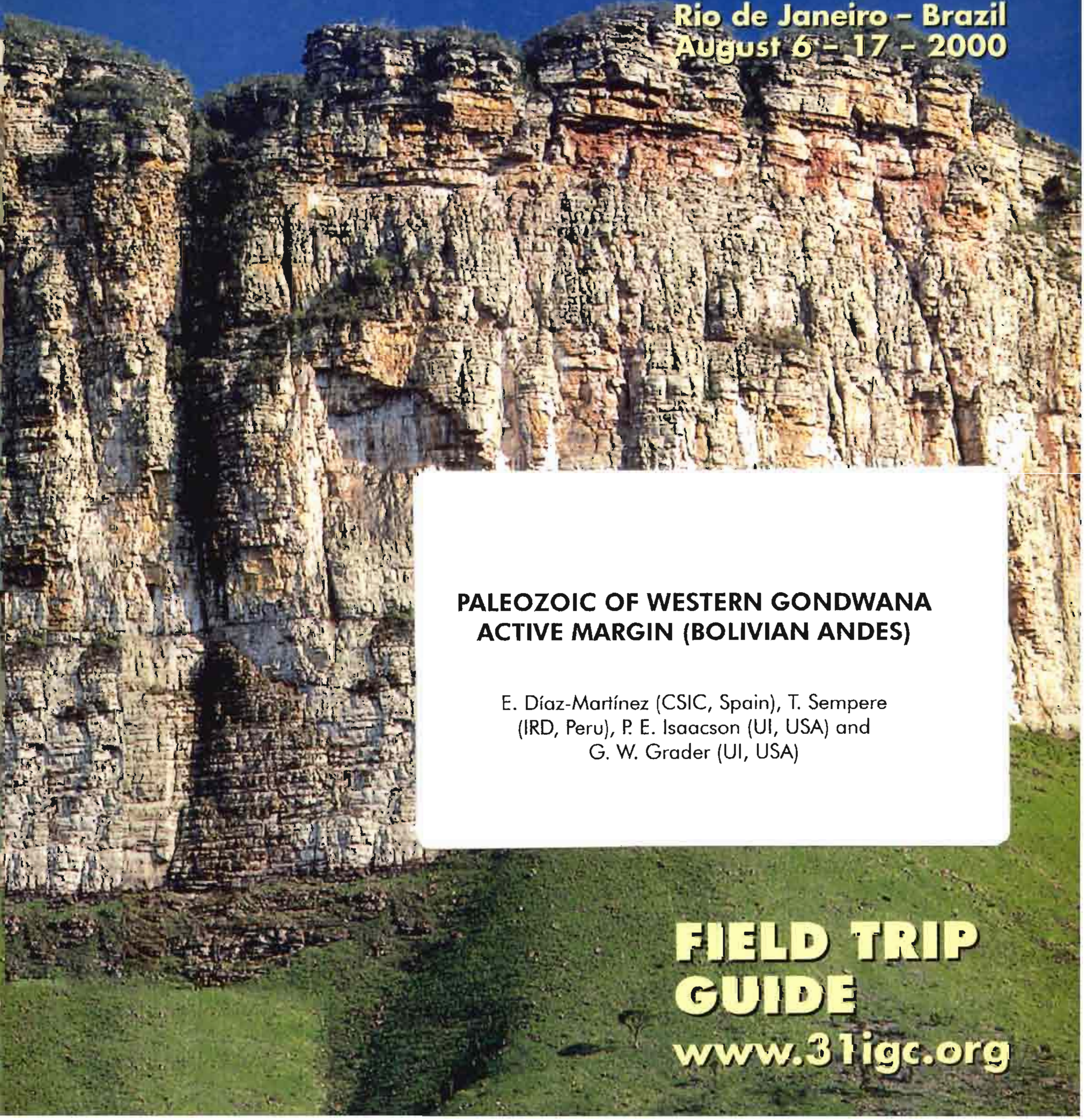
31st INTERNATIONAL GEOLOGICAL CONGRESS

Rio de Janeiro - Brazil
August 6 - 17 - 2000



PALEOZOIC OF WESTERN GONDWANA ACTIVE MARGIN (BOLIVIAN ANDES)

E. Díaz-Martínez (CSIC, Spain), T. Sempere (IRD, Peru), P. E. Isaacson (UI, USA) and G. W. Grader (UI, USA)

FIELD TRIP GUIDE

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FIELD TRIP SUMMARY

A visit to the main type stratigraphic sections of the Paleozoic record present in one of the larger Paleozoic basins of western Gondwana: the pericratonic (backarc and foreland) Peru-Bolivia basin of the Central Andes. This fieldtrip provides an opportunity to study the outcrops of the sedimentary record present in this basin as it relates to: a) orogenies affecting the continental margin; b) Ashgill-Llandovery and Famennian-Mississippian glaciations; c) deep and shallow marine siliciclastic environments; d) shift to Pennsylvanian-Early Permian mixed carbonate-siliciclastic ramp environments with evaporites resulting from the paleoclimatic and latitudinal changes of Gondwana; and e) sequence stratigraphy and diastrophic phases. Also included are visits to sites such as Lake Titicaca and the Tiwanaku ruins in the Altiplano, and the possibility of observing *in situ* the classical invertebrate fauna of the highly endemic Malvinokaffric biogeographic realm, and the West-Texas cosmopolitan faunas.

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INTRODUCTION

The area today known as Bolivia has been famous since prehistoric times for its natural resources, and in particular for its mineral wealth. In the 16th century, when the Spanish began to explore what was known to them as Upper Peru, they discovered that the native American people had been mining precious metals for hundreds of years. The unparalleled production of precious metals from the New World, including the silver mines of Bolivia, supported the development of Europe during the following centuries. The wars for independence culminated in the founding of Bolivia in 1825. The mineral and energy resources of this country have been developed in response to regional demand and world market economy: silver, copper, tin, tungsten, gold, hydrocarbon... Most of these resources have either originated, or are hosted, in units of Paleozoic age. Furthermore, many deposits which originated during the Mesozoic and Cenozoic development of the Andes, are frequently closely related with previous (Precambrian and Paleozoic) orogenic processes and inherited structures.

This fieldtrip is an attempt to contribute towards the understanding of the early geologic history of the Central Andes. This is done through visits to the main classical sections of the Paleozoic units around the city of La Paz. We herein will first provide an overview of the Paleozoic history of the Central Andes, then review the main characteristics of its stratigraphic record, and finally proceed to briefly describe the stops of the fieldtrip. It is this last part, the "hands on" experience, which we offer to other geologists interested in the region, allowing them to "touch and see" some of the evidence that has led us and other researchers to the particular interpretations, hypotheses and models. We hope that this will lead to fruitful and constructive discussions, enhance future work, and help better understand the modern distribution of natural resources in the region, as well as their development for a better future of Bolivia, one of the countries in Latin America with the richest natural resources, and at the same time with the poorest economies.

REGIONAL GEOLOGY OF LA PAZ

The Andean Cordillera of western South America is commonly referred to as the classic example of a convergent continental plate margin. Longitudinally, the cordillera consists of three segments -Northern, Central, and Southern Andes- each with similar but distinct geologic histories. The area covered by this fieldtrip, in central western Bolivia (Fig. 1), lies within the Central Andes, near a major change in the trend of the cordillera. The city of La Paz is located near the southern end of a NW-SE-oriented tract of the Andes, which at Cochabamba is deflected towards the south, adopting a N-S trend. This part of the cordillera consists of three contiguous morphotectonic provinces developed during the Cenozoic, which are, from west to east, the Western Cordillera, the Altiplano (or high plains), and the Eastern Cordillera. Within Bolivia, the city of La Paz is located near the boundary zone between the northern Altiplano and the northern Eastern Cordillera.

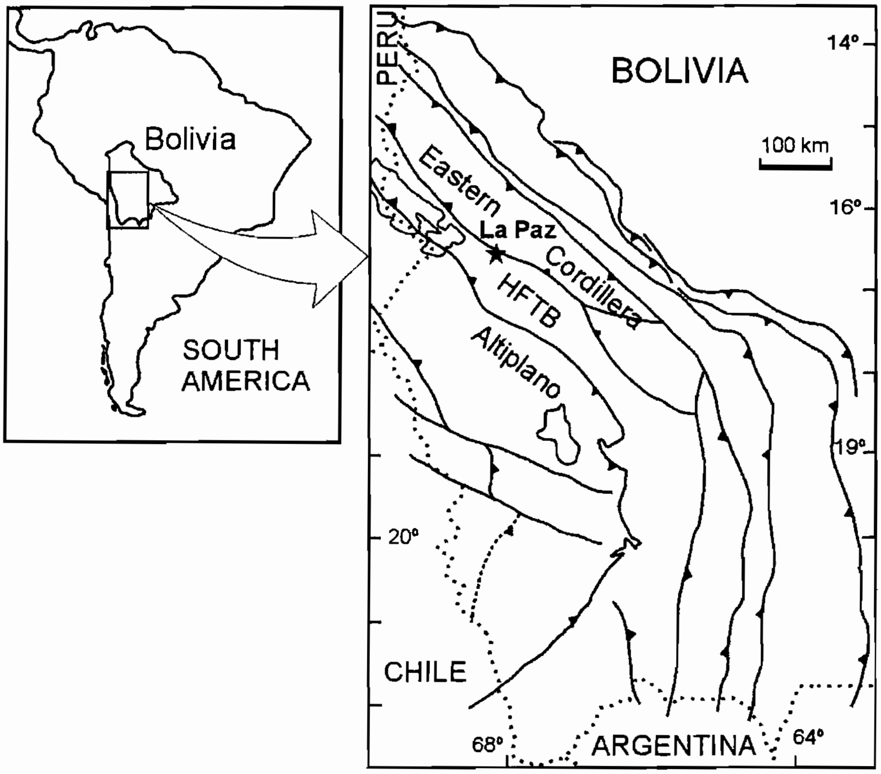


Figure 1: *Location of the La Paz area within Bolivia and South America. Tectonic scheme of Bolivia after Sempere (1995). HFTB: Huarina Fold-and-Thrust Belt.*

The Eastern Cordillera is a polygenic Cenozoic fold-and-thrust belt consisting largely of Paleozoic and Mesozoic rocks, deposited on Precambrian basement at the active margin of the Gondwana supercontinent. The evolution in time of different types of basins (deep marine backarc basin, then shallow marine retroarc foreland basin, and then complex transcurrent regime, all preceding the Andean evolution) is a result of the variable stress regimes during continental displacement and break-up of Gondwana. The modern Eastern Cordillera is the result of continental subduction (underthrust) of the Brazilian (Amazonian) craton beneath the Arequipa-Antofalla craton (or microplate) (Fig. 2).

The Western Cordillera is the volcanic arc resulting from Cenozoic active subduction along the margin of South America. To the east, the Altiplano consists of a series of high altitude, contiguous intermontane (endorreic) basins located between the Western Cordillera and the Eastern Cordillera. Most recent models explain the Altiplano as a result of the shortening and thickening of the continental crust during Andean deformation.

The geology of the area around La Paz consists of a complex SW-verging fold-and-thrust belt affecting Ordovician through Eocene units, and variably covered by syntectonic (and thus also partially deformed) deposits of Oligocene to Recent age. The morphological boundary between the Altiplano and the Eastern Cordillera morphotectonic regions is rather well defined, although it has no major geologic significance. Folds and thrusts have propagated towards the southwest, from the Eastern Cordillera and into the Altiplano. The Coniri thrust fault is traditionally considered the boundary between the tectonostratigraphic domains of the Altiplano and Eastern Cordillera. To the southwest of this fault, the Altiplano tectonostratigraphic domain is characterized by a few variably-metamorphosed Paleozoic and Precambrian outcrops, with a thin Cretaceous sedimentary cover, and a thick and laterally complex Cenozoic sedimentary and volcaniclastic pile exceeding 10 km. To the northeast of this fault, the Eastern Cordillera is characterized by a thick and extensive Paleozoic sedimentary sequence exceeding 10 km, with a Mesozoic sedimentary cover, and a thinner but also laterally complex Cenozoic pile filling piggy-back basins. The Coniri thrust fault also marks an important change in tectonic style, from the thin-skinned fold-and-thrust belt of the western flank of the Eastern Cordillera, to the thick-skinned and wrench structures of the northern Altiplano. The so-called Huarina Fold-and-Thrust Belt (HFTB, Fig. 1) corresponds to most of this thin-skinned fold-and-thrust belt of the western flank of the Eastern Cordillera tectonostratigraphic domain, which is confined between the Coniri fault to the SW, and the Tres Rios fault to the NE.

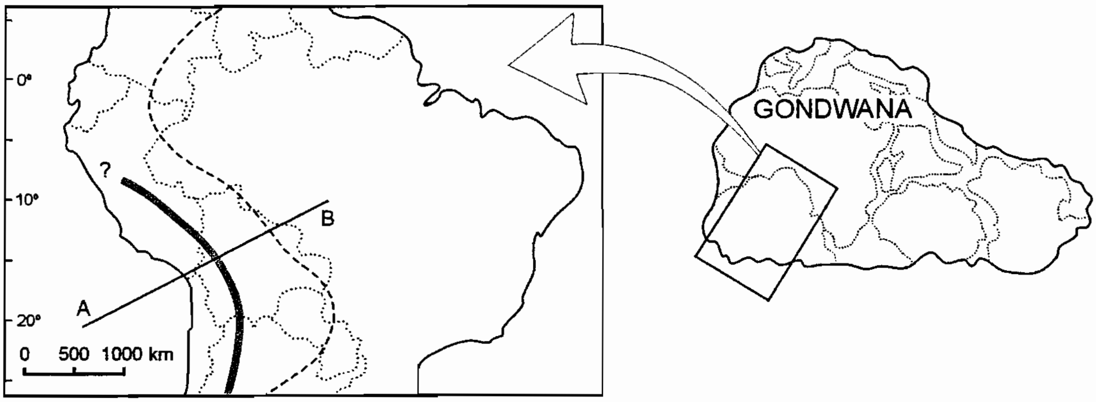


Figure 2: Location of the Central Andes within the rest of Gondwana. Thick grey line: boundary zone between the Arequipa-Antofalla craton and the Amazon craton, probably inherited from the Grenvillian orogen, and active throughout the Pahanerozoic. Dashed line: eastern boundary of the inferred maximum extent oj sedimentation in the "Peru-Bolivia" Paleozoic backarc/retroarc basin (does not include intraplate basins). A-B: location of the schematic geodynamic cross-sections of Figure 3. All locations are approximate.

PALEOZOIC EVOLUTION OF THE CENTRAL ANDES

This section attempts to provide a coherent overview of the paleogeographic and geodynamic evolution of the Central Andes during the Paleozoic, along with some comments on its Proterozoic basement. The synthesis has been compiled from different sources, and also includes some new concepts and interpretations. Due to space limitations, only the most recent and comprehensive references are mentioned and summarized in Table 1. Information on specific

Author(s)	**Age interval**	**Area**
Aceñolaza et al. (1990)	Late Proterozoic-Cambrian	NW Argentina
Astini et al. (1995)	Early Paleozoic	NW Argentina
Bahlburg & Breitkreuz (1991)	Paleozoic	N Chile and NW Argentina
Bahlburg et al. (1994)	Early Paleozoic	N Chile and NW Argentina
Bahlburg & Hervé (1997)	Paleozoic	N Chile and NW Argentina
Breitkreuz et al. (1988)	Paleozoic	N Chile
Breitkreuz et al. (1989)	Paleozoic	Central Andes
Breitkreuz & Zeil (1994)	Late Carboniferous-Triassic	N Chile
Damm et al. (1990)	Proterozoic-Paleozoic	N Chile and NW Argentina
Damm et al. (1991)	Ordovician	N Chile
Damm et al. (1994)	Proterozoic-Paleozoic	N Chile and NW Argentina
Díaz-Martínez (1996)	Late Devonian-Early Permian	Bolivia
Díaz-Martínez (1998a)	Late Devonian-Early Carboniferous	Bolivia
Díaz-Martínez (1998b)	Late Ordovician-Early Devonian	Peru and Bolivia
Díaz-Martínez (1999)	Late Devonian-Early Triassic	Peru and Bolivia
Díaz-Martínez et al. (1993)	Late Devonian-Early Triassic	Bolivia
Díaz-Martínez et al. (1996)	Late Ordovician-Early Carboniferous	Bolivia
Díaz-Martínez et al. (1999a)	Late Devonian-Early Carboniferous	Central Andes
Díaz-Martínez et al. (1999b)	Late Ordovician-Early Silurian	SE Peru
Díaz-Martínez et al. (2000)	Permian	N Chile
Eduardo (1991)	Paleozoic	E Peru
Frutos (1990)	Late Proterozoic-Cenozoic	Whole Andes
Gohrbandt (1993)	Paleozoic	Central Andes
González et al. (1996)	Silurian-Devonian	W Bolivia
González-Bonorino (1991)	Late Paleozoic	Chile-W Argentina
Grader et al. (2000)	Late Carboniferous-Permian	Bolivia
Gutiérrez-Marco et al. (1992)	Early Paleozoic	South America
Isaacson & Díaz-Martínez (1995)	Devonian-Permian	Bolivia
Isaacson et al. (1995)	Late Paleozoic	N Bolivia
Kley & Reinhardt (1994)	Phanerozoic	Southern Bolivia
López-Gamundí & Breitkreuz (1997)	Carboniferous-Triassic	Chile and Argentina
Montemurro (1994)	Silurian-Devonian	SE Bolivia
Mukasa & Henry (1990)	Early Paleozoic	SW Peru
Palacios (1991)	Silurian-Devonian	Peru
Racheboeuf et al. (1993)	Devonian	Bolivia
Rapela et al. (1998)	Late Proterozoic-Silurian	NW Argentina
Ramos (1988)	Late Proterozoic-Paleozoic	South America
Sempere (1989)	Paleozoic	Central Andes
Sempere (1991)	Cambrian-Silurian	Bolivia
Sempere (1993)	Late Cambrian-Jurassic	Bolivia
Sempere (1995)	Phanerozoic	Bolivia and adjacent regions
Sempere et al. (1992)	Permian-Triassic	Bolivia
Starck (1995)	Silurian-Jurassic	NW Argentina
Suárez-Soruco (1992)	Cambrian-Devonian	Peru and Bolivia
Suárez-Soruco (1995)	Silurian	Bolivia
Suárez-Soruco & Díaz-Martínez (1997)	Phanerozoic	Bolivia
Wilson (1990)	Permian	Bolivia

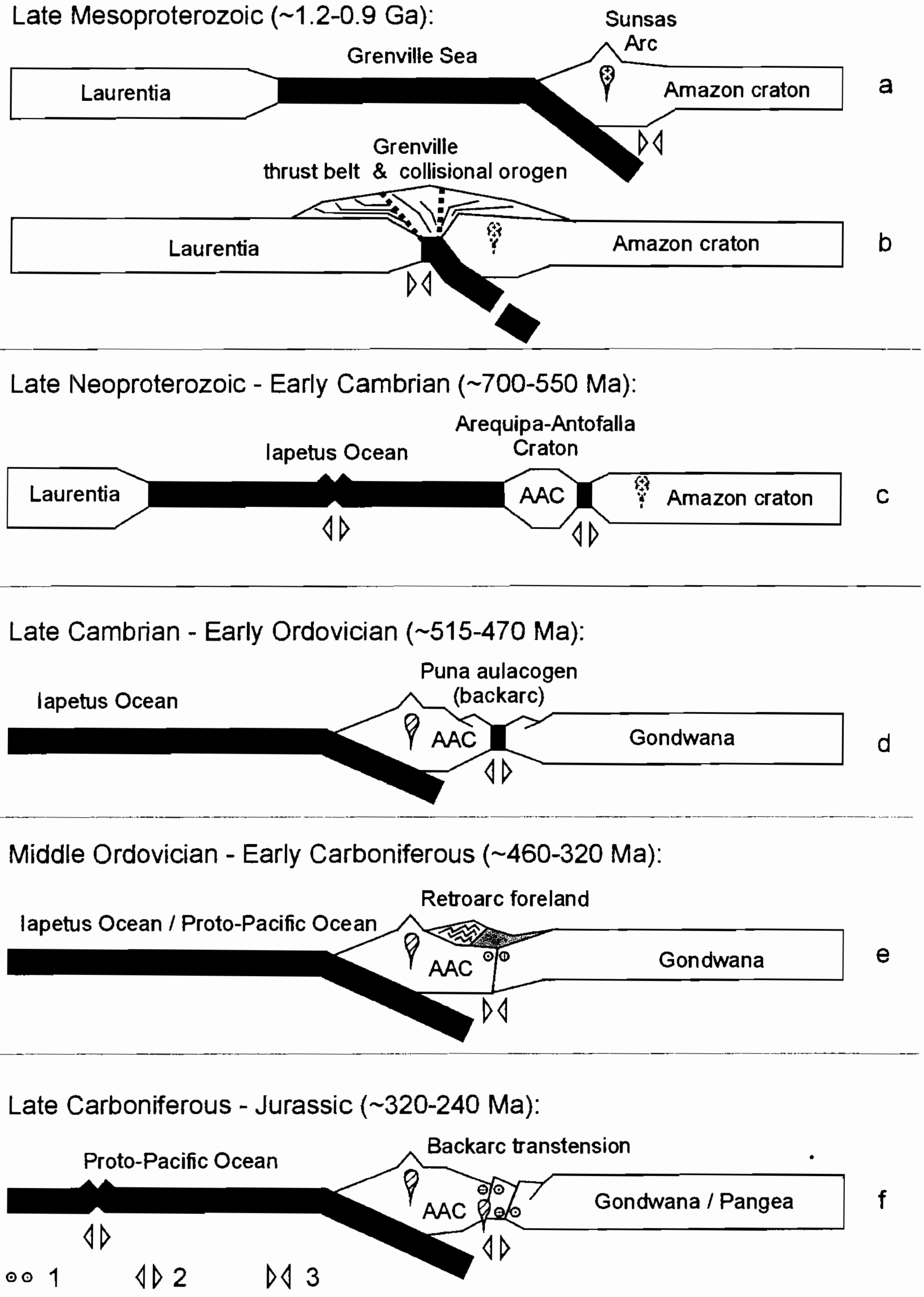
Table 1: Principal more recent (1988-2000) references on the Paleozoic of the Central Andes (5°-27°S).

topics, local details or narrower time intervals for the pre-Andean evolution if this area should be found among these references, some of which will be provided to fieldtrip participants in a separate reprints volume. The area here considered as Central Andes is roughly 5°-27°S, covering part of Peru, Bolivia, N Chile and NW Argentina (Fig. 2), and therefore excludes allochthonous terranes such as the Amotapes of NW Peru and S Ecuador, and the Precordillera of W Argentina.

In contrast with the rather complex Phanerozoic accretionary history of the South American margin corresponding to the Northern Andes (Colombia-Ecuador) and Southern Andes (Chile-Argentina), the evolution of the Central Andes is somewhat simpler, and there is no evidence for the accretion of allochthonous terranes during the Phanerozoic. Recent studies suggest that the crustal basement in most of the Central Andean area formed part of the Grenville orogen, as a result of the collision between Laurentia and Amazonia in the Middle Proterozoic (Wasteneys et al., 1995; Sadowsky & Bettencourt, 1996; Tosdal, 1996). Paleozoic rocks of the Central Andes record the breakup of the Late Proterozoic Protopangea (Rodinia) in the latest Proterozoic-Cambrian to form a passive margin along western Gondwana (Bond et al., 1984; Powell et al., 1993), and also record its later evolution as an active margin during most of the Paleozoic and until present times (Sempere, 1995). The continuous superposition of magmatic, tectonic and sedimentary events has led to complex lateral variations, both in cross section and along strike, and has originated a wide range of settings for the development of mineral deposits (Fontboté et al., 1990; Schneider, 1990; Fornari & Herail, 1991) and hydrocarbon generation and accumulation (Gohrbandt, 1995; Moretti et al., 1995; Tankard et al., 1995) related with Paleozoic rocks.

Proterozoic basement

The modern basement of the Central Andes consists of two crustal blocks with different origin: the Arequipa-Antofalla craton (Ramos et al., 1986), and the Amazon craton (Teixeira et al., 1989) or Central Brazil shield (Figs. 2 and 3). The Arequipa-Antofalla craton is a Proterozoic terrane interpreted to have originated as the tip of a pre-Grenville Laurentian promontory (formerly comprising Labrador, Greenland and Scotland) that was incorporated into the Grenville orogen (Dalziel, 1994; Wasteneys et al., 1995). At the same time, Pb isotopic compositions seem to contradict this model, indicating instead closer ties with the Amazon craton (Tosdal, 1996). The reconstruction of the remains of the Grenville orogen in South America (Sadowski & Bettencourt, 1996) indicates that the Central Andes corresponds to an area intermediate between the Grenvillian magmatic arc (represented by the Sunsas igneous province, in E Bolivia and W Brazil) and the Grenvillian thrust belt (SE Canada) of the orogen (Fig. 3-b). This interpretation explains the similar trends identified between the Proterozoic outcrops along the Andes, and those of the Brazilian shield (Litherland et al., 1985, 1989). Paleoproterozoic ages, indicated by Rb-Sr whole-rock isochrons and bulk U-Pb zircon geochronology, represent the pre-Grenville Laurentian-Amazonian protolith. Mesoproterozoic ages of granulite-facies metamorphism, indicated by U-Pb single-grain zircon geochronology, represent the main collisional events of the Grenville orogen (Wasteneys et al., 1995; Sadowski & Bettencourt, 1996; Tosdal, 1996). Rifting during break-up of Protopangea (Rodinia) in the Neoproterozoic-Cambrian led to separation of Laurentia from Amazonia (Fig. 3-c), leaving behind the parautochthonous Arequipa-Antofalla craton attached to Amazonia (Central Brazil shield). The boundary zone between the two crustal



Late Mesoproterozoic (~1.2-0.9 Ga):

Late Neoproterozoic - Early Cambrian (~700-550 Ma):

Late Cambrian - Early Ordovician (~515-470 Ma):

Middle Ordovician - Early Carboniferous (~460-320 Ma):

Late Carboniferous - Jurassic (~320-240 Ma):

Figure 3: *Conceptual model for the pre-Andean geodynamic evolution of the Central Andes (5-27°S) as proposed in the text. Approximate location of cross sections is indicated in Fig. 2. Figures (a) and (b) modified after Sadowski & Bettencourt (1996; their Figs. 4 and 5). Figures (c) through (f) modified after Ramos (1988), Díaz-Martínez (1995), Sempere (1995). Note the oversimplified character of the scheme, with no scale relation, and that certain time lapses are not represented. Symbol for Sunsas arc is maintained as a reference in (b) and (c). Thick dotted lines within the Grenville orogen in figure (b) correspond to inferred later breakup zones leading to the setting represented in (c) and the following figures. AAC: Arequipa-Antofalla Craton. Symbols for overall regional stress field: 1, transcurrent; 2, tensional; 3, compressional.*

blocks, located beneath the E Altiplano and Eastern Cordillera, constitutes a paleosuture and crustal weakness zone inherited from the Mesoproterozoic evolution of the Grenville orogen (Figs. 2 and 3). This zone remained active during the Paleozoic, and ever since, with variable behavior depending on the regional state of stresses (Ramos, 1988; Dorbath et al., 1993; Forsythe et al., 1993).

Tectonomagmatic episodes

Tectonic and magmatic events took place in the Central Andes in a rather continuous manner during the whole Paleozoic, shifting their foci and areal extent with time as a result of plate interactions, variable geometry of the plates involved, and the resulting stress regimes. This variable conditions led to apparently different styles of evolution depending on the local area under study. However, an overall tendency for the whole region may be discerned. Apart from the aforementioned Mesoproterozoic (1200-900 Ma) ages resulting from the Grenvillian granulite-facies metamorphism, and the Paleoproterozoic (2000-1900 Ma) ages obtained from its metagranitoid protolith, the crystalline basement underlying the Central Andes also presents Neoproterozoic to Middle Cambrian (600-520 Ma) ages of igneous and metamorphic events. These events are commonly assigned to the last phases of the Brazilian orogeny, which are referred to as Pampean orogeny in the southern Central Andes (Rapela et al., 1998). Rifting of eastern Laurentia from Gondwana in the Late Proterozoic and Early Cambrian led to the development of passive margins on both sides of the Southern Iapetus Ocean (Fig. 3-c). Along the pre-Andean margin of Gondwana south of 27°S, a westward shift of the spreading center is interpreted to have left oceanic crust between a detached continental block (the Pampean terrane) and the Gondwana margin (Rapela et al., 1998). Later eastward subduction and closure of this remanent sea during the Early Cambrian led to the collision of the Pampean terrane in the Middle Cambrian. North of 27°S, a similar history is also probable, with the Arequipa-Antofalla craton also partially rifting and then later colliding along its southeastern boundary with the Amazon craton. Meanwhile, the western margin of both the Pampean terrane and the Arequipa-Antofalla craton remained passive during most of the Cambrian (Fig. 3-c).

Beginning in the Late Cambrian or earliest Ordovician, a shift to active conditions is inferred for this western passive margin (Fig. 3-d). The San Nicolás batholith in SW Peru is interpreted as the roots of the magmatic arc resulting from east-ward subduction of oceanic crust along the active margin of Gondwana during the Ordovician-Devonian (Mukasa & Henry, 1990). Similar Ordovician-Devonian ages obtained for lower intercepts in U-Pb geochronology of basement rocks along the western Arequipa-Antofalla craton reflect thermal overprinting and Pb-loss coinciding with peaks of this mid-Paleozoic magmatic activity (Shackleton et al., 1979; Damm et al., 1990, 1994; Mukasa & Henry, 1990; Tosdal, 1996). The Paleozoic development of the active margin is characterized by backarc extensional conditions during the early phase (latest Cambrian-Early Ordovician) and late phase (Late Carboniferous-Permian), whereas a compressional regime (retroarc foreland) characterized the intermediate phase (Middle Ordovician-Early Carboniferous) (Fig. 3-e). An apparent lack of evidence for Silurian and Devonian tectonomagmatic activity in the southwestern Central Andes has been interpreted as evidence for a passive margin resulting from rifting off of part of the Arequipa-Antofalla craton (Bahlburg & Hervé, 1997). However, this interpretation is difficult to reconcile with the evidence for a coeval active plate margin in S Peru (down to 17°S) and N Chile and Argentina (up to 27°S), as well as with the Silurian age of igneous and metamorphic events in the same region (Damm et al., 1990, 1991, 1994).

With regard to Late Paleozoic tectonomagmatic events in the Central Andes, these have been traditionally assigned to a "Eohercynian" orogeny (Mégard et al., 1971; Bard et al., 1974; Dalmayrac et al., 1980), including Late Devonian-Carboniferous K-Ar and Rb-Sr ages, and regional stratigraphic and petrographic evidence. However, only one U-Pb zircon age is reported (330±10 Ma; Carlier et al., 1982). Other U-Pb zircon dates on granitoids along the NW-trending segment of the Eastern Cordillera of Peru and Bolivia establish their time of emplacement as Permian or younger (McBride et al., 1983; Heinrich et al., 1988; Farrar et al., 1990; Kontak et al., 1990). This more recent evidence questions the relation of the granitoids with widespread Late Devonian-Early Carboniferous ("Eohercynian") magmatism and orogenesis, as previously interpreted. Nevertheless, there is evidence for local transpressional uplift and deformation of the Eastern Cordillera in the latest Devonian and Early Carboniferous, which separated an Altiplano basin from a Subandean-Chaco basin (Mégard et al., 1971; Dalmayrac et al., 1980; Kley & Reinhardt, 1994; Sempere, 1995; Díaz-Martínez, 1996, 1998a). Maximum burial depths (locally exceeding 10 km) were attained in different areas of the Central Andean Paleozoic basin at different times during the Late Paleozoic (Late Devonian-Permian interval). As a result of this deep burial, and probably in conjunction with transcurrent stresses along the aforementioned suture zone (Sempere, 1995), the stratigraphically lower units (Ordovician-Silurian) reached very-low-grade to low-grade metamorphism, as indicated by vitrinite reflectance and illite crystallinity (Kley & Reinhardt, 1994). This thermal overprint must have induced the reset of K-Ar systems, thus explaining the Carboniferous-Early Permian ages obtained by some authors (Dalmayrac et al., 1980; Paton, 1990). At the same time, erosion related with the mid-Carboniferous global regression resulted in a disconformity or low-angle unconformity throughout the Central Andes, with Upper Carboniferous and Permian units directly overlying Devonian, Silurian or Ordovician units (Kley & Reinhardt, 1994; Isaacson & Díaz-Martínez, 1995; Díaz-Martínez, 1996, 1999). A similar unconformity is observed in the southern Central Andes (N Chile and NW Argentina), where the development of an active margin with related forearc, intra-arc and backarc basins took place during the Late Carboniferous and Permian (Breitkreuz et al., 1988, 1989; Bahlburg & Breitkreuz, 1991; Breitkreuz & Zeil, 1994; Díaz-Martínez et al., 2000). Thus, the reinterpretation of the evidence indicates that the alleged "Eohercynian" orogeny may be no more than the conjunction of different processes and events taking place during the Late Paleozoic throughout the Central Andean region, but not a single tectonomagmatic event or belt localized in space and time.

The sedimentary record in Peru and western Bolivia presents evidence for a marginal magmatic arc and volcanism beginning in the late Early Carboniferous (Ambo Group, 6-17°S; Dalmayrac et al., 1980; Díaz-Martínez, 1995, 1998a, 1999). Magmatic activity propagated to the south (16-24°S) along the active margin during the Late Carboniferous and into the Permian (Carlier et al., 1982; Bell, 1987; Breitkreuz et al., 1988, 1989; Bahlburg & Breitkreuz, 1991; Breitkreuz & Zeil, 1994; Sempere, 1995; Isaacson & Díaz-Martínez, 1995; Bahlburg & Hervé, 1997; Díaz-Martínez et al., 2000). Farther to the south (20-42°S), thick volcano-sedimentary successions developed in the Permian and Triassic (Choiyoi Group), with associated high-level intrusions (Kay et al., 1989).

Further evidence for Late Paleozoic magmatic activity is also found in the Eastern Cordillera of Peru and Bolivia. This activity began earlier in the Peruvian sector, with Late Permian-Triassic ages (Kontak et al., 1990), and migrated towards the south, developing in Bolivia during the Middle Triassic to Early Jurassic (McBride et al., 1983; Heinrich et al., 1988). The activity was not related to subduction processes, but instead, consists of alkaline volcanism and plutonism which are interpreted as a result of partial rifting and transtension along the suture zone between the Arequipa-Antofalla craton and the Amazonian craton (Fig. 3-f), due to regional shear stresses during Pangea breakup (Kontak et al., 1990; Atherton & Petford, 1991).

Tectonosedimentary cycles

Most of the Late Cambrian to Devonian sedimentation in the Central Andes took place along a wide and elongated epicontinental marine basin broadly parallel to Gondwana's margin (Fig. 2). The main source area for this basin was located to the W and SW, although this source area was not a rifted-off former "Pacific continent" (as considered by Bahlburg & Hervé, 1997). Instead, we have suggested that the source area was Gondwana's active margin itself (Isaacson & Díaz-Martínez, 1995; Sempere, 1995), influenced by its discontinuous activity, specially the uplift and forward migration of the fold-and-thrust belt. Deepening of the basin and increased subsidence rates in the foredeep broadly coincide in time with the aforementioned Ordovician-Devonian peaks of magmatic activity (Fig. 4), and demonstrate the syntectonic character of deposition, in close relation with tectonic piling and uplift along this fold-thrust belt (Sempere, 1995; Díaz-Martínez et al., 1996). The Paleozoic marginal orogen which fed the basin is today completely dismantled, with its roots cropping out in the Arequipa Massif and other smaller outcrops scattered throughout the Arequipa-Antofalla craton. Extreme burial depths locally exceeding 10 km were achieved during the Late Paleozoic in the basin, leading to the reset of isotopic ages during burial maxima, and previous to the widespread erosion of depocenter areas. Paleozoic basin fills were later variably eroded, and the resulting stratigraphic gaps are wider at the margins of the basin, specially towards the western uplifted areas. The original width of the Paleozoic orogen seems narrower today due to tectonic erosion along the western margin of the Arequipa-Antofalla craton (Stern, 1991), as well as telescoping due to Cenozoic folding and thrust-piling. Both processes (tectonic erosion, and dismantling of the orogen and basin fill) continued during Mesozoic and Cenozoic subduction, uplift and erosion in the Central Andes, and resulted in the scarcity of evidence for the more marginal (i.e., forearc and intra-arc) and older basins.

Paleozoic sedimentation in the Central Andes may be subdivided into three main tectonosedimentary cycles limited by major unconformities: latest Proterozoic-Middle Cambrian, Late Cambrian-Early Carboniferous, and Late Carboniferous-Early Triassic. The first tectonosedimentary cycle equates to the Pampean cycle of Aceñolaza et al. (1990). The second tectonosedimentary cycle equates to the Tacsarian and Cordilleran cycles of Suárez-Soruco (1989), and to the Tacsara, Chuquisaca and Villamontes supersequences of Sempere (1995). The third tectonosedimentary cycle equates to the Cuevo supersequence of Sempere (1995). Overall, Paleozoic sedimentation was rather continuous, although remarkable changes in subsidence rates took place during certain time intervals. Sedimentary evidence for increased tectonic instability and uplift occur near the Ordovician-Silurian and Devonian-Carboniferous boundaries (Díaz-

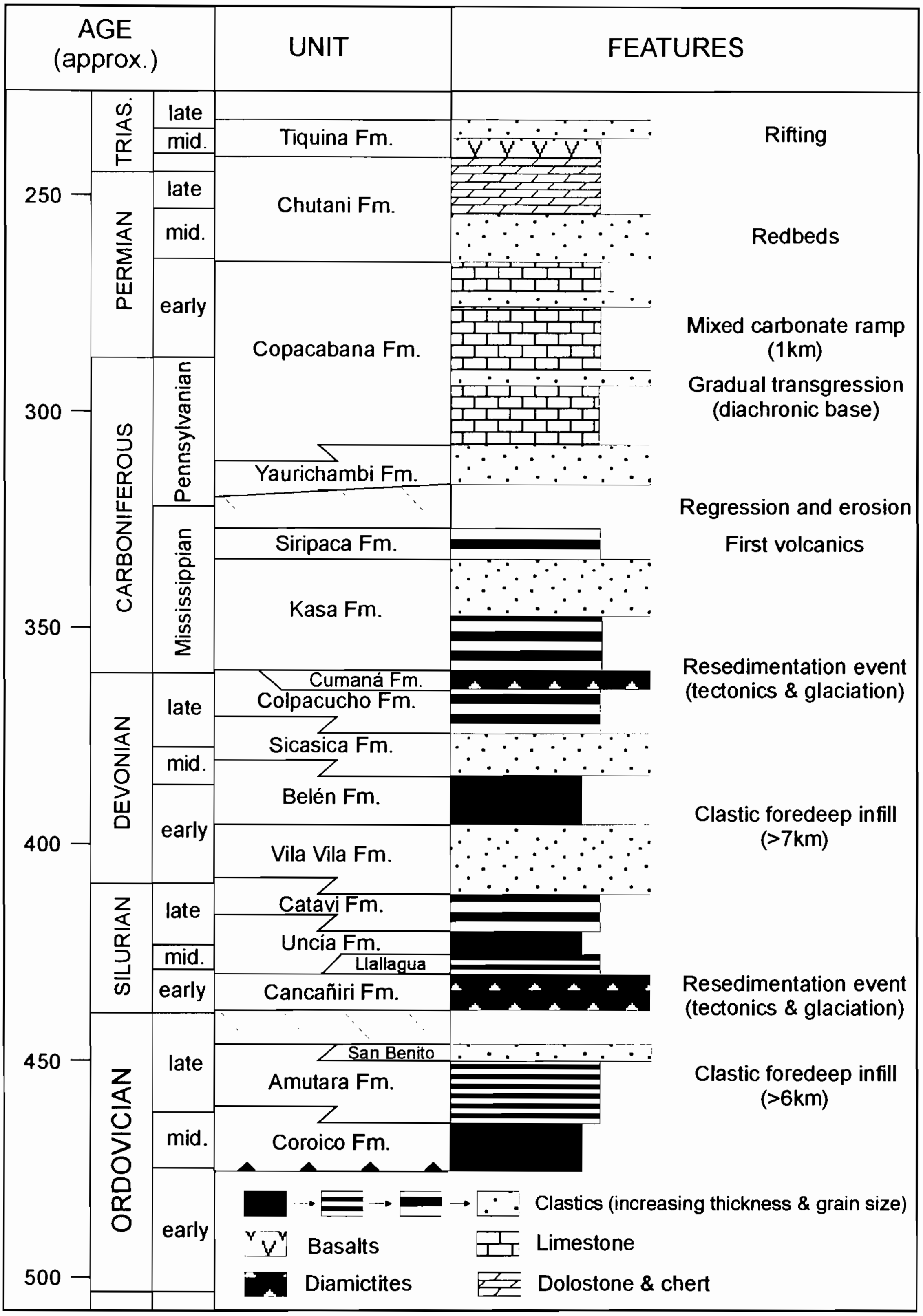


Figure 4: *Simplified stratigraphy of the La Paz area. The scheme applies to the Huarina Fold-and-Thrust Belt, and the Cordillera Real, both within the Eastern Cordillera tectonostratigraphic domain (see location in Fig. 1). Vertical time scale provides approximate ages, and not relative thicknesses.*

Martínez et al., 1996), which have been traditionally used for further subdivision of the sedimentary pile (Suárez-Soruco, 1989; Gohrbandt, 1992; Sempere, 1995). However, as mentioned above, tectonomagmatic processes along the margin have been rather continuous and synchronous with the development of basins. Hence, it does not seem appropriate to maintain the traditional subdivisions of the Paleozoic sedimentary record based on discrete orogenic events.

Paleogeography and paleoclimates

Deposition within a large marine epicontinental basin (Peru-Bolivia Basin) located adjacent and to the east of a marginal orogen prevailed during most of the Paleozoic (Figs. 2 and 3). The overall and progressive increase of rigidity and thickness of the marginal crust beneath this Paleozoic basin led to a gradual increase of continental (subaerial and lacustrine) sedimentation in the Late Paleozoic, in contrast with the previous widespread marine environments. Fluvial deposits were very rare until the Devonian, and begin to become frequent in the Carboniferous. Eolian deposits begin to be present in the Late Carboniferous and are frequent until the Jurassic. The areal extent of marine deposition in the Late Permian and Triassic was very limited.

The Central Andes underwent important latitudinal movements during its drift as part of Gondwana's western margin in the Paleozoic. Despite the scarcity of confident paleomagnetic data, several models have been proposed for the Paleozoic paleogeographic evolution of the region. The overall trend consists of a subtropical (30°) latitudinal position during the Early Cambrian, and a shift towards higher latitudes in the Middle and Late Cambrian (Courjault-Radé et al., 1992). During the Ordovician, Silurian and Devonian, the Central Andes remained at mid to high latitudes, with small variable shifts. A gradual shift towards lower latitudes took place during the Early Carboniferous, and the area has remained at tropical latitudes ever since the Late Carboniferous (Díaz-Martínez et al., 1993; Isaacson & Díaz-Martínez, 1995; Sempere, 1995; López-Gamundí & Breitkreuz, 1997).

Paleozoic tropical carbonates and evaporites in the Central Andes are present only within Early-Middle Cambrian deposits and Late Carboniferous-Permian deposits. Thin carbonate-bearing units are present in the Ordovician, Silurian and Devonian systems, containing cool-water faunal associations. Plant remains are frequent in the sedimentary record beginning in the Middle Silurian, but coal development only begins in the late Early Carboniferous (Ambo Group) and is observed in the Late Carboniferous-Early Permian (Copacabana Formation).

Glacially-influenced deposits are preserved within latest Ordovician-Early Silurian units, and within Late Devonian-Early Carboniferous units. However, true tillites and glacially-striated pavements of Paleozoic age are only very rarely found in northern Argentina (Starck, 1995). Except for this, most of the evidence consists of glacially faceted and striated clasts, both as dropstones and within resedimented units (Díaz-Martínez et al., 1999). These glacially-related deposits are interpreted as a result of glaciation of local tectonically uplifted highlands, and therefore unrelated with the large continental icecaps in Gondwana.

Synthesis of plate tectonic settings

The Central Andes developed as a passive margin in Late Proterozoic to Middle Cambrian times, as a result of the rifting and breakup of Protopangea (Rodinia), and opening of the Southern Iapetus Ocean between eastern Laurentia and Gondwana (Fig. 3-c). Subduction began in the Late Cambrian, with the development of an active continental margin (Fig. 3-d). Ever since, marginal magmatic arcs have developed as a result of eastward subduction, with different rates of activity and sense of migration of the arc depending on regional plate stresses and inhomogeneities. During the Paleozoic evolution of the margin, basin development changed according to these plate interactions. An extensional regime during the early stage (Late Cambrian-Middle Ordovician) resulted in the development of a backarc basin over a strongly subsiding thinned crust, with partial rifting and synsedimentary basic volcanism (Fig. 3-d). The progressive increase of plate-margin rigidity, in conjunction with a shift to a compressional regime, resulted in the development of a large retroarc foreland basin during the intermediate stage (Middle Ordovician-Early Carboniferous), with progressive onlap of units over the distal cratonic margin of the basin, and episodic development of transpressional uplifts (Fig. 3-e). An extensional regime during the late stage (Late Carboniferous-Early Triassic) resulted in the development of forearc, intra-arc and backarc basins, with local transpression and transtension (Fig. 3-f). An overall change from an accretionary to an erosive plate margin took place during the Late Paleozoic, similar to what happened in other margins of Pangea (Breitkreuz, 1990), and resulted in the progressive tectonic erosion of the margin during the Mesozoic and Cenozoic (Stern, 1991).

Inherited pre-Andean structures

From the aforementioned observations and interpretations it is obvious that the structures inherited from the pre-Andean geodynamic evolution of the Central Andes have exerted an important influence on its later development. Proterozoic orogens led to the formation of the crust beneath the Central Andes. The trend of the structures developed during the formation of these orogens greatly conditioned later Paleozoic basin formation and crustal weakness zones, and therefore influenced the geometry and distribution of tectonism and deposition. The boundary zone between the Arequipa-Antofalla craton and the Amazon craton is the principal of these features (Fig. 2), probably inherited as a suture zone from the collision between Laurentia and the Amazon craton as part of the Grenville orogen (Fig. 3). This crustal weakness zone was the location of (a) rifting in the Late Proterozoic and Cambrian, (b) backarc and foreland successor basin formation from the Ordovician to Carboniferous, (c) synsedimentary magmatism in the Ordovician and Silurian, (d) transpressive stresses originating local uplifts in the Devonian and Early Carboniferous, and (e) synsedimentary magmatism, and transtensional stresses originating semigrabens and grabens in the Late Carboniferous to Jurassic. In turn, the resulting Paleozoic features also influenced later events. For instance, (a) Paleozoic basin geometry and facies distribution greatly conditioned the location of décollement levels and lateral variations in the propagation of thrusts during Cenozoic tectonism (Baby et al., 1989, 1992; Sempere et al., 1991), and (b) listric faults originated during Late Paleozoic-Early Mesozoic tensional conditions were reversed during the Cenozoic. The same crustal weakness zone was active with magmatism and strong tectonism during the Cenozoic, resulting in the formation of the Eastern Cordillera and Subandean fold-and-thrust belts.

PALEOZOIC STRATIGRAPHY OF LA PAZ AREA

Proterozoic crystalline basement

The oldest rock described in the La Paz area is a metagranite of the Precambrian basement. It was perforated in the basal section of the San Andrés de Machaca well, at a depth between 2744 and 2814 m, unconformably underlying Cretaceous sediments. The plutonic episode has a Rb/Sr age of 1050 ± 100 Ma (Middle Proterozoic, corresponding to the Grenville orogen), and is affected by a late phase of metamorphism of the Brazilian (Pampean) orogenic cycle with a K/Ar age of 530 ± 30 Ma (Lehmann, 1978). The Proterozoic rocks exposed in southern Peru and forming the Arequipa Massif, continue to the south of Peru, below the Phanerozoic cover, and into Bolivia, where they are exposed in the Uyarani ranges, south of Sajama volcano (highest peak in Bolivia, with 6542 m). These rocks are of the same age as those at the base of the San Andrés de Machaca well. Seismic data, geochemisty of the Phanerozoic igneous rocks, and presence of gneiss clasts and other Proterozoic rocks within Phanerozoic siliciclastic units, demonstrate the existence of a Proterozoic crystalline basement as a major part of the continental crust which underlies the Bolivian Andes.

Lower Paleozoic (Ordovician?) rocks in the northern Altiplano

Rocks exposed in the Chilla and Jesús de Machaca ranges consist of deep marine mudstones (slates and phyllites), sandstones (quartzites) and diamictites deposited by turbidity currents and debris flows. The sequence also includes interbedded basaltic pillow-lavas, and basaltic sills and dolerite dikes. Chemical analyses of the latter rocks indicate a tholeitic magma emplaced within a back-arc rift near the continental margin (Paton, 1990; Sempere, 1993). An Ordovician age is inferred for this sequence based on regional stratigraphic correlation with similar units in Bolivia (Pelechuco, Yani, Ayopaya, Capinota, Conde Auqui, etc., along the Eastern Cordillera) (Avila-Salinas, 1996) and in Peru (Umachiri and Ilave outcrops, in the Peruvian Altiplano), all of them following the same NW-SE tectonic trend.

Whole-rock K-Ar datings in basalts of the Chilla Range gave a minimum age of 285 ± 6 Ma (on the Carboniferous-Permian boundary), which was interpreted as the age of the metamorphism which affected the basaltic lavas and doleritic sills (Paton 1990). The whole sequence presents development of cleavage and fracture schistosity, similar to the Ordovician rocks found in the Eastern Cordillera. The Chilla Range is separated by reverse faults from the surrounding Cenozoic units, while the exposures in the Jesús de Machaca area (and the extreme southeast of the Chilla Range) unconformably underlie Cretaceous sediments. Smaller outcrops located to the N and NW of Caquiaviri also present similar characteristics, although no basic igneous rocks are observed there.

Ordovician rocks along the Eastern Cordillera

Apart from the aforementioned exposures of Jesús de Machaca and the Chilla Range, which may also belong to the Tacsarian cycle (Late Cambrian-Ordovician), Middle and Upper Ordovician rocks are well represented in the Eastern Cordillera tectonostratigraphic domain. These rocks are well exposed along the La Cumbre-Coroico, La Cumbre-Chulumani and Milluni-Zongo roads. The Coroico Fm. (Llanvirnian) and Amutara Fm. (Caradocian) characterize this unit (Fig. 4).

The **Coroico Formation** consists of mudstones (slates, phyllites and schists) with subordinate sandstone interbeds (quartzites), reaching a total thickness in excess of 3 km. This formation contains an important fauna of trilobites, brachiopods, and graptolites, particularly *Hoekaspis yahuari*, *Huemakaspis teopontensis*, *Incaia nordenskioeldi* and *Tissintia* sp. (Suárez Soruco, 1992), which belong to the Llanvirnian. The rocks in this formation underwent metamorphism and deformation with development of microfolds and flow cleavage.

The **Amutara Formation** consists of thin, medium to fine grained quartzites and sandstones, interbedded with banded shaly beds. Locally, light-colored, massive, quartzitic sandstones of 1 to 4 m thick beds are observed as a lateral and vertical change to the overlying **San Benito Formation**. The Amutara Formation is estimated to be 3 km thick. Ichnofossils of the *Cruziana* ichnofacies are present in this formation, together with trilobites and brachiopods: *Dinorthis* sp., *Homalonotus (Brongniartella) bistrami,* etc. The Coroico Formation is an equivalent of the Capinota Formation, while the Amutara Formation can be correlated to the Anzaldo and San Benito formations, found to the SE in the central Eastern Cordillera (Suárez-Soruco, 1992; Suárez-Soruco & Díaz-Martínez, 1996). These Ordovician units were deposited in a deep marine shelf environment during the Llanvirn and Caradoc. Deposits of early Ashgill age have been identified in other parts of the Eastern Cordillera, but not yet in the La Paz area.

Upper Ordovician-Lower Silurian rocks

A marked tectonic instability took place in the Peru-Bolivia basin near the Ordovician-Silurian boundary (Fig. 5), resulting in the sedimentation of the **Cancañiri Formation** in unconformity with previous Ordovician units. In the northern Eastern Cordillera of Bolivia this unit disconformably overlies the Amutara and San Benito Fms. The Cancañiri Formation consists of massive diamictites, with interbeds of shale, sandstone and quartzite, frequently found as resedimented blocks within the diamictites. Reducing conditions are inferred from the frequent occurrence of pyrite. Its regional distribution and conspicuous lithology allow to use this formation as a stratigraphic marker unit to indicate the beginning of Silurian sedimentation. The thickness is extremely variable, reaching 1.5 km towards the south of the Eastern Cordillera (Tica Tica; Suárez-Soruco, 1992, 1995). In the La Paz area, it varies from 150 to 300 m thick..

The Cancañiri Formation is not yet well dated. Ordovician fossils within it are reworked. However, it is generally thought to be Early Silurian (Llandoverian), as younger fossils have also been identified (Suárez-Soruco, 1995; Y. Grahn, pers. comm.). The Cancañiri Formation consists of submarine resedimented deposits caused by mass slides and debris flows, together with turbidites and local synsedimentary slumping. The presence of striated and faceted clasts, as well as large granitoid boulders, within the mass-gravity debris flows indicates that glaciers reached the margins of the Paleozoic sedimentary basin previous to the resedimentation.

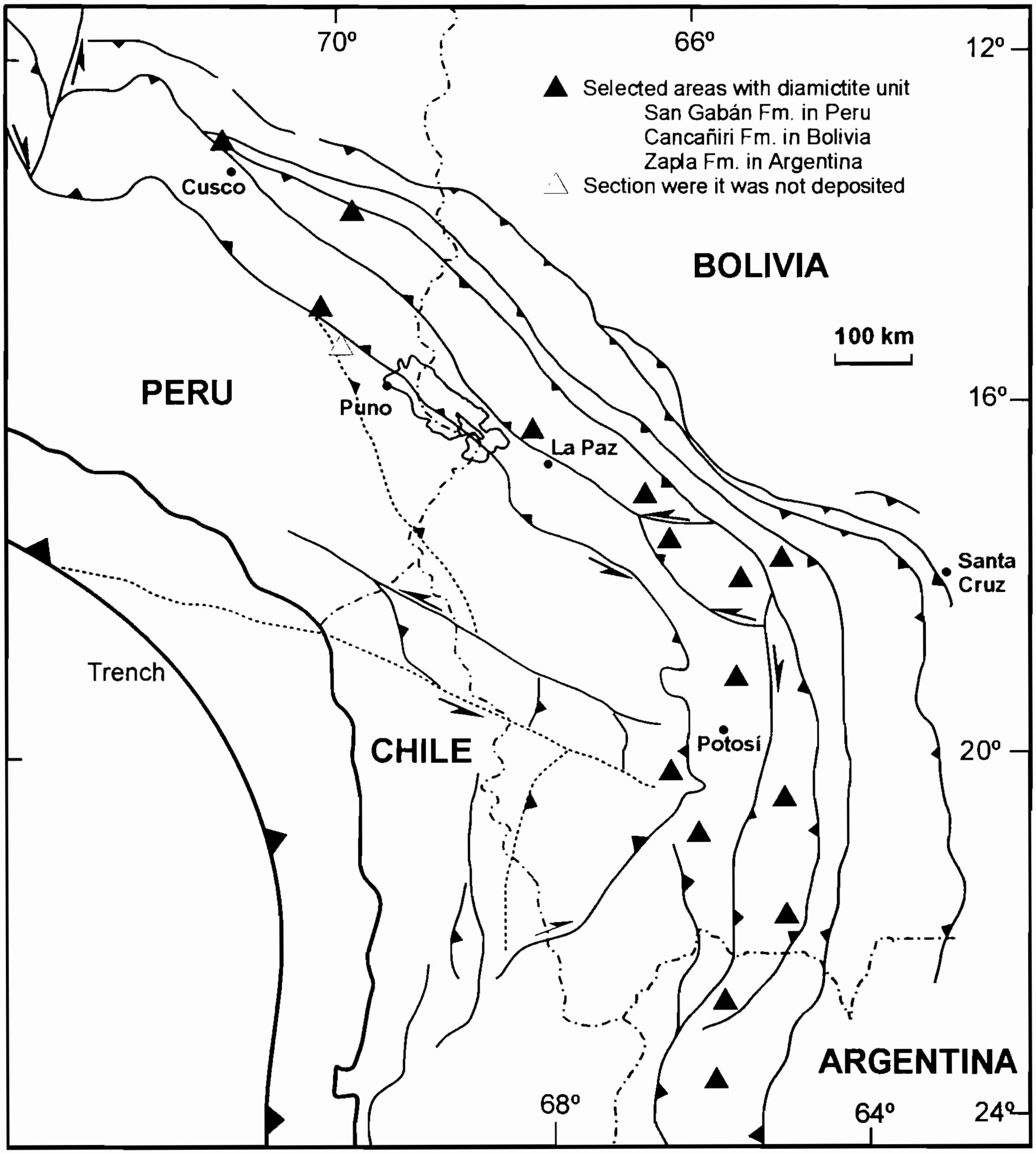


Figure 5: Distribution of the Lower Paleozoic (latest Ordovician-early Silurian) diamictite unit in the Central Andes, indicating selected areas where it was or was not deposited (after Díaz-Martínez et al., 1999b). The area of Cochabamba (between La Paz and Santa Cruz) presents a complex isopach distribution, including some sections were it was not deposited (Suárez-Soruco, 1995). Notice considerable extent of the unit (over 1000 km in length).

Silurian and Devonian rocks

Silurian and Devonian rocks are principally exposed in the Huarina Fold-and-Thrust Belt (HFTB). The **Llallagua Formation** (Llandovery-?Wenlock) was deposited to the southeast of the La Paz area, with less than 50 m, whereas thicknesses exceed 1.5 km between Oruro and Potosí (González *et al.*, 1996). This formation consists of turbidite deposits with alternating sandstone and shale beds, lying conformable on the Cancañiri Formation. **The Uncía Formation**, of Wenlock-Ludlow age, conformably overlies it, and consists of dark laminated shales with thin interbeds of sandstone and siltstone. The age of the formation has been established according to the invertebrate fossils assigned to the *Pristiograptus, Phragmolites-Dualina*, and *Harringtonina australis* zones (Suárez-Soruco, 1992), with an approximate thickness of 1.2 km. The upper part of the formation is characterized by a greater sand content, in transition with the sandstones of the **Catavi Formation** of Pridolian age. The latter consists of fine-to-medium-grained sandstone beds, which alternate with shale beds and siltstone horizons. In the La Paz area, the Catavi Formation is between 500 and 800 m thick.

Silurian and Devonian rocks constitute most of the filling of the Paleozoic retroarc foreland basin, and were deposited in a tide- and storm-dominated proximal marine shelf and nearshore environment, prograding from SW to NE (Sempere, 1995; Díaz-Martínez *et al.*, 1996).The significant lateral and vertical facies changes between these formations does not permit precise correlation on a regional scale. The Silurian-Devonian boundary is traditionally placed at the contact between the Catavi and Vila Vila formations, although recent studies (Rachebouef *et al.*, 1993) confirm that the pelitic members towards the top of the Catavi Formation contain Devonian (Lochkovian) taxa at certain sections. However, the transitional character of the contact between these two units makes it difficult to precisely locate the boundary between the Silurian and Devonian in all sections. The progradation in time of the highstand systems tract produced a diachronism of the facies and of the lithostratigraphic boundary. As a result, the boundary between the Catavi and Vila Vila formations becomes older towards the source area, located to the SW (González *et al.*, 1996; Díaz-Martínez *et al.*, 1996; Suárez-Soruco & Díaz-Martínez, 1996).

Similarly to the Silurian, outcrops of Devonian sedimentary rocks are also widespread throughout the Huarina Fold-and-Thrust Belt. The **Vila Vila Formation**, of Lochkovian age, transitionally overlies the Catavi Formation, and consists of fine-to-medium-grained sandstone and quartzite beds with fequent cross-bedding. The Vila Vila Formation varies in thickness, averaging 500-800 m, but exceeding 1.5 km towards the south of La Paz (González *et al.*, 1996). A change in facies occurs towards the top, consisting of shale and siltstones with thin interbeds of fine grained sandstone beds, in the transition to the **Belén Formation**. This latter formation represents a relative rise in sea level, and the start of a new sequence of coastal progradation. The Belén Formation (Praghian-Eifelian) exhibits alternating thin beds of fine grained sandstone and dark shale, with an average thickness of 1.8 km. The base of the Cruz Loma Quartzite (at the base of the overlying Sicasica Formation) yielded chitinozoans which include *Alpachitina* sp., *Ancyrochitina langei* and *Cladochitina* sp., and indicate the passage from Eifelian to Givetian (Racheboeuf *et al.*, 1993). The **Sicasica Formation** conformably overlies the Belén Formation. It begins with the Cruz Loma Quartzite, and continues with thin shale beds interbedded with sandstone and quartzite. In general, the sandstones are fine-to-medium grained and the shale beds are dark gray. Its average thickness is 600 m, and its age is Givetian-Frasnian (Racheboeuf *et al.*, 1993).

The Devonian ends with the **Colpacucho Formation**, which consists of alternating shale and siltstone, interbedded with thick sandstone beds. The average thickness for the whole formation is 600 m, and it reaches 1 km to the south of La Paz (González *et al.*, 1996). Goniatites similar to *Tornoceras simplex* and *T. uniangulare,* which are known from the Givetian to Famennian, were found in the Colpacucho (or Collpacuchu) Formation (Racheboeuf *et al.*, 1993). Fish remains (arthrodire placoderms) identified near the top of the formation in the Cumana Peninsula have been dated as Lower Famennian (Díaz-Martínez *et al.* 1996). The age of this formation is probably Late Frasnian to latest Famennian.

Some problems have been found when using certain taxa as guide fossils in the Silurian and Devonian of Bolivia. Such is the case of *Clarkeia antisiensis, Scaphiocoelia boliviensis* and *Tropilodeptus carinatus*, which have traditionally been used for local and regional correlations. Some of them are facies-related fossils, and their presence depends on the existence and/or preservation of the particular facies within each unit (González *et al.*, 1996). Furthermore, the recurrence of facies within the Silurian and Devonian sequence, its extraordinary thickness (over 5 km), and the structural complexities resulting from Cenozoic tectonism, complicate stratigraphic correlation and the determination of the age of the sequence at each particular thrust sheet and stratigraphic section. Too frequently, conspicuous sandstone and quartzite beds have been used as stratigraphic markers, despite their being laterally discontinuous (as would be expected for these migrating subaqueous tide- and storm-dominated sandridges and sandbodies). This is the case for the classical Devonian sections south of La Paz: Ayo Ayo, Patacamaya, Sica Sica and Belén. In this area, some sandstone and quartzite beds were assumed to be continuous markers, and correlated from thrust sheet to thrust sheet and from section to section (Condoriquiña, Cruz Loma, Santari). For instance, the quartzites at the base of the Devonian type section at Ayo Ayo were traditionally considered to be the Vila Vila Formation, but a recent revision found them to be just one more sand body within the Belén Formation.

Lower Carboniferous rocks

Lower Carboniferous sedimentary rocks crop out in the Huarina Fold-and-Thrust Belt, and consist of siliciclastic units corresponding to the **Ambo Group**. This group begins with the **Cumaná Formation**, consisting of diamictites and resedimented sandstones, interpreted as debris flows and mass slides with evidence for a glacially-related origin (Díaz-Martínez & Isaacson, 1994). This formation is correlated with the Itacua Formation of the central and southern Subandean region, and both of them are dated as Late Famennian-?earliest Tournaisian. The Cumaná Formation has an average thickness of 100 m, but varies locally due to the irregular relief at its base. At the type locality it presents a channelized geometry, whereas north of Lake Titicaca it was not depoited (Villa Molino section). It is conformably overlain by the **Kasa Formation**, of Tournaisian-Visean age, with a lower sandstone and shale member, and an upper member of whitish siliceous cross-bedded sandstones. The total thickness of the Kasa Formation reaches 1 km, and represents the complex progradation of coalescing braid delta systems into a storm-dominated clastic shelf. It is conformably overlain by the **Siripaca Formation,** of late

Visean-early Serpukhovian age, and composed of variegated sandstones and shale with thin coal horizons and abundant plant residue, representing delta plain and distal alluvial plain deposits. It is only exposed on the Isla del Sol and the Copacabana Peninsula, where it is over 100 m thick, thinning to the SE as a result of the Middle Carboniferous erosional event. As a result of this erosion, the Siripaca Formation does not crop out in the Cumaná Peninsula and Calamarca synclines, where the upper part of the Kasa Formation is also partially eroded.

The overall sedimentary environment of the Ambo group was a storm-dominated shallow siliciclastic shelf. The Cumaná Formation represents a resedimentation event which includes glacigenic material (faceted and striated clasts including granite blocks), possibly related to synsedimentary tectonic activity (Díaz-Martínez & Isaacson 1994; Díaz-Martínez *et al.* 1996). Where the Cumaná Formation was not deposited, such as at Villa Molino (north of Lake Titicaca), the Devonian-Carboniferous boundary is found within a shale unit corresponding both to the uppermost Colpacucho Formation and to the lower member of the Kasa Formation. The Kasa Formation constitutes a complex sequence of deltaic progradation which culminates with a deltaic plain and distal alluvial plain represented by the Siripaca Formation.

Upper Carboniferous and Permian rocks

The **Titicaca Group** (Pennsylvanian-Early Triassic) crops out in the Huarina Fold-and-Thrust Belt, and includes predominantly carbonate lithologies, with variable clastic input. The best outcrops are found in the Copacabana Peninsula of Lake Titicaca, on both sides of the Tiquina strait, and in the Cumaná and Colquencha synclines. In the area of La Paz, the Titicaca Group unconformably overlies different units, either the Early Carboniferous Ambo Group (such as at Villa Molino, Copacabana Peninsula, or Cumaná), or Devonian units (such as at Ancoraimes, Yaurichambi, Colquencha, or Luribay). During the Middle Carboniferous regression, a change in the style of sedimentation occurred, with a predominance of carbonate sedimentation (limestone, marl, and dolostone), most probably as a consequence of the climatic change resulting from the latitudinal displacement of Gondwana. The Late Carboniferous marine transgression was associated with a decrease in tectonic activity (reduced subsidence) and a warmer and dryer climate.

The sandstones of the **Yaurichambi Formation**, at the base of the Titicaca Group, have not been precisely dated, but overlie early Serpukhovian deposits of the uppermost Ambo Group, and underlie Late Bashkirian and younger limestones of the Copacabana Formation. The Yaurichambi Formation is thin, from just 20 m at the type locality (Cerro Jaccha Khatawi) to some 180 m at the Colquencha syncline. At some localities (Ancoraimes) it is even thinner, reaching just one or two meters. Sandstones are bimodal and with variable composition depending on the local source, with very thin chert and dolostone horizons towards the top. After the Middle Carboniferous regression and erosion, the Yaurichambi Formation represents the siliciclastic deposits left during the Late Carboniferous transgression in a coastal, fluviodeltaic environment with frequent aeolian deposits. Their thickness varies according to the paleorelief originated during the erosive event of the Middle Carboniferous.

The **Copacabana Formation** consists of alternating limestones with frequent silica nodules, marl, shale, fine-to-medium-grained green sandstone, and coarse grained red sandstone. The carbonate rocks are rich in microfossils such as foraminifers, calcareous algae, and conodonts, which date the formation as Late Carboniferous-Early Permian (Grader et al., 2000, and references therein). The maximum thickness of the formation is around 600 m, although it is generally less, as the upper part has been eroded. It was deposited in a shallow mixed carbonate-siliciclastic homoclinal ramp located in an interior basin (epicontinental sea).

The **Chutani Formation** conformably overlies the Copacabana Formation and consists of sandstone, dolostone and limestone with shale and chert horizons. The unit is approximately 400 m thick, and was deposited in a shallow, epicontinental marine environment, with subordinate aeolian and fluvial deposits. It is correlated with the Vitacua Formation of the southern Subandes, both of which are dated as Late Permian-Early Triassic (Sempere *et al.* 1992).

FIELDTRIP STOPS

The following is only a brief description of the location and units to be observed at each stop. Further details will be provided in the field, and can also be found in the text above, and in the reprints to be distributed to all participants on their arrival to La Paz, as part of the documentation for the fieldtrip.

Day 1 (Sunday July 30th):

Late Paleozoic (Devonian-Permian) record at the Tiquina and Copacabana Peninsulas (Lake Titicaca).

Stop 1-1: Road from La Paz to Tiquina, near the town of San Pablo de Tiquina (Tiquina Peninsula).

The road cut presents a good section of the Belén Formation siliciclastic nearshore deposits (Early-Middle Devonian) thrusted over the Chutani Formation sabkha, tidal flat, and aeolian deposits (Late Permian-Early Triassic), and of the overlying Tiquina Formation redbeds. Interbedded are tuffs and basaltic lavas associated to rifting.

Stop 1-2: Road from Tiquina to Copacabana, near San Pedro de Tiquina (Copacabana Peninsula).

The road cut presents a good section displaying the typical facies and associations of the Copacabana Formation (Late Carboniferous-Early Permian).

Stop 1-3: Quebrada de Chamacani (taking a left turn on the road from Tiquina to Copacabana, in the Copacabana Peninsula).

Along the creek and lateral slopes, good exposure of dropstones in uppermost shales of the Colpacucho Formation (Late Devonian), and granite boulders and glacially-striated clasts in the Cumaná Formation diamictites (Late Famennian).

Stop 1-4: Yampupata section, along the road from Copacabana to Yampupata (Copacabana Peninsula).

Excellent contiunuous exposure of the upper member of the Kasa Formation (Tournaisian-Visean), as well as of the Siripaca Formation (Late Visean-Serpukhovian), Yaurichambi Formation, and lower Copacabana Formation (Late Carboniferous-Early Permian).

Depending on time available, there may be other stops along the way (Hinchaka, Huatajata, etc.).

Day 2 (Monday July 31st):

Late Paleozoic (Devonian-Permian) record at Cumaná Peninsula (Lake Titicaca).

Stop 2-1: Surroundings of Cumaná.

Sandstones in the upper Colpacucho Formation (Late Devonian) with placoderm plates. Channelized base of the Cumaná Formation eroding uppermost Colpacucho Formation. Facies in the diamictites of the Cumaná Formation.

Stop 2-2: Road from Cumaná to antennas (Cerro Huayna Japuta).

Good exposure of facies in the upper member of the Kasa Formation, and in the Yaurichambi and Copacabana formations. Erosional contact between Ambo and Titicaca groups.

Stop 2-3: Road from Cumaná to Cuyavi.

Complete Late Devonian-Early Permian section. Cumaná Formation not deposited between Colpacucho and Kasa formations. Good exposure of facies in the upper member of the Kasa, and in the Yaurichambi and Copacabana formations. Erosional contact between Ambo and Titicaca groups.

Depending on time available, there may be other stops along the way (Devonian near Aygachi).

Day 3 (Tuesday August 1st):

Late Paleozoic (Devonian-Permian) record at Yaurichambi, and at Villa Molino (Choguaya-Mina Matilde road).

Stop 3-1: Yaurichambi Hill (Cerro Jaccha Khatawi), along the road from La Paz to Copacabana.

Middle Carboniferous unconformity between Devonian and Titicaca Group. Good exposure of facies in the Yaurichambi and Copacabana formations. Erosional contact at base of Yaurichambi Formation. This is the classic fossil site discovered by Alcides d'Orbigny in 1832.

Stop 3-2: Villa Molino section, along the road from Choguaya to Mina Matilde.

Complete Late Devonian-Permian section. Cumaná Formation was not deposited between Colpacucho and Kasa formations, but there is evidence for synsedimentary mass transport (slided slabs and slumps). Good exposure of facies. Transitional contact between the Colpacucho Formation and the Kasa Formation includes the Devonian-Carboniferous boundary, with continuous outcrop and excellent preservation of palynomorphs. Erosional contact between the Ambo and Titicaca groups. This is the thickest section for the Yaurichambi Formation, and one of the best for the Copacabana Formation.

Depending on time available, there may be other stops along the way (Ancoraimes).

Day 4 (Wednesday August 2nd):

Devonian record at Calamarca, and Ayo Ayo-Patacamaya region.

Stop 4-1: Surroundings of Calamarca.

Excellent exposure of typical facies in the uppermost Colpacucho Formation (storm-dominated subtidal bars), and in the Cumaná Formation (diamictites with synsedimentary deformed and slided quartzite slabs). Plant remains (*Haplostigma* sp.) and debris-flow in Colpacucho Formation.

Stop 4-2: Road from Ayo Ayo to Caracato.

Type area for the Devonian units (Belén, Sicasica and Colpacucho formations). Thickest continuous outcrops (now even thicker after recent revision of the stratigraphy; see next stop). Several stops along the road, on different parts of the sequence.

Stop 4-3: Surroundings of Muruhuta.

Previously mapped as Late Silurian Catavi Formation, the axis of this syncline was recently mapped by the Bolivian Geological Survey (SERGEOMIN) as Early Devonian based on the fossil fauna, thus implying a much thicker Belén Formation. Excellent exposure of facies in this unit, including abundant fossils.

Depending on time available, there may be other stops along the way (Chiarumani, Chacoma, Belén).

Day 5 (Thursday August 3rd):

Lower Paleozoic record at Jesús de Machaca and Chilla Range.

Stop 5-1: Ruins of Tiwanaku (Tiahuanacu).

Guided tour to museum and ruins of the ancient Tiwanaku culture (guided by Bolivian geoarchaeologist Leocadio Ticlla). Rocks used in the classical architecture are mostly Cenozoic lithologies available in the nearby area, but also include quartzites and basic igneous lithologies from the Lower Paleozoic.

Stop 5-2: Quebrada Sewenkani, near Jesús de Machaca.

Excellent partial exposures of facies in the Lower Paleozoic of the Bolivian northern Altiplano: mudstones (shales, slates), turbidites, dolerite dikes and sills (displaying columnar jointing and vesicles in upper contact). Angular unconformity with Late Cretaceous units.

Stop 5-3: Northwest end of Chilla Range syncline.

Optional hike to Lower Paleozoic outcrops with interbeds of basaltic lava flows with well-defined pillow structures. View of the thrust over the Eocene Tiwanaku Formation. Those not feeling confident with their lungs/heart resistance may instead visit the modern town of Tiahuanacu.

Day 6 (Friday August 4th):

Lower Paleozoic (Upper Ordovician-Early Devonian) at La Cumbre and Milluni.

Stop 6-1: Upper Ordovician-Lower Silurian along the road from La Cumbre to Unduavi.

Roadcut with excellent continuous exposure of typical facies: turbidites in the Amutara Formation, diamictites and resedimented slabs and blocks (including granite boulder) in the Cancañiri Formation,

Stop 6-2: Late Silurian-Early Devonian along the road from La Cumbre to La Paz.

Exposures of facies in the Catavi and Vila Vila formations: braid delta progradation over storm-dominated shallow clastic shelf.

Stop 6-2: Upper Ordovician-Lower Silurian along the road from Milluni to Zongo.

Glacially-abraded and polished outcrops with facies of the Amutara, Cancañiri, Llallagua and Uncía formations.

Depending on time available (and adaptation to altitude), optional hike to the Upper Silurian (Catavi Formation) at Mt. Chacaltaya: 5600 m.

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