smaller fields developed, mainly in relation to substantially thinner fluvial-deltaic sand intervals (i.e. Aguas Blancas and Bermejo fields). Towards the east, the offshore counterparts received bypassed sands; thus, lower sand volumes, and a diminished folding-fracturing intensity, could have only resulted in fields of lesser magnitude. Consequently, the location of the ramp is one of the main components involved in prospecting large volumes of reservoir rocks.

A low sedimentary supply from the Brazilian shield was responsible for a condensed stratigraphic record along the NE border, composed of E-W elongated sand belts, equivalent to Santa Rosa, Icla and Huamampampa SSts. Based on regional seismic interpretation, the uppermost sandstones of Roboré Fm. seem to be equivalent to the base of Huamampampa SSt., while the lower Roboré (= Yapacani,4750m.TD-SJN x-2) and Sara sandstones seem to be a condensed record of the Santa Rosa and Tarabuco sandstones respectively. This portion of the basin is assumed to be highly productive based on the proven structural plays, as well as on the potential plays related to stratigraphic-diagenetic pinch-outs and capillarity seals.

The Los Monos-Iquiri interval is subdivided in two prograding SSts around 1000 m. thick each. An important thickness reduction - up to 1000 m for the Los Monos-Iquiri interval - is shown in the composite seismic section from Bolivia to Argentina. The Lower Los Monos SSt. is characterized by downlap terminations towards the south, becoming considerably thinner in Argentina, resembling a condensed section. The sandstones present at the top of Lower Los Monos or at the base of Upper Los Monos have often been misinterpreted from well logs as belonging to the top of Huamampampa SSt (i.e Miraflores,SJNx-2).

A structural restoration was attempted in order to aid the paleogeographic interpretation. Though this preliminary results are regional in nature and considerable more imput of data will be required, this work has allowed us to develop an alternative basin-generating mechanism, which would have involved asymmetrical lithospheric extension by simple shear. This hypothesis accounts for any spatial offset between the fault-controlled depocenters in the Altiplano region and the zone of interpreted maximum lithosphere thinning to the east in the Subandean and Chaco regions, where the L.Silurian-Devonian basin axis was driven by thermal subsidence.

INTRODUCTION

The main goals of the study were to contribute to a better understanding of the Chaco Basin (northwestern Argentina, central and southern Bolivia) sedimentary system evolution during the Silurian and Devonian periods, and the prediction of sand volumes of the potential reservoir units in different basin positions. (Fernandez Seveso et.al., 1997).

The sequence stratigraphic framework was defined in several outcrop locations and well data both in Argentina and Bolivia (Fig.1). These control points were correlated within coherent models of paleoenvironment relationships and sedimentary cycles assemblages, being this interpretation represented in a series of stratigraphic sections covering key sectors of the basin.

Given the fact that most of the basin's area with exploratory interest lies within the subandean thrust belt setting, where the basin shortening can reach more than 100 km., the control points were restored to their pre-deformation original positions. The reservoir correlation was constrained by seismic composite sections, where seismic data allowed that, and the results were finally mapped in sandstone isopach maps.

SEQUENCE ANALYSIS

Using a sequence stratigraphy point of view (Posamentier and James,1993) an integrated analysis of each stratigraphic unit was made, emphasizing the third order cycles (sequences), that represent regressive-transgressive marine episodes. These sequences were grouped to form sequence sets in order to identify the second order regressive-transgressive cycles.

The chronological assignment of these sequences was made in an interactive way with the eustatic global chart and the biostratigraphic record. The latter is rather imprecise probably due to the lack of integrated studies for the whole basin, independently of the European biochrons, and also due to the fact that successive expansions and contractions of the basin could undoubtedly cause many biostratigraphic material retransport episodes.

The basin´s stratigraphic record begun with the Cancañiri Formation deposited (and equivalent Formation names) during the early Silurian-Ordovician?, filling important depocenters, and areally restricted to western positions, where nowadays is the Altiplano Boliviano (Fig.1). With a complex filling lithology, more than 2000 mts. thick, and composed of all kind of gravity flows and slumps (Limachi et al, 1996), these deposits are interpreted as controlled by synsedimentary active faulting. Towards the East, in the Subandean realm, these deposits, are reduced to a few hundreds of meters (Fig.4b). The Andean age, west verging faulting that bounds these sediments to the West in the Altiplano, fits very well with a model of tectonically inverted synsedimentary master normal faults (Fig 1, 7c).

The Kirusillas+Tarabuco Formations (1400m.) represent a highstand sequence set (SSt) composed by inner basin deposits. They correspond to a basin expansion stage, caused by the eustatic rising episodes of the Silurian in a regional subsidence regime (Fig 2). Lower order eustatic fall episodes represented by turbiditic lowstand fans and lowstand prograding shoreface systems are also identified. Among the latter, the most important one corresponds to the Tarabuco Fm. levels (Fig. 2, 4b).

During the early Devonian (Lochkovian) the most important eustatic fall took place, conducting important volumes of continental (Stark, 1996) and shallow marine sands into the basin. It is known as Santa Rosa Fm. (500m), and is interpreted as a lowstand+transgressive SSt. The Icla, Huamampampa, Los Monos and Iquiri formations represent the transgressive+highstand part of this important second order eustatic cycle that spans for all the Devonian times. There were also lower order eustatic effects represented by third order cycles(Fig.2). Among these, four marine flooding episodes occurred, represented by the lowermost and uppermost section of the Icla Fm. and the basal sections of the lower and upper Los Monos Fm. Also four marine regression events are recorded by the middle section of Icla Fm., Huamampampa Fm., and the uppermost sections of lower Los Monos Fm. and upper Los Monos Fm.(Iquiri Fm).

The basin received a huge sedimentary supply from the SW during the Devonian times, where a wave dominated coastal ramp developed, and sands were distributed along shore as strand plains by the action of waves and coastal currents (see Walker & Plint, 1990, Stark, 1995), creating important sand bodies parallel to the shoreline, (Fig. 2, 3). The distal setting was characterized by gravity flows deposits, that bypassed the shoreface and reached the offshore areas, like those outcroping in the El Mataral section (Fig. 5b). The sedimentary environments that prevailed during the Devonian times representative of the Huamampampa Fm. and supported with cores and well log facies analysis, are shown in Fig. 2.

Regarding to the Huamampampa Fm., a huge volume of sands were constrained to a coastal ramp setting as "lowstand prograding shoreface deposits" along the SW border. These deposits represent a lowstand+transgressive SSt. subdivided in four sequences (H1,H2 ,H3, H4) (see Fig.3,4,5). The abrupt signature at the top of the shoreface deposit seen in the H2 and H3 sequences in the Ramos, Aguaragüe and Vespucio wells is caused by an important increase in water depth, and a consequent decrease in the environment energy, punctuated by an intense bioturbation (Fig 2).Toward the west, thinner sand intervals typical of Huamampampa border zones were deposited, where transport predominated over deposition. Towards the east, the offshore counterparts received turbiditic bypassed sands, and therefore lower sand volumes. The isopach map shows the present sand distribution (Fig.7a), while the restored isopach map (Fig.7b), allows to delineate the original basin paleogeography for Huamampampa that is characterized by NNW elongated sand bodies with a total thickness about 400m., and sets up along 400 km of extended strand plains.

A low sedimentary supply from the Brazilian shield was responsible for a condensed stratigraphic record along the NE border, composed of E-W elongated sand belts, equivalent to Santa Rosa, Icla and Huamampampa SSts. These SSts. are wedging out by onlapping towards the margin (Fig. 5, 6), being only represented by a reduced section with a gross sand thickness of about 200 mts (Fig.7). Based on regional seismic interpretation, the uppermost sandstones of Roboré Fm. seem to be equivalent to the base of the Huamampampa SSt., while the lower Roboré Fm. (= Yapacani, 4750m.TD in SJN x-2.) and Sara sandstones seem to be a condensed record of the Santa Rosa and Tarabuco SSts respectively (Fig.5b).

BASIN ANALYSIS

The presence towards the West, in the Altiplano zone, of important Early Silurian-Ordovician?(Cancañiri Fm.) depocenters, controlled by north-south striking and east dipping normal faults, and inverted tectonically by the Tertiary compression (Fig.1), allows to postulate a lithospheric asymmetric extension hypotesis of basin generation (Wernicke, 1985) . According to this model, shown in figure 7c, during the Early Silurian, asymmetrical lithospheric extension would have taken place, by simple shear of the entire lithosphere mechanism. This mechanism produce the spatial offset of the upper crust normal fault-fragile extension zone, and the zone of maximum lithosphere thinning, that occurs where the megafracture reaches the astenosphere towards the east. When the extension ceased, thermal stabilization took place, and the uplifted astenosphere cooled down, passing to integrate the lithosphere. This cooling produces contraction, density increase, and sinking by isostatic compensation, known as thermal subsidence. With this thermal subsidence regime, the sag basin is installed. It begun in the post-Cancañiri Silurian and ended with the building in the Tertiary of the subandean orogen, and the generation of the synorogenic Tertiary foreland basin. The transtensive episodes that would have initiated the Carboniferous.Permian basin (Fernandez Seveso & Tankard, 1995) would have been overimposed to this long regional subsidence process.

This hypotesis constitute an alternative for other several previous interpretations that coincide in assigning a foreland genesis to the Chaco Silurian-Devonian basin (Isaacson y Martínez, 1995; Ramos, 1988; Sempere, 1995; Stark, 1995). Many intriguing observations came up when managing the data for the basin mechanism, that are still not totally constrained. 1)There isn't visible thickening of the Silurian-Devonian cycle towards the West in well logs and surface cross sections, but a tabular parallel pattern, constant in thickness in between second order maximum flooding surfaces. 2)There is no forebulge, or contemporaneous flexural uplift that should have been occurred towards the East in case of an active orogen westward. 3)The sequential stratigraphic correlation shows a westward thinning of the Huamampampa SSt, and probably also of the Santa Rosa SSt. This depicts the presence of a basin marginto the west, which also is supported by the spatial assemblage of the interpreted depositional systems. 4)There is poor evidence for the long transport thrust sheets in the Arequipa Massif and the Arco Puneño (Altiplano), that would be needed to explain the increased load on the lithospheric plate. 5)The internal geometry of those areas is poorly fitted for the installment of a thrustbelt, given the intense internal preexisting deformation, that would have obliterated the needed regional detachment levels ("cratonized").

IMPACT ON EXPLORATION & CONCLUSIONS

The development of a “coastal ramp” for the basal sequences of the Huamampampa sequence set in northwestern Argentina, is one of the main conditioning factor for field sizes (Fig 3,4,5,7). These large volumes of sandstones constrained to the ramp, subsequently folded and fractured during the Tertiary Orogeny, constitute the largest gas and condensate fields as the Aguaragüe and Ramos Fields (3-to-5 TCF each). Aguas Blancas and Bermejo Fields (1 TCF each) constitute examples of smaller size fields related to Huamampampa border zones developed to the West of the ramp setting (Fig.3). Towards the east, lower sand volumes and a diminished folding-fracturing intensity, could have only resulted in fields of less magnitude. Therefore, although the reservoir properties are given by the fracturing degree obtained by thrusting of these quartz-cemented sandstones, it is evident that the available volume of sand also conditions the field’s resulting size. Consequently, the ramp location (Fig.7a,b) becomes an important diagnostic element in the search of large volumes of reservoir rocks.

The interpretation of the composite seismic sections from Argentina to Bolivia (Fig 6).allowed to subdivide the Los Monos-Iquiri interval in two prograding SSts of around 1000 m. thick each. An important thickness reduction - up to 1000 m - for the Los Monos-Iquiri interval - is shown. The Lower Los Monos SSt. is characterized by downlap terminations towards the south, that becomes considerably thinner in Argentina, as a condensed section. The sandstones present at the top of Lower Los Monos or at the base of Upper Los Monos with gas and condensate have often been misinterpreted in well logs as belonging to the top of Huamampampa SSt . That is the case of Miraflores and SJN x-2 wells among others (Fig.2,5b).

The isopach map of the Santa Rosa Fm. SSt. shows the same pattern of Huamampampa, in the sense of having a geographically similar depositional axis, defined by the Espejos, El Mataral and Yapacani control points, although probably being less displaced towards the Brazilian shield than the Huamampampa sequence set axis (cf. Montemurro, 1994). In coincidence with the southwestern basin margin zones, the sand record of the Santa Rosa Fm., even though in subsurface does not show the same quality as the Huamampampa cylindrical electric log patterns, is generally thicker and when possible to be investigated, it constitutes always an additional target.

Up to date, neither diagenetic nor integrated whole basin modeling studies have been done. Then, it can not be discarded the existence of potential plays related to quartz cement inhibition processes (early hydrocarbon migration, clay rims, overpressure, etc.), preserving the original porosity or creating it by dissolution (cf. Fernandez-Seveso & Surdam, 1997). Managing an integrated approach like that, it could be possible to assess the hydrocarbon potential for Los Monos and Huamampampa sandstones in the Chaco Plain subsurface, as well as pinch-outs towards the Brazilian shield. It is also worth to mention, that in the plains, the previous tops of Santa Rosa SSt. in the Tucavaca and Otuquis wells (Proyecto cooperativo de estudios de hidrocarburos en cuencas subandinas) based on regional seismic interpretation are re-interpreted as Huamampampa Top.

Finally, the proposed Chaco Basin reviewed framework not only allows to relate the productive reservoirs of different areas and to attempt predictions over those not investigated yet, but also it helps to plan future works to be carried out.

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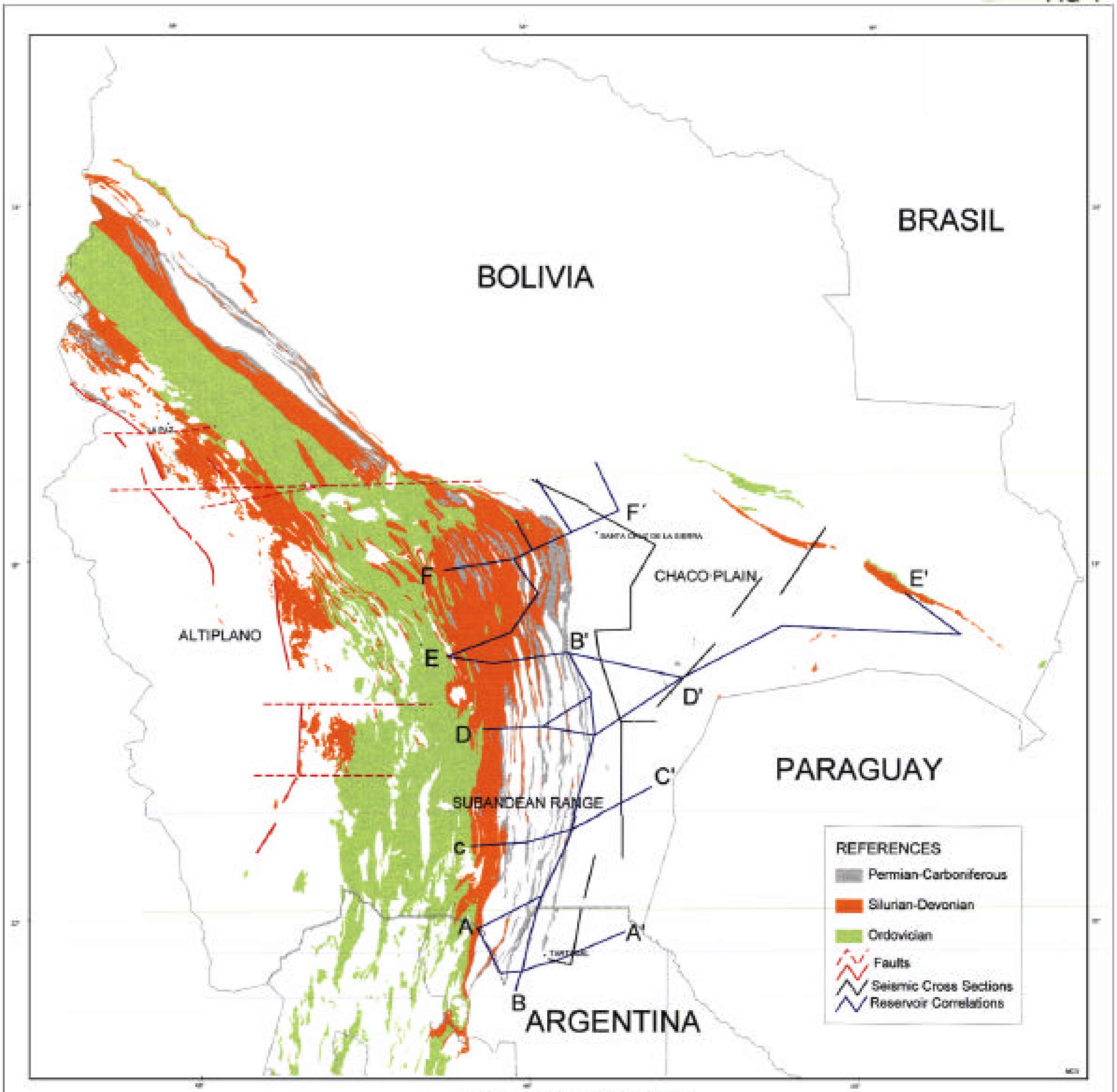
FIGURES

FIG 1

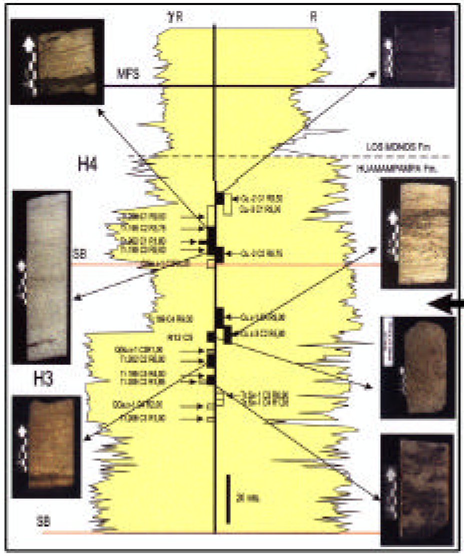


LOCATION MAP

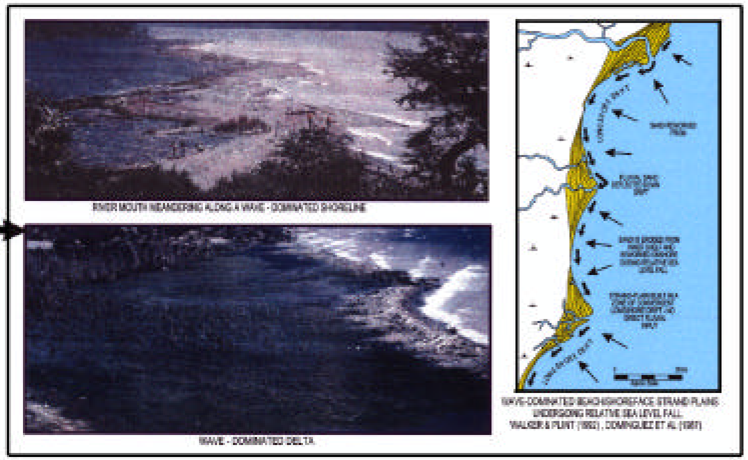
FIG 2

SED. & STRAT. APPROACH

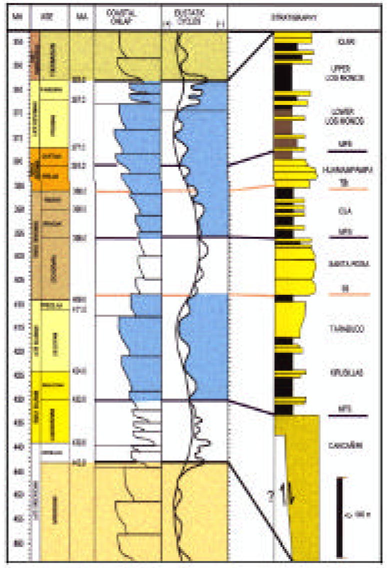
LOG PATTERN - SEQUENCE H3 & H4
HUAMAMPAMPA AND LOS MONOS CORES



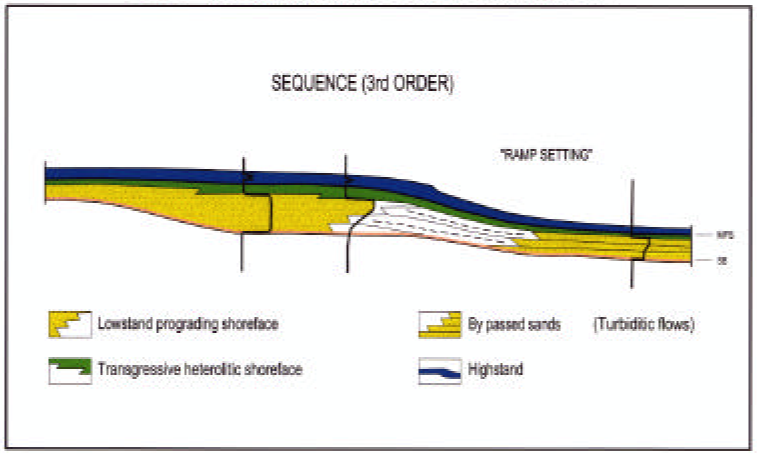
PRESENT-DAY ANALOGS CLOSE TO DEVONIAN ENVIRONMENTS (ARGENTINA)



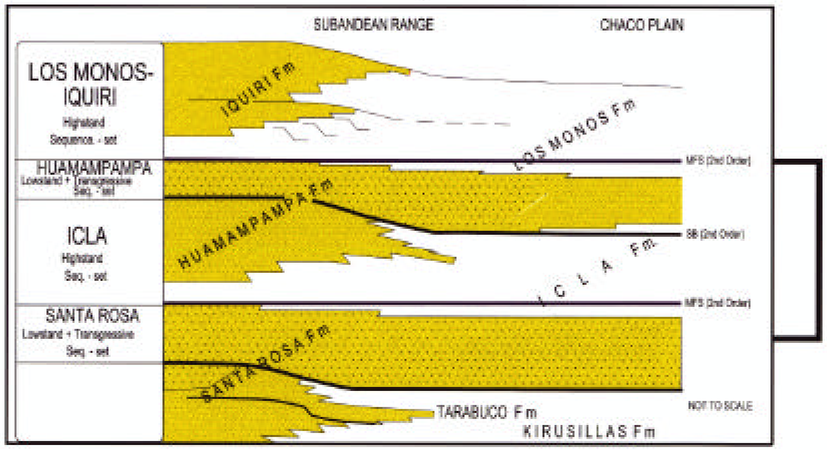
CHACO BASIN GLOBAL CORRELATION
(eustatic cycles after A. HALLAM 1992)



ICLA - HUAMAMPAMPA CONCEPTUAL MODEL



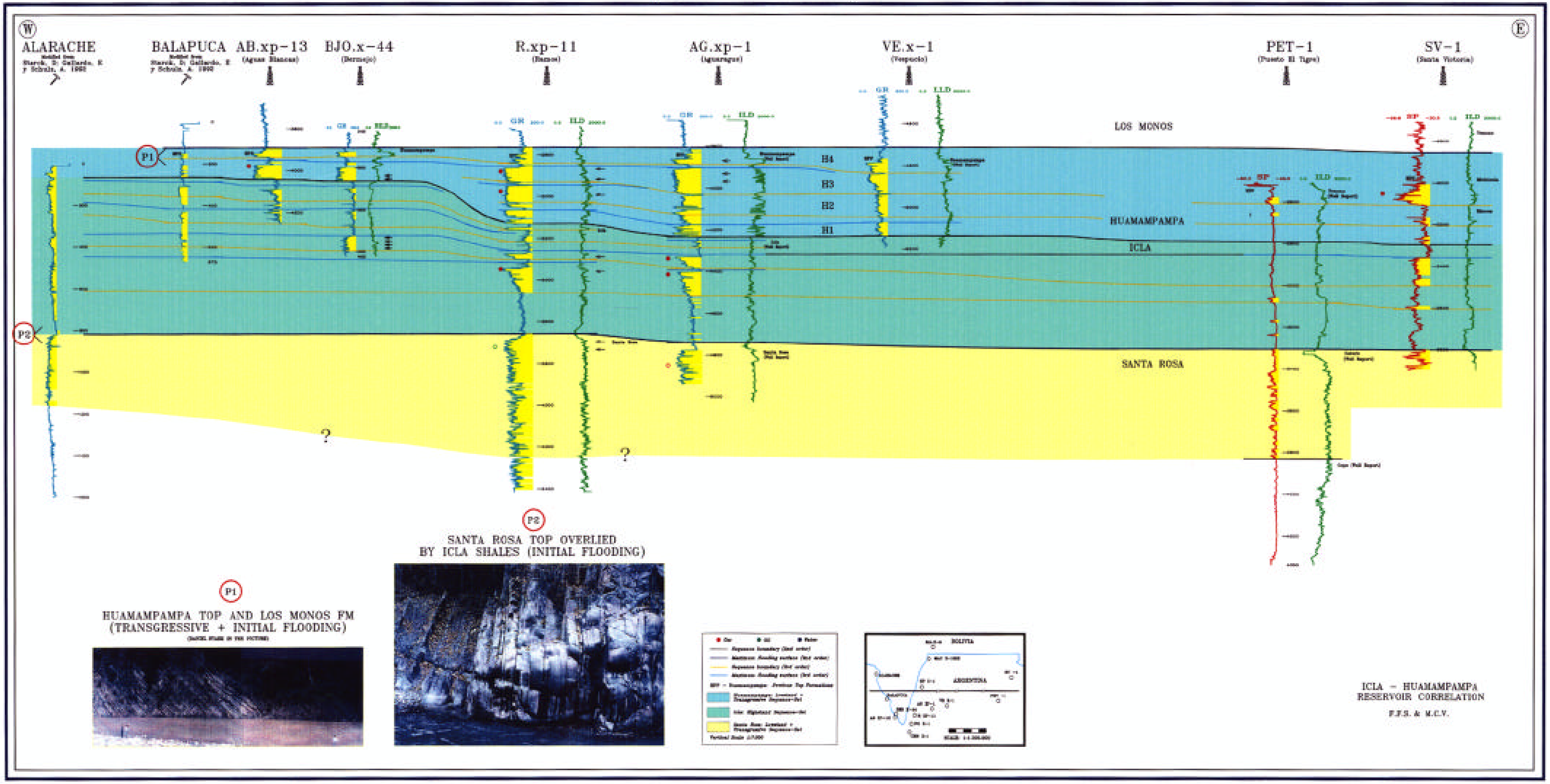
SEQUENCE SET (2nd Order)



ALARACHE-SANTA VICTORIA (A-A')

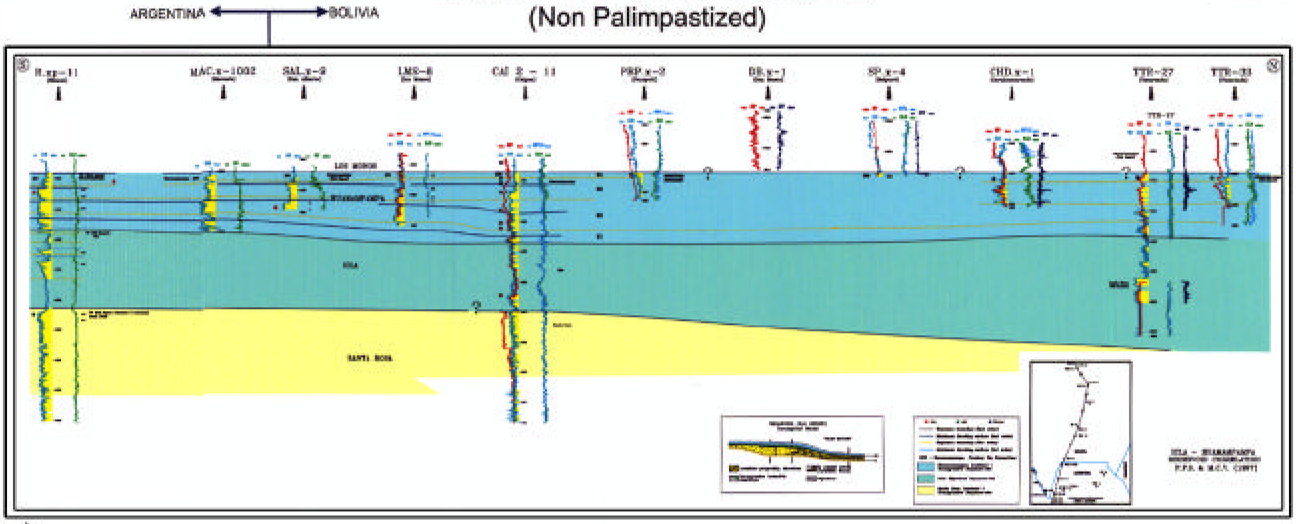
(NON PALIMPASTIZED)

FIG 3



RAMOS-TATARENDA (B-B') FIG 4

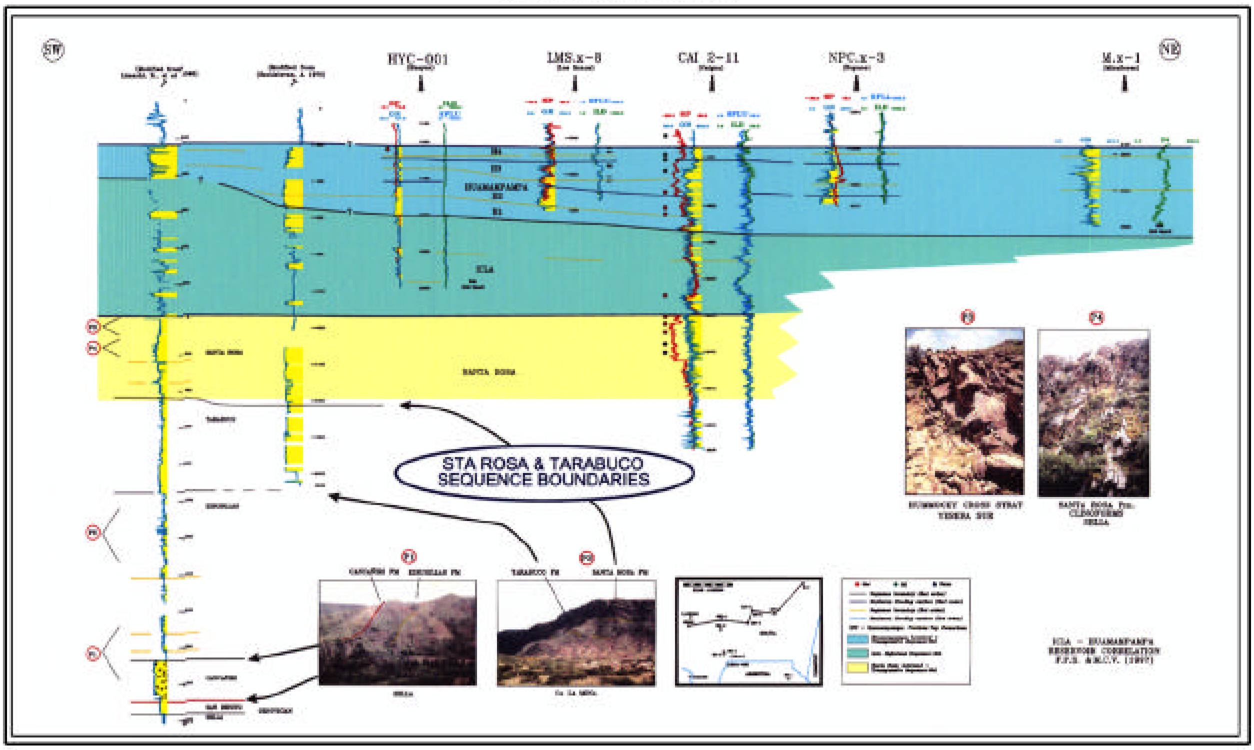
(Non Palimpastized)



a)

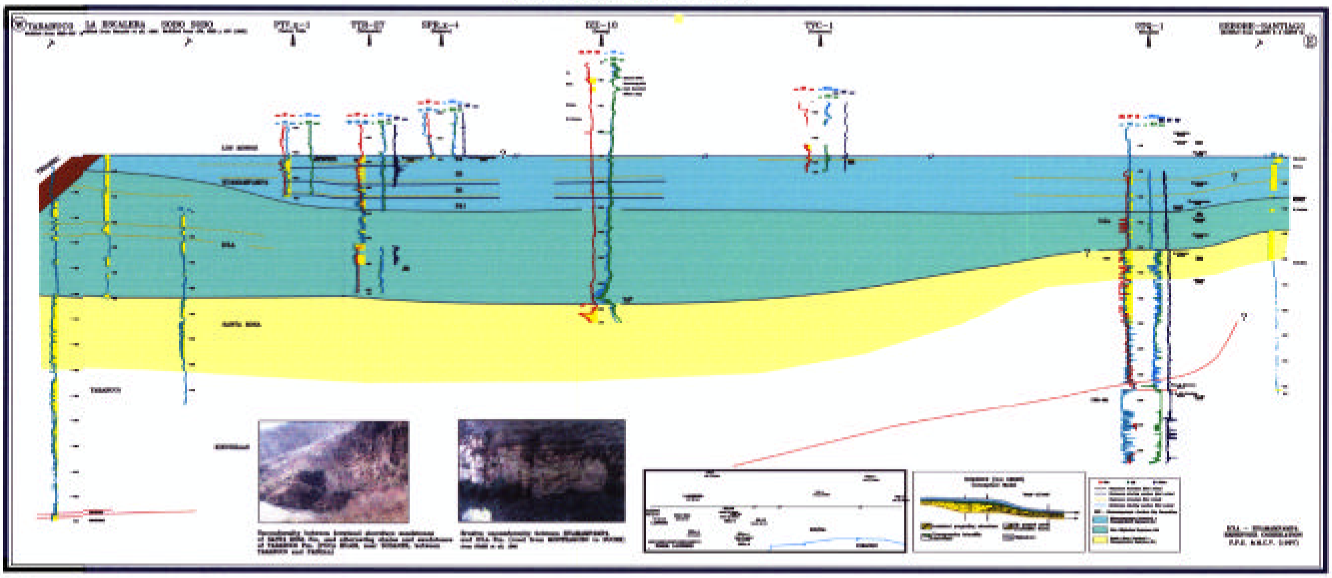
SELLA-YESERA - MIRAFLORES (C-C')

(Non Palimpastized)



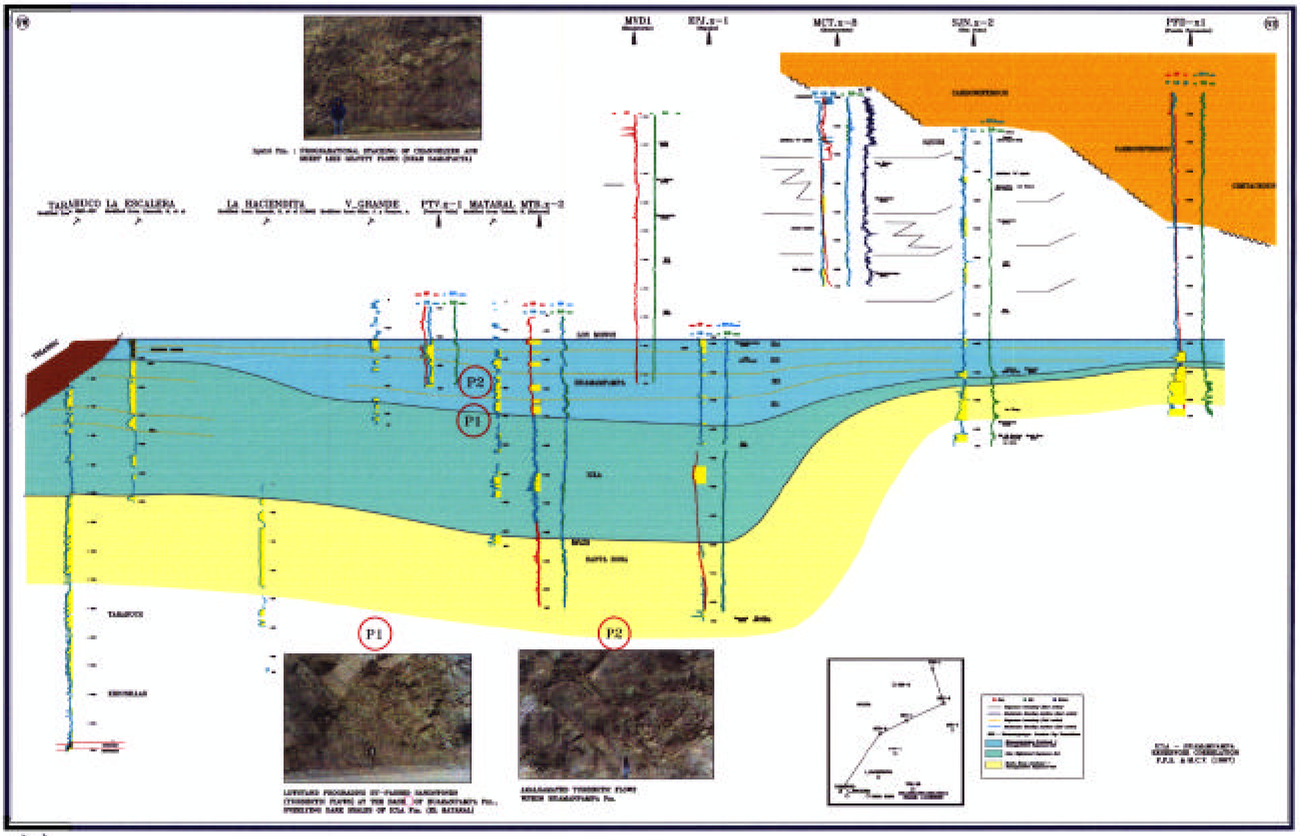
b)

TARABUCO-OTUQUIS (E-E') FIG 5
(Non Palimpastized)



a)

TARABUCO-PUESTO FERNANDEZ (E-F')
(Non Palimpastized)



b)

FIG 6

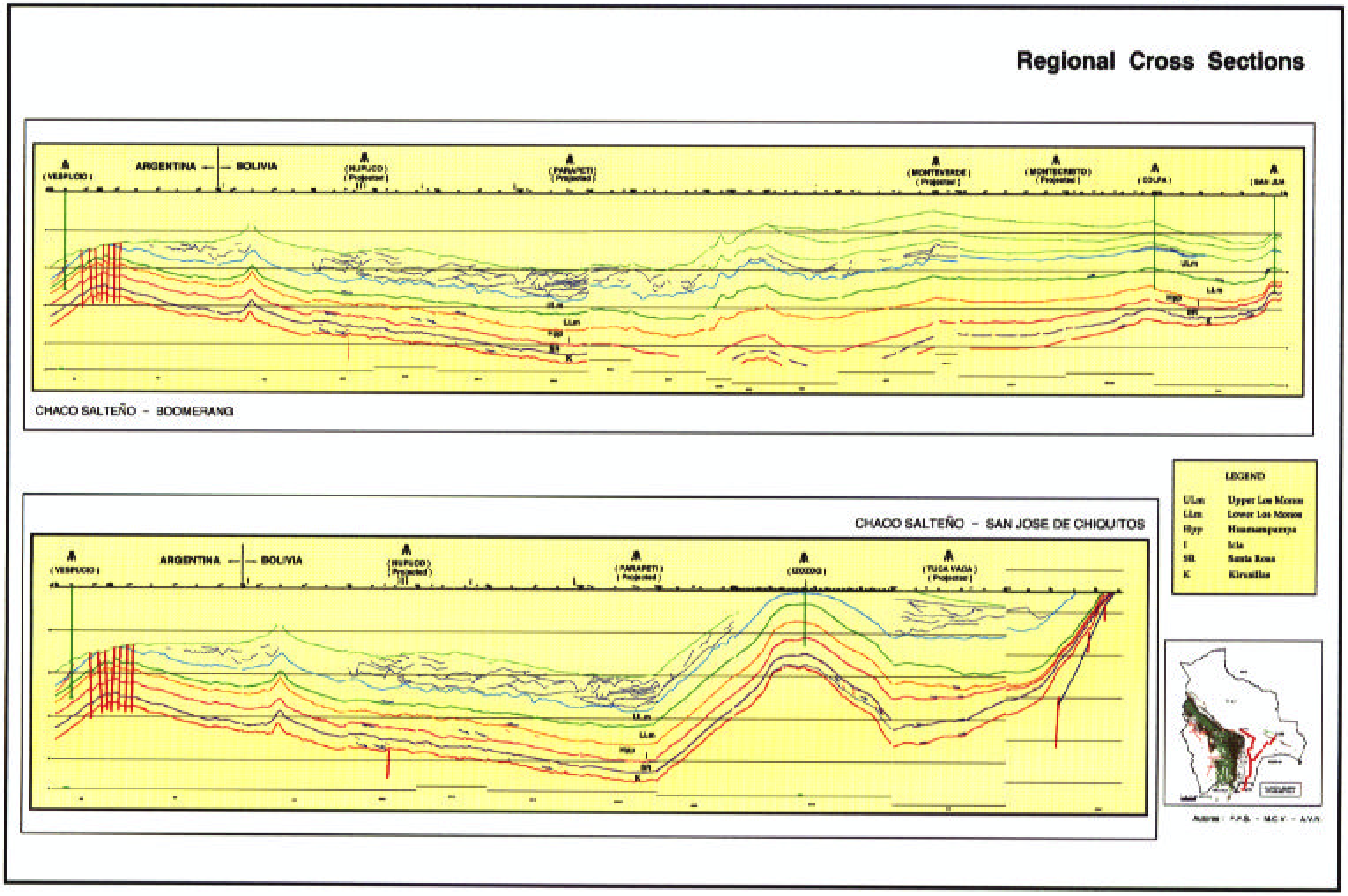
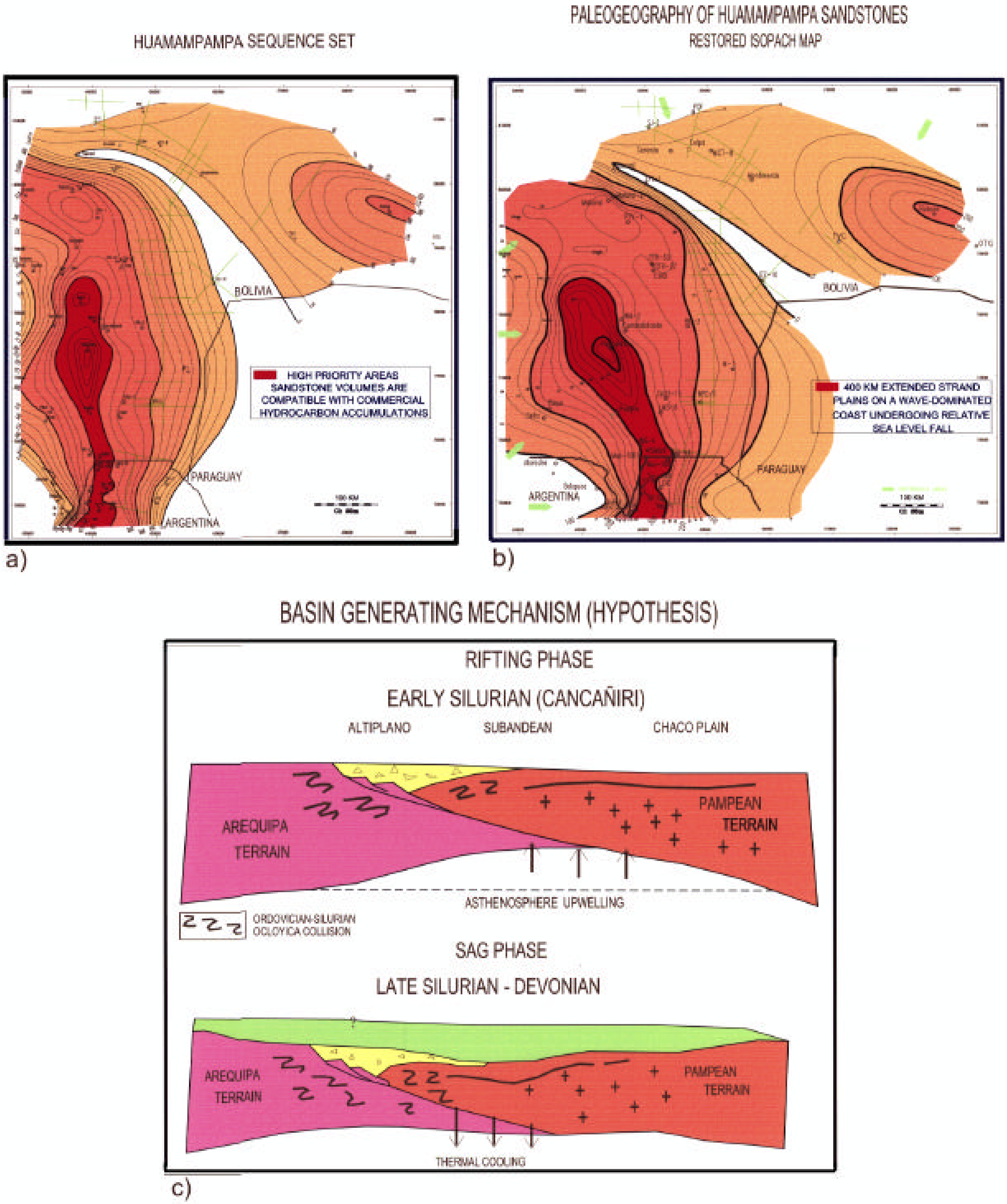

Regional Cross Sections
ARGENTINA — BOLIVIA
(VESPUCIO)
(PARAPETI) (Projected)
(MONTEVERDE) (Projected)
(MONTECRISTO) (Projected)
(SAN JUAN)
ULm
LLm
Hyp
I
SR
K
CHACO SALTEÑO - BOOMERANG
CHACO SALTEÑO - SAN JOSE DE CHIQUITOS
(TUCA VACA) (Projected)
LEGEND
ULm Upper Los Monos
LLm Lower Los Monos
Hyp Huamampampa
I Icla
SR Santa Rosa
K Kirusillas

FIG 7


HUAMAMPAMPA SEQUENCE SET
PALEOGEOGRAPHY OF HUAMAMPAMPA SANDSTONES
RESTORED ISOPACH MAP
BOLIVIA
PARAGUAY
ARGENTINA
HIGH PRIORITY AREAS
SANDSTONE VOLUMES ARE
COMPATIBLE WITH COMMERCIAL
HYDROCARBON ACCUMULATIONS
400 KM EXTENDED STRAND
PLAINS ON A WAVE-DOMINATED
COAST UNDERGOING RELATIVE
SEA LEVEL FALL
100 KM
a)
b)
BASIN GENERATING MECHANISM (HYPOTHESIS)
RIFTING PHASE
EARLY SILURIAN (CANCAÑIRI)
ALTIPLANO
SUBANDEAN
CHACO PLAIN
AREQUIPA
TERRAIN
PAMPEAN
TERRAIN
ASTHENOSPHERE UPWELLING
ORDOVICIAN-SILURIAN
OCLOYICA COLLISION
SAG PHASE
LATE SILURIAN - DEVONIAN
AREQUIPA
TERRAIN
PAMPEAN
TERRAIN
THERMAL COOLING
c)