COMMENTS ON THE TECTONIC EVOLUTION AND SEQUENCE STRATIGRAPHY OF THE CORDILLERAN BASIN, SILURIAN AND DEVONIAN OF BOLIVIA

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Resumen

Comentarios sobre la evolución tectónica y la estratigrafía secuencial de la Cuenca Cordillerana, Siluro- devónico de Bolivia.

Este trabajo presenta una revisión geológica del Siluro-devónico de Bolivia, depositado en la denominada Cuenca Cordillerana. Incluye el análisis de las distintas hipótesis de evolución de la cuenca y la aplicación de los conceptos de estratigrafía secuencial para correlación regional de datos de afloramientos y pozos exploratorios. A pesar de la escasez de datos paleogeográficos y estructurales confiables relativos al Siluro-devónico de Bolivia, la hipótesis de “rifting” en el Silúrico Inferior seguido por una fase de subsidencia térmica (“sag”) en el Silúrico Superior-Devónico sería la más adecuada en relación con los datos actualmente disponibles. Los datos estratigráficos analizados comprenden descripción de afloramientos, análisis palinológicos, recolección de datos cintilométricos y análisis de perfiles de pozos exploratorios de Bolivia y norte de Argentina. La interpretación de facies sedimentarias y sistemas deposicionales, ajustada con datos bioestratigráficos de detalle, posibilitó el reconocimiento de secuencias estratigráficas de 2ª orden (denominadas TAK, ISR y LMH). Este nuevo enfoque llevó a la realización de correlaciones estratigráficas regionales más consistentes que las tradicionales, basadas en una visión litoestratigráfica. El tracto de sistemas de mar bajo de la Megasecuencia LMH, que contiene los reservorios más importantes de gas de Bolivia (areniscas de la Fm.Huamampampa), fue subdividido en cuatro secuencias de 3ª orden (LMH-1 a 4), regionalmente correlacionables a través de la cuenca. El origen de potentes cuerpos arenosos aislados descriptos en las Secuencias LMH-1 y LMH-4 fue analizado a través de los conceptos de estratigrafia secuencial, con evidentes consecuencias para la futura exploración de gas en el sector centro-sur de Bolivia.

INTRODUCTION

The recent discovery of giant gas fields related to devonian reservoirs in southern Bolívia led to an increasing interest in detailing the basin evolution and stratigraphy of the Silurian and Devonian intervals deposited in the Cordilleran Basin of Bolivia and northern Argentina.

The geological evolution of the western margin of South America is closely related to the geodynamics of the southwestern margin of Gondwana. This margin comprised a mosaic of exotic terrains, amalgamated prior to the end of Proterozoic. The Brazilian tectonic event, which affected this region from Late Proterozoic to Early Cambrian, would have defined the structural framework of the subsequent Phanerozoic basins (Tankard et al. 1995). Several Early Paleozoic depocenters were created along this margin, representing its major 1st order tectonic-sedimentary cycles: Tacsarian (from Late Cambrian to Late Ordovician) and Cordilleran Cycles (Silurian and Devonian) (Soruco 1989; Zalan et al. 1990; Milani 1997). The Silurian-Devonian depocenters, with N-S and NW-SE trends, encompassed a broad area along the present-day southern Peru, Bolivia and northern Argentina. This depocenter is recognized in this study as Cordilleran Basin (Soruco 2000), instead of the generally accepted term Subandean basin, in order to avoid any direct relationship with the effects of the Tertiary Andean Orogeny. This orogeny intensively reactivated and masked most of the Early Paleozoic structural and paleogeographic elements (Figs. 1 and 2).

An extremely active geotectonic environment would explain the high subsidence rates during most of the Paleozoic. Several major marine transgressions led to the deposition of a predominant shallow marine siliciclastic section. On the other hand, the stratigraphic record is mostly continental from Mesozoic to Recent in this area (Sempere 1995).

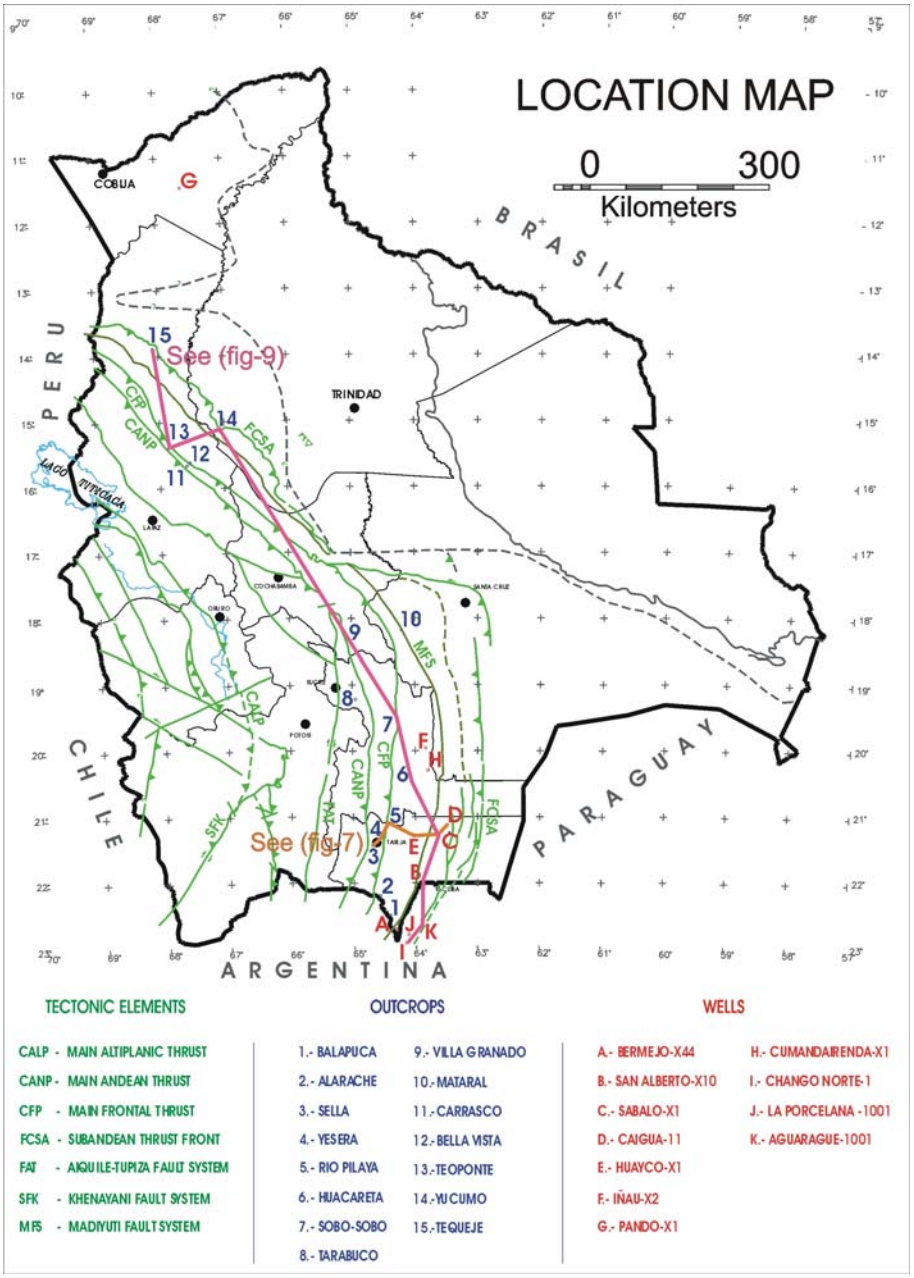


Figure 1. Location map of the well and outcrop sites investigated in this study.

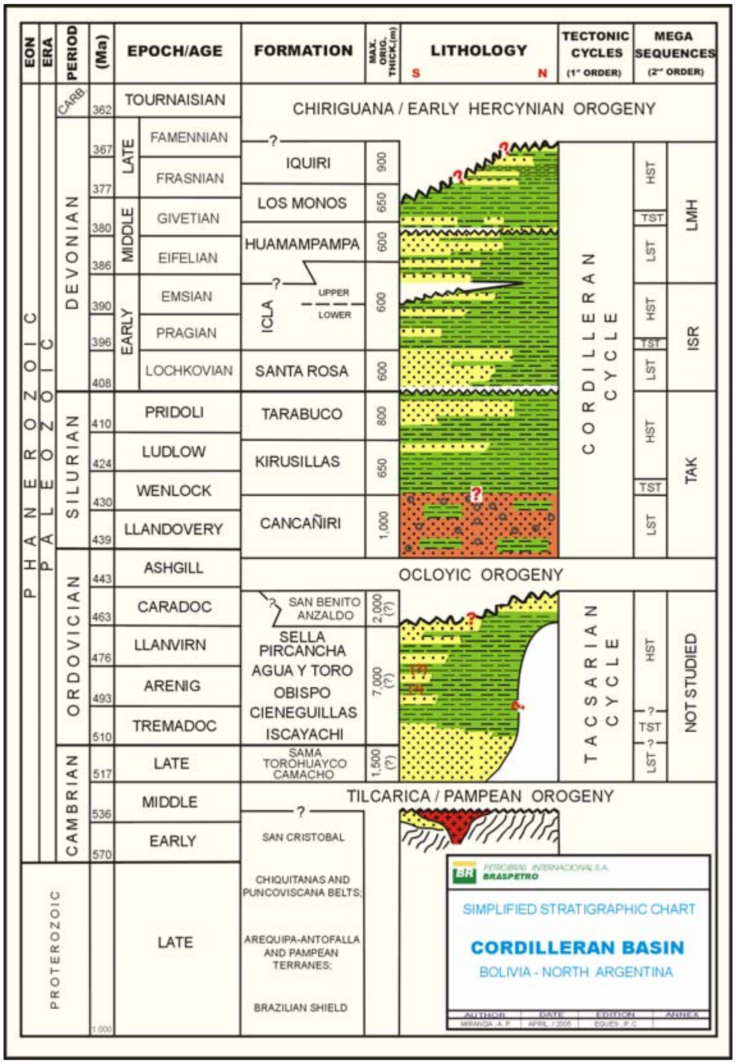


Figure 2. Stratigraphic Column.

During the Silurian and Devonian, according to the available geological data, there were no magmatic and metamorphic activities in Bolivia. Also, there is no evidence of contemporaneous fold & thrust belt, migration of any peripheral bulge and associated erosion effects in order to characterize the Cordilleran Basin in a foreland setting. Instead, the occurrence of fault-controlled Early Silurian depocenters (Sempere 1995) indicates that the origin of the Cordilleran Basin might be associated with a rifting process, followed by a subsequent thermal subsidence (sag) phase which lasted until at least the end of Devonian (Fernandez Seveso et al. 2000; Williams 1995). The tectonic regime at the plate margin was probably divergent during this period (Dalziel 1997; Bahlburg and Breitkreuz 1991). Transtensional and transpressional reactivations of the main tectonic elements of the basin might have controlled the depositional pattern during the Devonian.

A modern chronostratigraphic approach was only recently established for the Cordilleran Basin in Bolivia (Starck 1995, Souza Cruz et al. 1999, Miranda et al. 2000 and 2003), instead of the traditional lithostratigraphic nature of most of the available information. The application of sequence stratigraphic concepts allowed consistent regional correlations from northern Argentina to northern Bolivia.

Three major 2nd order Megasequences, denominated TAK, ISR and LMH, were defined in the basin, comprising major Silurian to Devonian eustatic cycles (Fig. 2). The lowstand system tract of the LMH Megassequence, which contains the main gas reservoirs discovered in the basin, was divided into four 3rd order sequences (LMH-1 to 4). The origin of the isolated paralic sand bodies observed in sequences LMH-1 and LMH-4 was discussed and related to a new potential gas exploration frontier in Bolivia.

METHODOLOGY

Sequence stratigraphic concepts were applied in this study, ìn order to analyze selected outcrop and well log data, distributed throughout Bolivia and northern Argentina (Fig. 1). This methodology, associated with a proper biostratigraphic input, led to the definition of 2nd and 3rd order sequences with a regional expression.

Outcrop data analysis consisted of the description of sedimentary facies and depositional systems, paleocurrents measurements, palynological sample collection and scintillometric data collection. The description of facies and depositional systems was much easier and effective in southern Bolivia, due to the well-preserved outcrops in such semi-arid environment, than in the north, where the humid tropical rainforest prevails. Paleocurrents were measured in sandstones deposited through unidirectional flow regime, consistently indicating a northward direction. As a consequence, siliciclastics were predominantly supplied to the basin from southern high areas in Argentina. The use of a modern biostratigraphic approach, based on palynological analysis in more than 200 samples collected in selected stratigraphic intervals, was a key tool for the purposes of this study.

Well data analysis consisted of the interpretation and correlation of selected wells in Bolivia and northern Argentina. Only few samples from selected wells were analyzed within the same palynological approach as the outcrop dataset. On the other hand, scintillometric data collected in outcrops showed very good correlation with well log data, allowing the refinement of regional correlations through outcrops and wells.

REVIEW OF CORDILLERAN BASIN ORIGIN AND EVOLUTION

The southwestern margin of Gondwana was submitted to several orogenic and magmatic events during Early Paleozoic, such as plate subduccion, collision of exotic terranes, rifting, uplift and erosion.

During the Tacsarian Cycle (Late Cambrian – Late Ordovician), a narrow half-graben was established in a back-arc setting, from northwest Argentina to southern Peru, filled by a siliciclastic section (Gohrbandt 1993). At the end of Ordovician, the collision of the Precordillera Terrain with Gondwana led to basin inversion and syn-orogenic magmatism in northwest Argentina. This orogenic event (Ocloyic Orogeny) produced remarkable uplift and erosion of Upper Ordovician sediments in the southern part of Bolivia and northern Argentina. The effects of the Ocloyic Orogeny are not clearly recognized in the north of Bolivia and south of Peru, where the Upper Ordovician sediments were apparently preserved. This fact might indicate that the collision of the Arequipa Terrain with Gondwana was not contemporaneous to the Precordillera event.

According to the divergent regime proposed for the plate margin during most of Paleozoic (Dalziel 1997; Bahlburg and Breitkreuz 1991), the clockwise translation of Laurentia along the southwestern Gondwana margin could have been responsible for the collision of distinct microplates with this margin from Ordovician to Carboniferous (Fig. 3). The younger age (post-Devonian) of syn-orogenic magmatism in Peru (San Nicolas Batholiths) than the one (Late Ordovician) observed in Argentina (Sierras Pampeanas) (Ramos, *pers.commun*.) might be related to this relative movement of Laurentia. As a consequence, the concept of a “proto-Cordillera” formed in response to the docking of a large continuous exotic terrain into the southwestern margin of Gondwana (from Chile to Peru) by the end of Ordovician (Arequipa-Belen-Antofalla Terrain) would be unlikely.

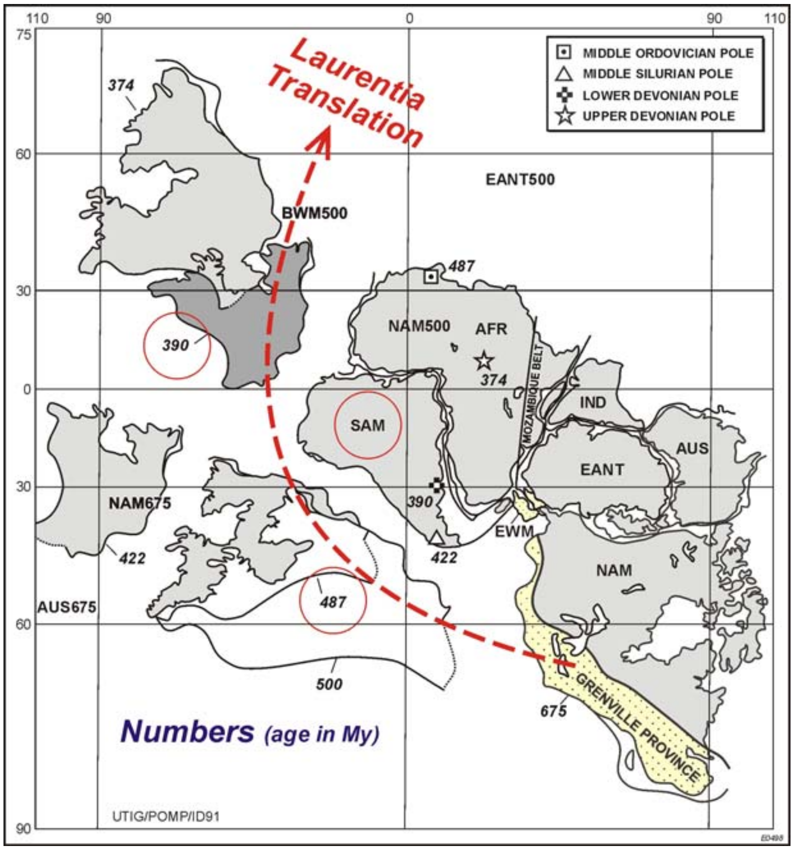


Figure 3. Paleozoic Translation of Laurentia (*after* Dalziel 1997).

During the Cordilleran Cycle (Silurian - Devonian), no magmatic and metamorphic activities, contemporaneous fold and thrust belts, erosional patterns due to forebulge translation or sedimentary patterns of a typical foreland setting have ever been described in the geological and geophysical dataset related to the Silurian and Devonian of Bolivia (Ramos 2001, Dalenz et al. 2002). On the other hand, some evidences indicate a possible extensional event that might have been associated with the creation of the Cordilleran Basin (Fernandez Seveso et al. 2000; Sempere 1995; Williams 1995).

A Latemost Ordovician (?) / Early Silurian rifting phase would have generated N-S trending fault-controlled depocenters, filled with glaciomarine sediments. The main rift faults might have reactivated some Late Cambrian structural elements. Available seismic data reveal that major folds and reverse faults related to the Andean Orogeny were developed over such Early Paleozoic horsts, which would have promoted discontinuities along detachment surfaces related to the Tertiary compressional regime (Fig. 4). In this sense, a tentative Early Silurian structural and paleogeographic configuration in Bolivia might take into account the present distribution of major regional Andean structural elements (Fig. 5).

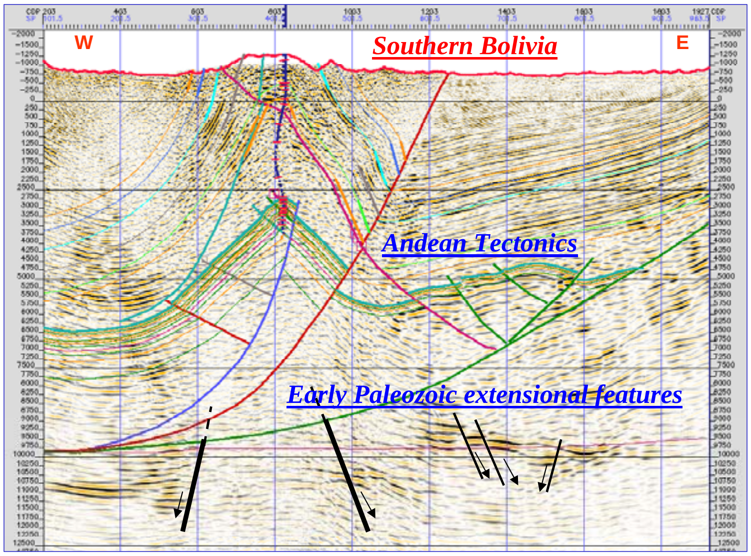


Figure 4. Seismic data showing the expression of Early Paleozoic extensional features.

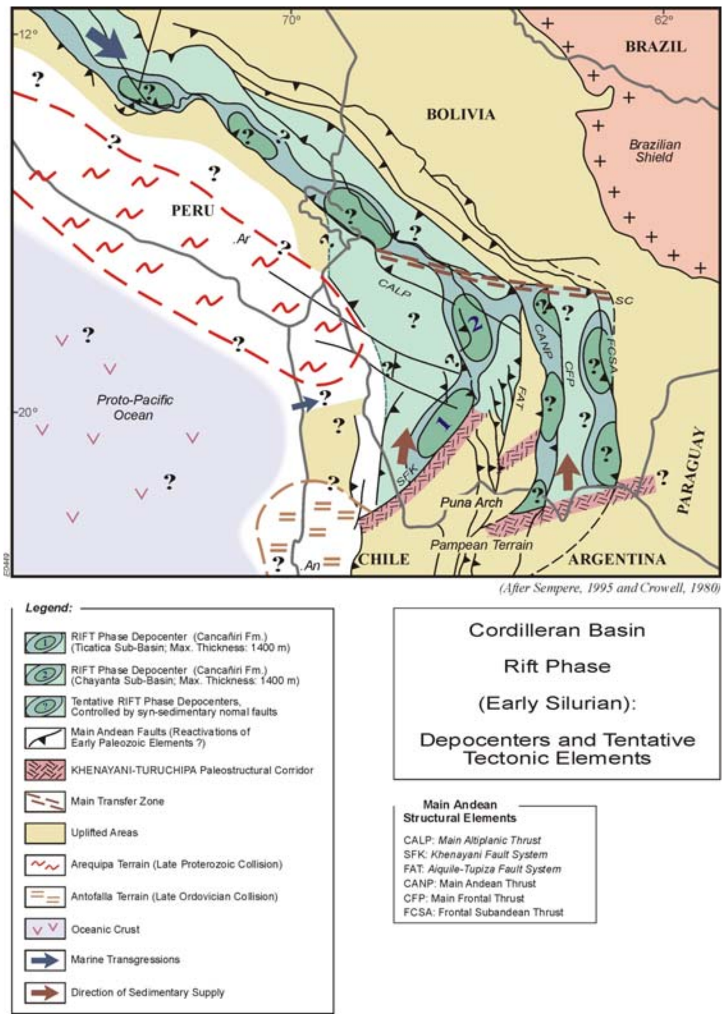


Figure 5. Early Silurian Rift Phase - Tentative Map for Bolivia and adjacent areas.

During the Late Silurian-Devonian thermal subsidence (sag) phase, transcurrent stresses generated at the plate margin would have been transmitted into the Cordilleran Basin. Transtensional reactivations of the previous main rift faults might have controlled the geometry and sedimentary filling along N-S trending structural lows during the Devonian. Such fault-controlled depocenters, mainly developed in southern Bolivia, were preferential zones for capturing fluvial drainage, forming incised valleys during major lowstands. Consequently, coarser clastic sediments, carried by rivers from the southern clastic supply areas (Pampean Terrain), could reach more basinal portions, northwards, through incised valleys in a fluvial-estuarine setting. Regional transgressions coming from the north over these low-gradient depocenters were responsible for their subsequent shallow marine siliciclastic filling. Transpressional reactivations of the extension of the Puna High into southern Bolivia and the NW-SE trending elements in northern Bolivia might have provided local clastic supply for the basin (Fig. 6). In this sense, thickness variations observed during Pragian in some outcrops in southern Bolivia would express a local tectonic control (Fig. 7).

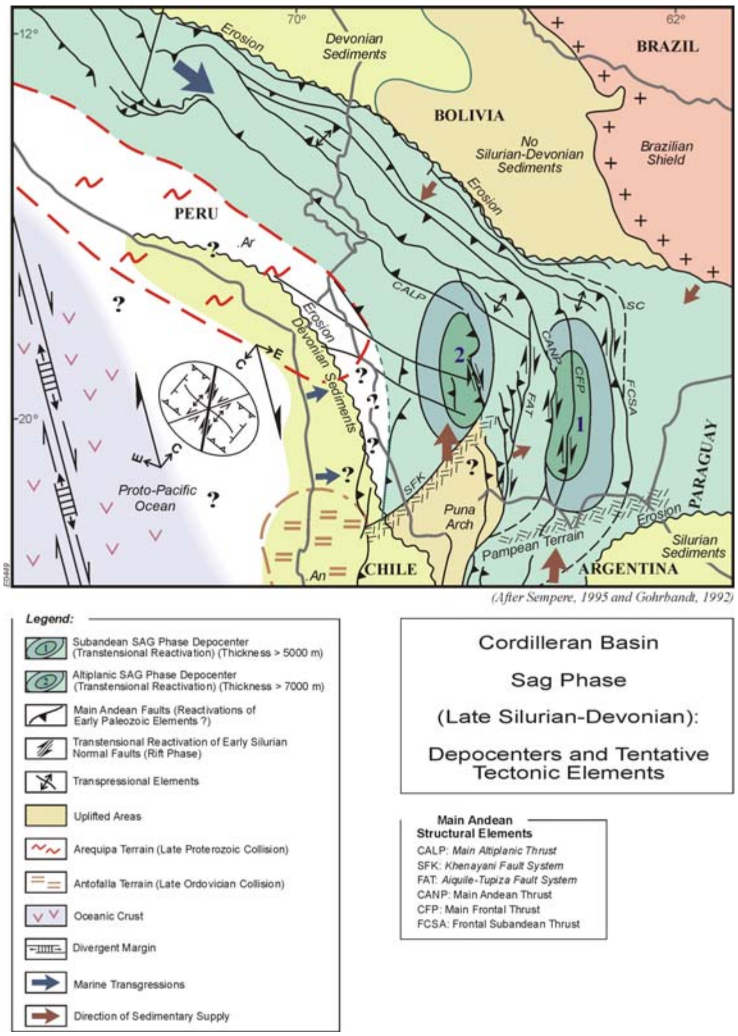


Figure 6. Late Silurian – Devonian Sag Phase – Tentative Map for Bolivia and adjacent areas.

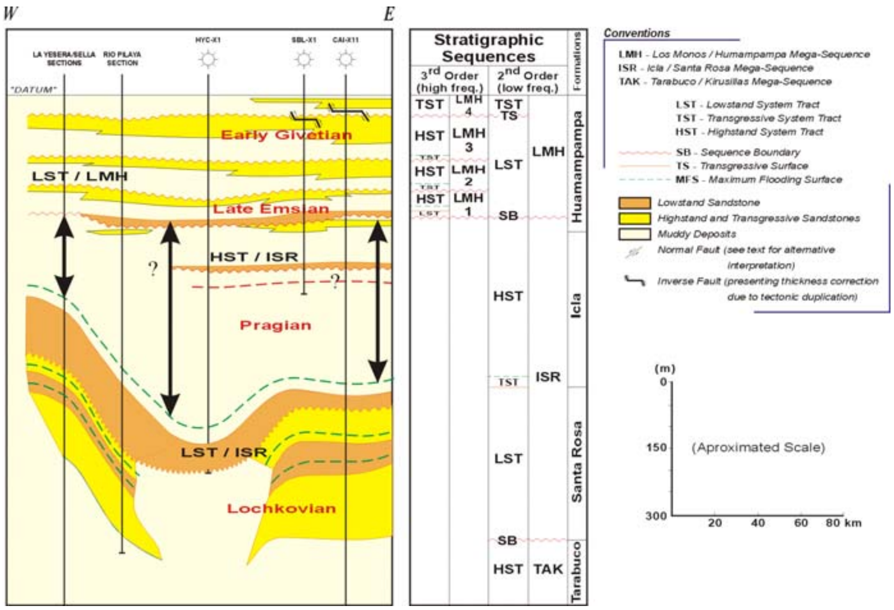


Figure 7. Thickness variations in the Pragian section of southern Bolivia (see Fig.1 for location).

The rift-sag evolution of the Cordilleran Basin was modeled through tectonic subsidence curves (Williams, 1995; this study) (Fig. 8). Larger sedimentary rates are normally associated with major 2nd order transgressive and highstand tracts, except for the interval that filled the Early Silurian depocenters, a major 2nd order lowstand, revealing a clear tectonic influence.

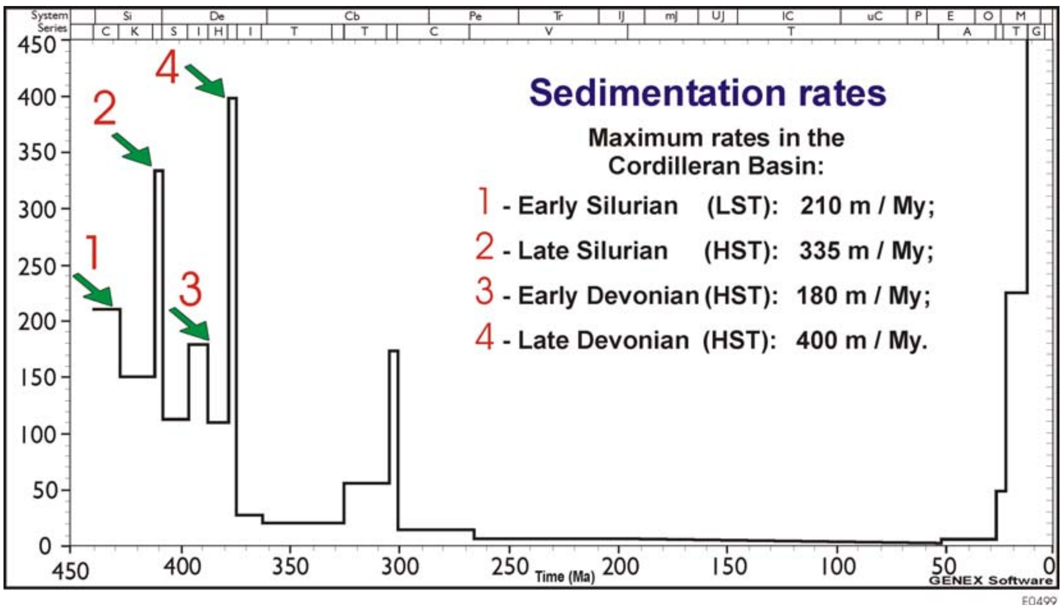


Figure 8. Sedimentation rates, Burial Geohistory and Lithospheric Strechting Curves.

SEQUENCE STRATIGRAPHY OF THE CORDILLERAN BASIN

As previously commented, the Early Paleozoic interval was subdivided into two 1st order stratigraphic cycles, already recognized by the existing literature, denominated Tacsarian and Cordilleran Cycles. The Cordilleran Cycle was divided into three 2nd order megasequences, denominated TAK, ISR and LMH Megasequences (Miranda et.al., 2000 and 2003).

The TAK Megasequence was partially described in this study, only related to the upper part of the Kirusillas and Tarabuco Fms., representing its transgressive (TST) and highstand system (HST) tract of the TAK Megasequence (Fig. 2). In southern Bolivia, this megasequence was described at Sella, Sobo Sobo and Tarabuco outcrops (Fig. 1). The lowstand system tract (LST) is represented by glaciocontinental and glaciomarine sediments (Cancañiri Fm.), of Latemost Ordovician to Early Silurian age, deposited in fault-controlled depocenters. The transgressive system tract (TST) is predominantly formed by shallow marine shales (Kirusillas Fm.), of Late Silurian age, while the highstand tract (HST) is composed by marine shales and tempestites with HCS (hummocky cross-stratification), of Late Silurian age, deposited in middle to upper shoreface (Tarabuco Fm.). Locally, coarser sandstones with tangential and parallel cross-stratification were deposited in upper shoreface to foreshore environments, at the top of the TST and HST coarsening upward parasequences. In northern Bolivia, this megasequence was only observed at Rio Carrasco outcrop, represented by fine-grained shallow marine clastics. There, in other outcrops, the Devonian section directly overlies Ordovician sandstones, showing a pronounced erosion or non-deposition of the Silurian package in most of northern Bolivia (Fig. 9).

The ISR Megasequence was described in southern Bolívia at Sella, La Yesera, Pilaya, Sobo Sobo, Tarabuco and Alarache outcrops and, in northern Bolívia, at Rio Carrasco, Tequeje, Teoponte, Yucumo/Arroyo Seis and Bella Vista outcrops (Figs. 1 and 2). In southern Bolivia, the basal limit (SB) of the ISR Megasequence is represented by a regional unconformity, related to a major relative sea-level fall in the beginning of the Lochkovian.

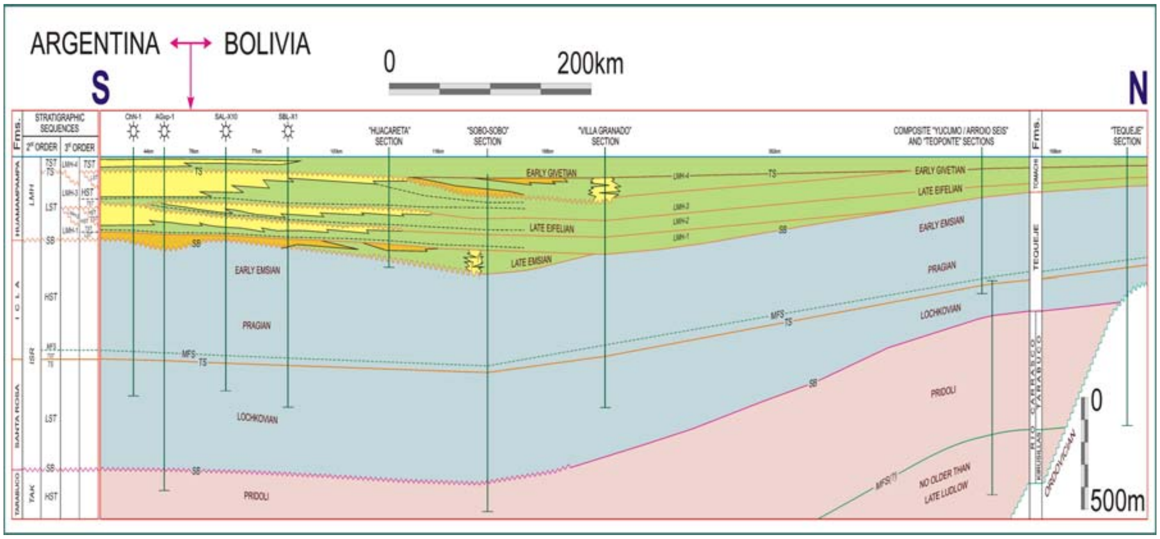


Figure 9. N-S Stratigraphic (Dip) Cross-Section from Argentina to Bolivia, based on sequence stratigraphic concepts (datum: 2nd order TS of LMH Megasequence) (see Fig.1 for location).

The LST is predominantly composed by thick sandstones with trough and sigmoidal cross-bedding, of Lochkovian age, deposited in fluvial, deltaic and shallow marine environments (Santa Rosa Fm.). A transgressive surface (TS) was formed as a response to a quick relative sea level rise in the beginning of Pragian, showing an anomalous concentration of marine fossils and wave-reworked deposits. Since the maximum flooding surface (MFS) was rapidly achieved, the TST (basal part of Icla Fm.) is constituted by a thin shaly package. The HST is composed by thick prograding deposits, forming coarsening upward parasequences (upper part of Icla Fm.), of Pragian to Early Emsian age, also deposited in a wave-dominated shallow marine platform. In northern Bolivia, the basal SB of ISR Megasequence is represented by its correlative conformity.

A thick shaly interval interbedded with minor tempestites (Tequeje Fm.), deposited in a shallow marine environment, encompasses the LST, TST and HST related to this megasequence (Fig. 9).

The LMH Megasequence was described in all analyzed outcrops (Figs. 1 and 2). In southern Bolivia, the basal limit (SB) of the LMH Megasequence is represented by a regional unconformity, related to a major relative sea-level fall during the Middle Emsian. This unconformity is consistently correlated through outcrop and well data along this area (Melo 2000).

The LST of the LMH Megasequence, of Late Emsian to Early Givetian age, was subdivided into 3rd order sequences (LMH-1 to 4) and regionally correlated throughout southern Bolivia (Huamampampa Fm.) (Fig. 9). The 3rd order LSTs were only developed and partially preserved at the base of LMH-1 and LMH-4 sequences. Thick argillaceous lowstand sandstones were deposited in a fluvial-estuarine environment. These sandstones, with a clear tidal influence (occurrence of mud couplets and mud drapes), bypassed the platform towards distal areas to the north, through fault-controlled incised valleys, during forced regressions. The 3rd order TSTs and HSTs are predominant, as expected in a ramp-type basin. Thick clean sandstones interbedded with minor bioturbated fine-grained sandstones, siltstones and shales, predominantly deposited in HST braid-deltas and upper shoreface environments, are distributed not far from the southward clastic supply areas in Argentina. Northwards, into southern Bolivia, these cleaner sandstones grade to fine-grained clastics with higher mud content, deposited in a shallow marine platform. The recognition of discrepancies between lithostratigraphic and chronostratigraphic approaches is critical for the analysis of the LST of LMH Megasequence. Although its major sand/shale limit is lithostratigraphically related to the contact between Huamampampa and Icla Fms., this surface is indeed diachronous, as expressed by the age of LMH-1 (Late Emsian) and LMH-4 (Early Givetian) basal contacts (Fig. 10). The TST of the LMH Megasequence, of Middle Givetian age, is characterized by a rapid regional transgression that reworked the top of lowstand deposits (TS). A relatively thin shallow marine shaly section (basal Los Monos Fm.) was deposited prior to the MFS. The HST of the LMH Megasequence, of Late Givetian to Famennian age (upper part of Los Monos and Iquiri Fms.), was only described in very few outcrops due to the intense erosion caused by the Early Hercynian Orogeny.

In northern Bolivia, the Middle Emsian relative sea level fall event is expressed by its correlative conformity, a condensed section observed by the analysis of palynological data from Tequeje outcrop. No LST was recorded in this relatively distal platform area. The TST and HST of LMH Megasequence are represented by a thinner shaly interval also deposited in a shallow marine setting.

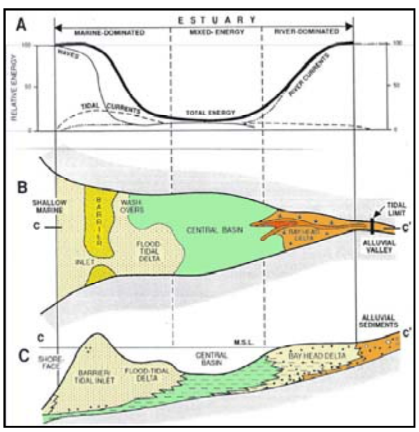
Figure 10. Chronostratigraphic x Lithostratigraphic approach (contact between Icla and Huamampampa Fms.)

A schematic regional N-S (dip) stratigraphic cross-section, from north Argentina to north Bolivia (> 1,000 km), was made based on the concepts of sequence stratigraphy applied to both outcrop and well data (Fig. 9). This chronostratigraphic section shows the remarkable lateral persistency of 2nd and 3rd order sequences throughout the basin. Most of these sequences tend to get thinner northwards, away from the most important clastic supply areas situated in the Pampean Terrain in Argentina. Besides this, the transtensional reactivation of N-S trending rift faults would have created more effective accomodation spaces along central and southern Bolivia (Fig. 6).

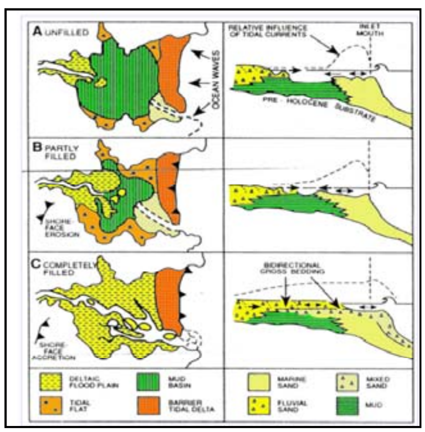
ISOLATED FLUVIAL-ESTUARINE SAND BODIES

The origin of isolated sand bodies deposited in shallow marine environments has been intensively debated during the last decade (Snedden and Bergman 1999). After comparing several distinct models regarding the Cordilleran Basin, the present study concludes that the most appropriate model for the isolated lowstand sand deposits of LMH Megassequence (LST of both LMH-1 and LMH-4 sequences), deposited in central / southern Bolivia, is the wave-dominated estuarine model (Dalrymple et al. 1992) (Fig. 11). These estuaries present a typical tripartite distribution: a more proximal fluvial and bay-head delta systems, an intermediate central basin, filled by fine-grained sediments, and a sand plug at the mouth of the estuary, presenting a thick clean sand interval with parallel to tangential cross-bedding, deposited in foreshore to upper shoreface environments. All these elements were described in the LMH-1 and LMH-4 lowstand deposits (Figs. 12, 13, 14 and 15). Sediment reworking due to subsequent transgressions may promote erosion of fluvial-estuarine sandstones, which become isolated, surrounded by paralic shales. A clear progradational pattern can be observed by the analysis of the fluvial-estuarine systems deposited in the lowstand system tract of the 2nd order LMH Megassequence, as suggested by the gradual northward shift of the forced regressions (Figs. 9, 12, 13, 14 and 15). This progradational pattern was interrupted after the major marine transgression recorded by the 2nd order transgressive surface (TS), of Early Givetian age, relative to the LMH Megassequence (Fig. 9).

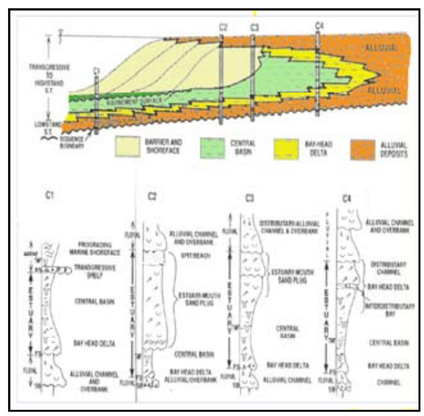
Stratigraphic or combined traps defined through geological and geophysical mapping of these isolated devonian sand bodies (up to 100 m-thick), in southern and central Bolivia, may constitute a new exploration target for the Cordilleran Basin.



Schematic Configuration of Wave-dominated Estuaries



Sedimentary Filling Stages of Wave-dominated Estuaries



Sequence Stratigraphic System Tracts defined in a schematic dip cross-section along a Wave-dominated Estuary

Figure 11. Model for Wave-dominated estuaries (Dalrymple, 1992).

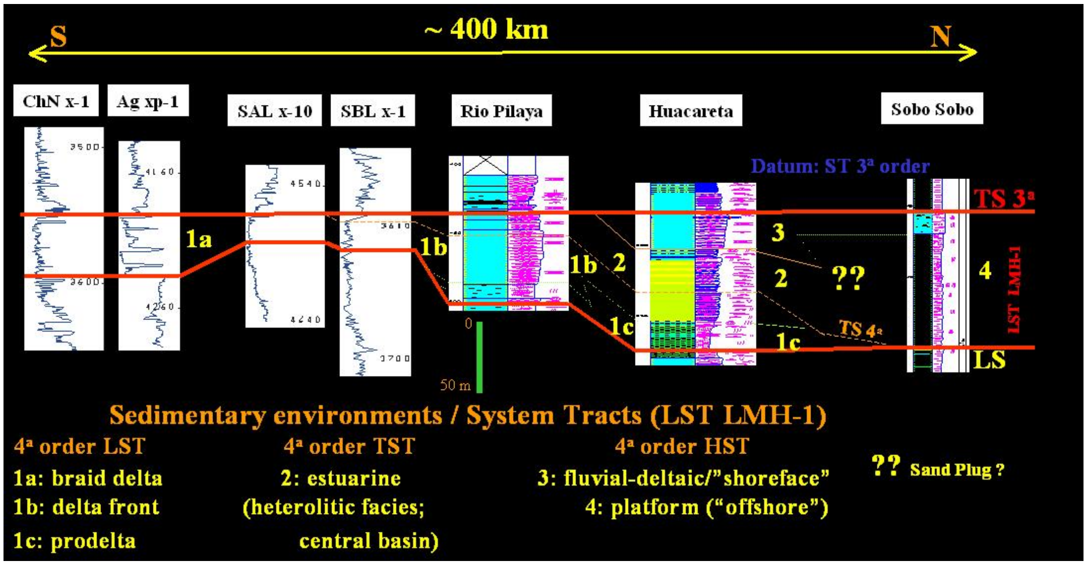


Figure 12. N-S Stratigraphic Cross-Section - 3nd order LST of LMH-1 Megasequence.

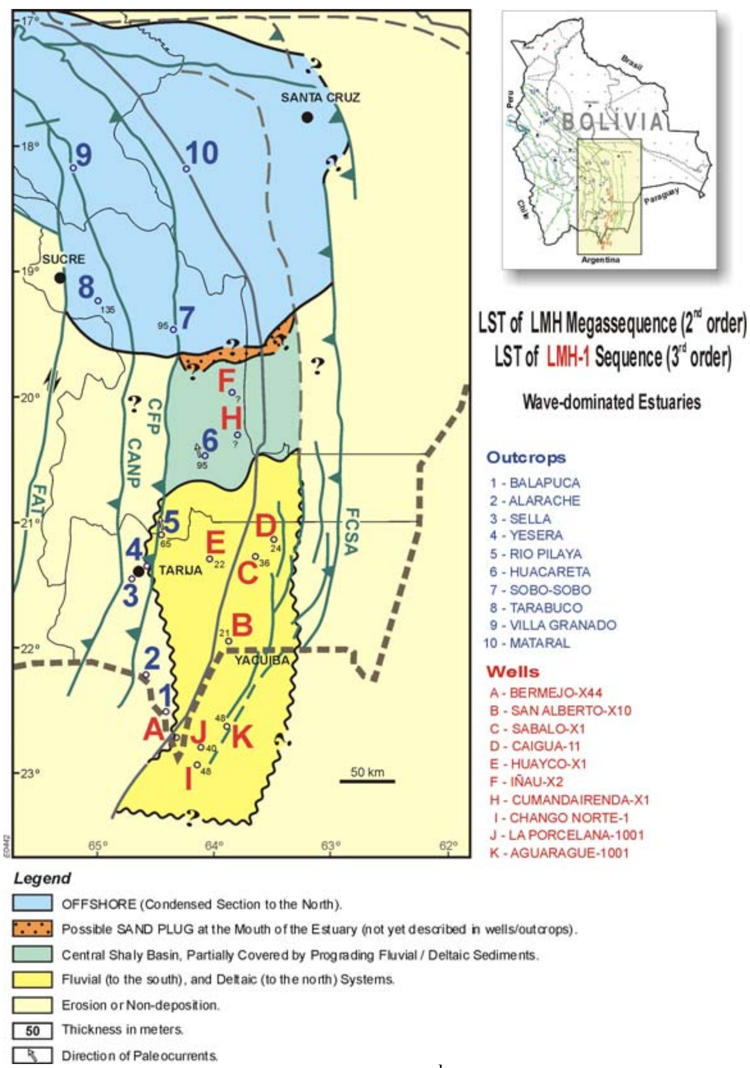


Figure 13. Paleogeographic map - 3nd order LST of LMH-1 Megasequence.

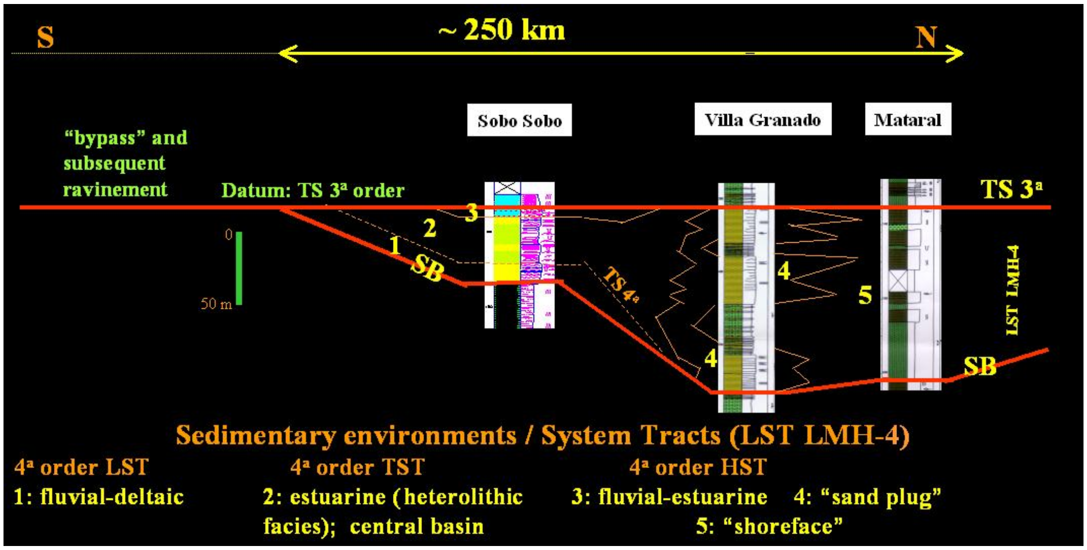


Figure 14. N-S Stratigraphic Cross-Section - 3nd order LST of LMH-4 Megasequence.

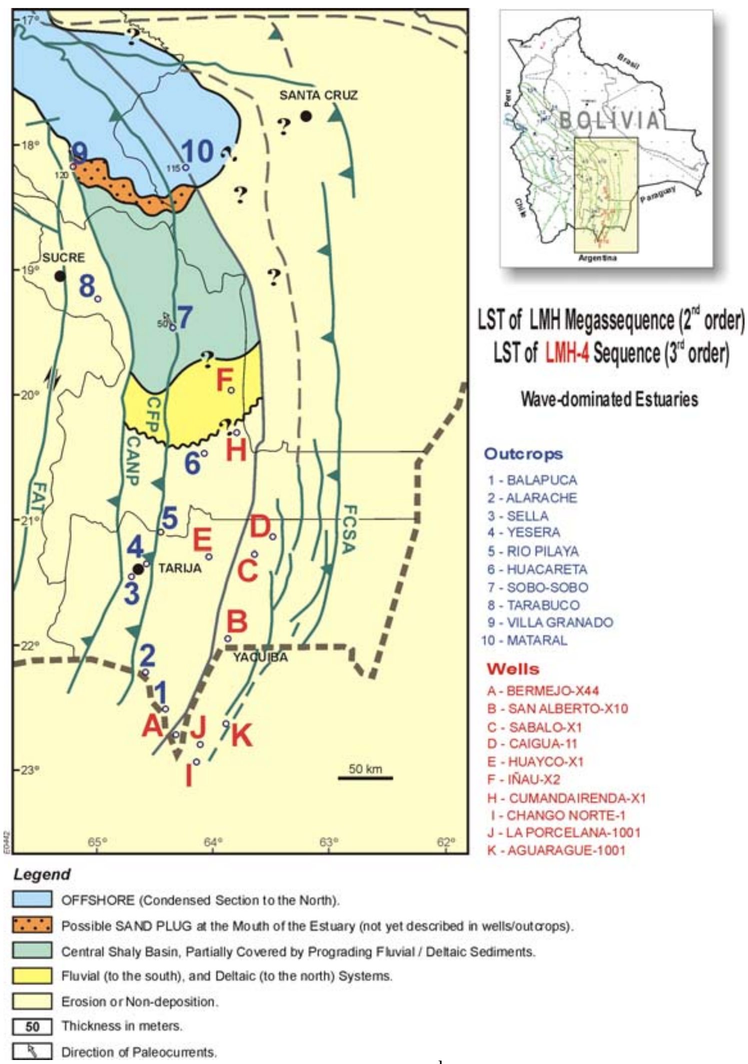


Figure 15. Paleogeographic map - 3nd order LST of LMH-4 Megasequence.

CONCLUSIONS

1) The intense deformation observed in the Phanerozoic section of Bolivia resulted from the effects of the Tertiary Andean Orogeny. As a consequence, there are few direct evidences of the structural and paleogeographic setting of the Silurian - Devonian Cordilleran Basin. A review of the available information led to the conclusion that the origin and evolution of this basin is related to a Late Ordovician (?) / Early Silurian rift and subsequent Late Silurian - Devonian thermal subsidence (sag) phases.

2) The 1st order Cordilleran Cycle was subdivided into three 2nd order megasequences (TAK, ISR and LMH). The lowstand system tract (LST) of the LMH Megasequence was then subdivided into 3rd order sequences, containing the most important gas reservoirs of the Cordilleran Basin. The 2nd and 3rd order sequences were easily recognized in both well and outcrop data and controlled by adequate biostratigraphic data.

3) Within de 2nd order LST of the LMH Megasequence, thick clean 3rd order HST fluvial and deltaic sand bodies were predominantly deposited southwards, in the proximal area of the basin, closer to the main clastic supply areas in Argentina. In southern Bolivia, thick 3rd order LST fluvial estuarine sand bodies were deposited, some of then isolated due to subsequent ravinement. In the more distal area of the basin, from central to northern Bolivia, the sand content is dramatically reduced and the sequences are basically composed of thinner shaly intervals, deposited in a shallow marine platform.

4) The genetic and paleogeographic characterization of the isolated fluvio-estuarine sand bodies of Devonian age may contribute for the definition of a new exploration frontier for the Cordilleran basin. Additional geological and seismic data must be acquired in order to allow the mapping of potential stratigraphic or combined traps.

5) Future stratigraphic studies to be performed in the Phanerozoic of Bolivia would have to apply the sequence stratigraphy methodology in order to obtain reliable regional correlations, with proper chronostratigraphic support.

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