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ARTICLE

Juruá Orogeny: Brazil and Andean Countries

Orogenia Juruá: Brasil e Países Andinos

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ABSTRACT: Seismic data from Petrobras (Brazilian state-owned petroleum company) show wide deformation and many reverse faults throughout the Solimões and Acre basins of northern Brazil. This deformation was observed for the first time in the Juruá River in 1976 in the Solimões Basin, and it increases toward Acre and Subandean basins from Argentine and Chile to Colombia and Venezuela. Structural inversions, block uplifts, and asymmetrical folds are attributed to compression and shearing stresses along this wide area. The severe diastrophism seen in the Juruá River area is of Late Jurassic (Kimmeridgian) age. It probably coincided with the final separation between Laurasia and Gondwana continents and the initial opening of the Central Atlantic Ocean. In Peru and neighboring countries, the same Late Jurassic orogeny is also present. It occurs in the form of widespread regional uplifts, structural inversions, tilting, faults and asymmetrical folds beneath a pronounced regional parallel or angular unconformity of latest Jurassic age, marking a first-order sequence boundary above the Upper Jurassic Sarayaquillo Formation and equivalent formations, as well as above older formations. The depositional hiatus at the upper part of the Jurassic System is attributed to reorganization of stress fields that resulted in basin inversions, followed by widespread peneplanation. The uppermost Jurassic or lower Cretaceous beds, deposited above this regional unconformity, were not affected by this tectonism in Brazilian and Subandean basins. The stratigraphy of Peruvian Subandean sedimentary basins is similar to that of the Acre Basin.

KEYWORDS: Juruá Orogeny; Late Jurassic; Kimmeridgian; North Brazil basins; Subandean basins.

RESUMO: *Dados sísmicos da Petrobras (Companhia Brasileira Estatal de Petróleo) mostram ampla deformação e muitas falhas inversas ao longo das bacias do Solimões e do Acre no norte do Brasil. Esta deformação foi observada pela primeira vez no Rio Juruá em 1976 na Bacia do Solimões e aumenta para a Bacia do Acre e bacias subandinas desde a Argentina e Chile até Colômbia e Venezuela. Inversões estruturais, blocos soerguidos, dobras assimétricas são atribuídas à compressão e ao cisalhamento ao longo desta vasta área. O severo diastrofismo tem idade neojurássica (kimmeridgiana) na área do Rio Juruá. Ele provavelmente é coincidente com a separação final entre os continentes Laurásia e Gonduana e a abertura inicial do Oceano Atlântico Central. No Peru e em países vizinhos, a mesma orogenia neojurássica também está presente. Ela ocorre como soerguimentos regionais amplos, inversões estruturais, basculamentos, falhamentos e dobramentos assimétricos sob uma pronunciada discordância regional paralela ou angular de idade neojurássica, marcando um limite de sequência de primeira ordem acima da Formação Sarayaquillo e formações equivalentes de idade neojurássica, bem como acima de formações mais antigas. O hiato deposicional na parte superior do sistema Jurássico é atribuído à reorganização dos campos de esforços que resultou na inversão das bacias, seguido por peneplanação generalizada. As camadas do topo do Jurássico ou do Cretáceo Inferior, depositadas acima desta discordância regional, não foram afetadas por este tectonismo nas bacias brasileiras e subandinas. A estratigrafia das bacias sedimentares subandinas peruanas é semelhante à da Bacia do Acre.*

PALAVRAS-CHAVE: *Orogenia Juruá; Neojurássico; Kimmeridgiano; bacias do norte do Brasil; bacias subandinas.*

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INTRODUCTION

The Acre Basin, approximately 40,000 km^2 in area, is a small sedimentary basin located at the border with Peru and Bolivia. It is separated from the Peruvian Ucayali Basin on the western side by the Cenozoic basement-involved Divisor Reverses Fault (Serra do Divisor) and from the Solimões Basin on the eastern side by the Late Jurassic Envira Arch (Fig. 1). An E-trending Paraguá High, caused by the Juruá tectonism, divides the Acre Basin into the Jaquirana Trough in the north and the Central Trough in the south (Oliveira 1994).

The Solimões Basin is bounded on the north by the Precambrian Guiana Shield and on the south by the Precambrian Brazilian Shield. The basin with approximately 440,000 km^2 in area is separated from the Marañon (Peru) and Acre (Brazil) basins on its western margin by the Envira Arch (Caputo 2012b), and from the Amazon Basin in the east side by the Purus Arch (Fig. 2). An intrabasinal Carauari High separates the basin into a western Jandiatuba Subbasin and an eastern Juruá Subbasin. Acre, Solimões, Madre de Dios, Ucayali, Marañon, and other Subandean basins originally formed a single major basin, that was later subdivided during various tectonic events. The transpressional faults and folds as old as the Late Jurassic constitute good hydrocarbon traps in Brazil and in many Subandean basins. Plutonic and volcanic rocks of the same age are the best hosts for copper and gold ores in Chile (Vivallo & Henriquez 1998).

Previous studies of this structural framework and tectonism were carried out in Brazil by Szatmari (1981, 1983), Caputo (1985a, 1985b, 1991, 2012a), Porsche (1985), Mosmann *et al.* (1986), Campos and Teixeira (1988), Arana *et al.* (1990), Oliveira (1994), Oliveira *et al.* (1995), and Zalán (1991, 2004). Barros and Carneiro (1991), Kennan and Pindell (2006), and Zelasco (2010) and many other investigators addressed specific Subandean basins.

There is an apparent disagreement about the age of this Juruá orogenic event. Szatmari (1981, 1983) first considered the deformation of the Juruá River area as old as Middle Permian age, triggered by the Tardy–Hercynian Orogeny, and then he considered the Juruá tectonism, as old as Triassic age, related to the separation of North America from South America. Caputo (1985a, 1985b, 1991, 2012a) proposed a Late Jurassic age for this deformation in the ENE-trending Solimões–Acre basin tract; Campos and Teixeira (1988) attributed an Early Cretaceous age; Zalán (1991) and Barros and Carneiro (1991), who coined the terms Juruá Orogeny, used the same name, derived from the Juruá River area deformation, for a Triassic Orogeny in Peru. Oliveira (1994) and Oliveira *et al.* (1995) interpreted the Juruá Orogeny as a Jurassic event, and Zalán

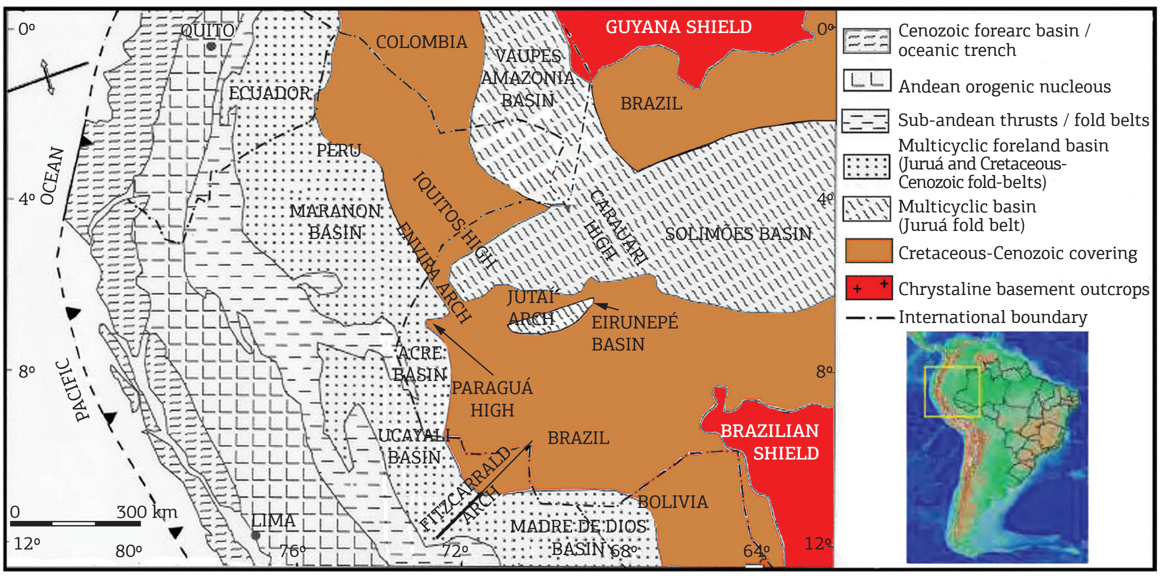

Figure 1. Tectonic geological map of westernmost South America. The Neogene Peruvian Iquitos High corresponds to a small bulge in the Solimões Basin that does not separate it from the Acre Basin. This separation is done by the Late Jurassic Envira Arch. Modified from Barros and Carneiro (1991), Oliveira *et al.* (1995), Duarte (2011), and Kroonenberg and Reeves (2011).

(1991, 2004 p. 610) first attributed a Late Permian-Early Triassic age and later an Early Cretaceous age (140 Ma). In the Peruvian geological literature, the Juruá Orogeny is also placed in many different stratigraphic positions (Kennan & Pindell 2006; Rosas *et al.* 2007). In other words, geological and geophysical reports show that there are four orogenic events in Peru – Late Permian, latest Permian – Triassic, Middle Jurassic, and Late Jurassic – all of them have been referred as the "Juruá Orogeny". Kennan and Pindell (2006) addressed the problem of age and the relations of the "Juruá" shortening and they stated that the age and relations of "Juruá" shortening depends on real dating in Western Brazil.

The age miscorrelation of this tectonic event should be set. The main aim of this article is to date the Juruá Orogeny more precisely and to show its wide extent in western Brazil and Andean countries.

STRATIGRAPHY

The Acre Sedimentary Basin is composed of a Phanerozoic stratigraphic section up to 6,000 m thick, very similar to that of the Ucayali Basin of Peru, as observed in the Stratigraphic correlation chart (Fig. 3), but less complete. In the Acre Basin, Ordovician to Devonian formations are unknown because oil and gas exploration drillings have not penetrated the deepest basin depocenters, but seismic data indicate their presence.

The oldest section observed in outcrops and wells, the Apuí Formation (conglomerates, sandstones, thin shales, and diamictites), correlates with the Mississippian Ambo Group of Peru and Bolivia (Fig. 3). Above, the Lower Permian Cruzeiro do Sul Formation comprises the same lithotypes (limestones, shales, and fossils) as the upper part of the Copacabana Group of Peru and Bolivia. The uppermost part of the Cruzeiro do Sul Formation, composed of organic black shale and limestone beds, corresponds to the Ene Formation of Peru. The next section is a new unit named here as Serra do Divisor Formation, which consists of red and white sandstone beds as old as Late Permian to Early Triassic age. It is correlated with the Mitu Group of Subandean basins. The next section is the Rio do Moura Formation, composed of brown sandstone and sandy siltstone, gray and red shale, and thin limestone beds of Late Triassic to early Middle Jurassic age. It correlates

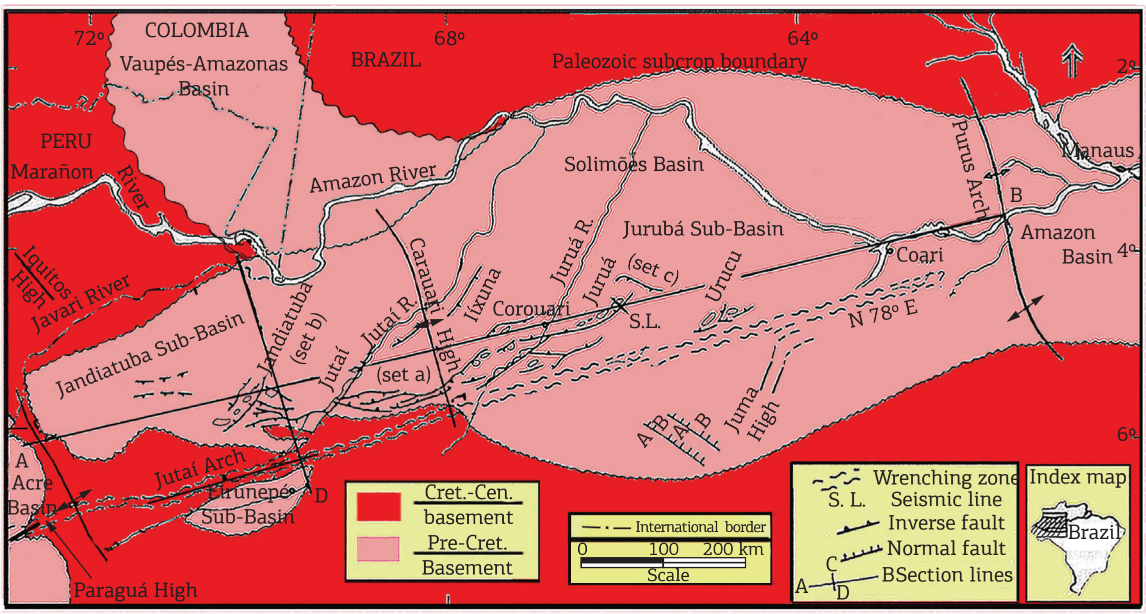

Figure 2. Location and structural framework map of the Solimões Basin with main structural features. Portion of the western Solimões Basin was uplifted and reduced in area by erosion. Eirunpé and Acre basins were disconnected from the Solimões Basin by the Jutaí and Envira arches, respectively, during the Juruá Orogeny. Part of the western Precambrian basement was exposed in the Late Jurassic (red area) and buried in the Cretaceous and Cenozoic times. The Neogene Peruvian Iquitos High corresponds to a small bulge in the Solimões Basin that does not separate it from the Acre Basin. Modified from Caputo (1991) and Kroonenberg and Reeves (2011).

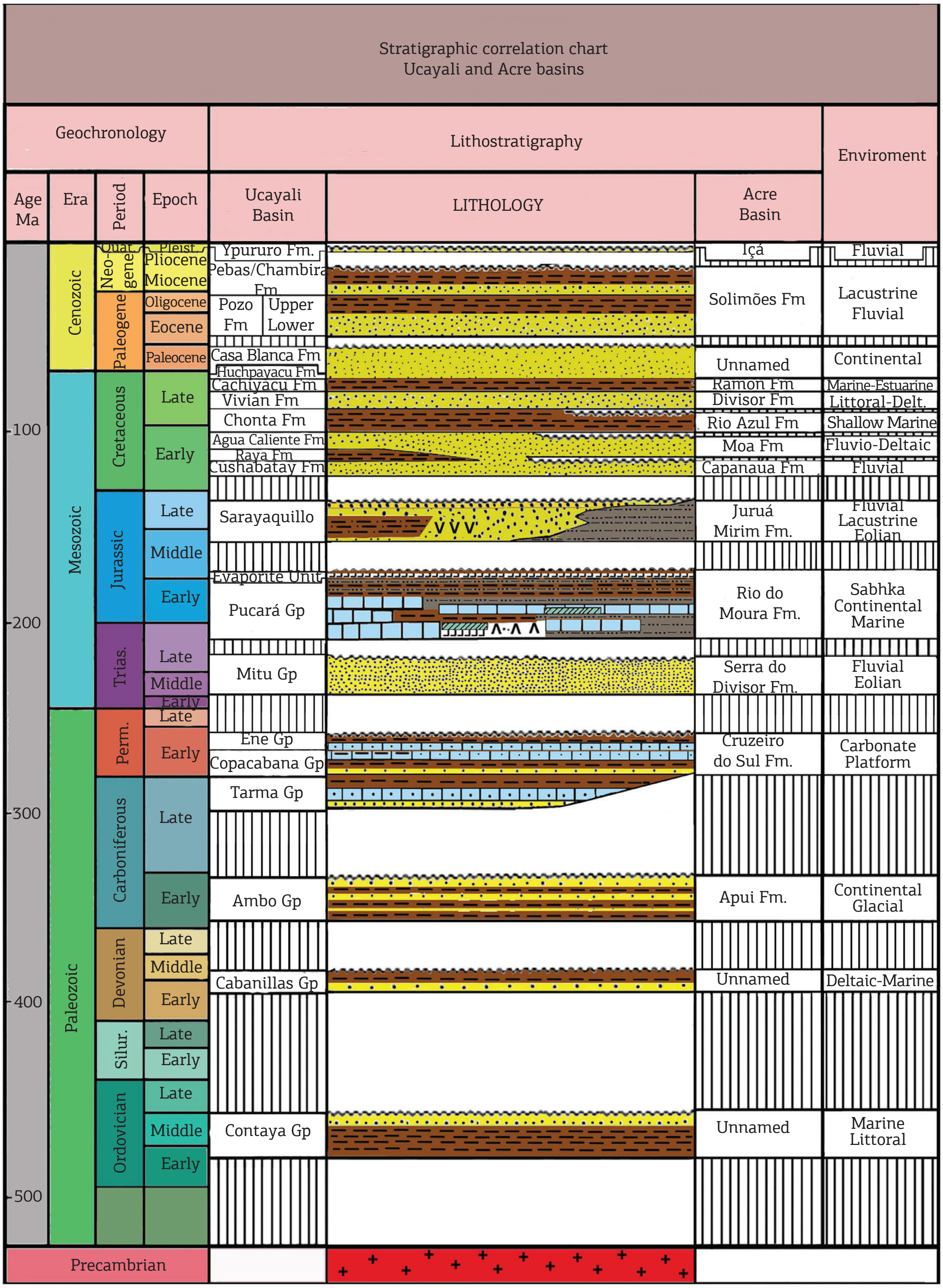

Figure 3. Lithostratigraphic correlation chart of Ucayali and Acre basins. Modified from Barros and Carneiro (1991) and Cunha (2006, 2007).

with the Pucará Formation of Peru. The upper part of the Pucará sequence is marked by evaporite sabkha deposits identified in outcrops and in the subsurface by drilling and seismic data (Fernandez *et al*. 2002). The salt beds of the Upper Pucará Formation are named as the Evaporite Unit in Peru, but they are unnamed in Brazil. There are intrusive alkaline stocks connected to lacoliths, as old as 194 ± 12 Ma (Oliveira 1994) in the Rio do Moura Formation. The overlying Juruá Mirim Formation is a succession as old as the Middle to Late Jurassic time, composed of siltstone, red and brown shale, and red beds with a thick conglomerate on the top. This formation is believed to correlate with the Middle to Late Jurassic Sarayaquillo Formation of Peru. Two extrusive basic events were detected in the section. One of them, as old as 177 ± 8 Ma (Cunha 2007), was dated by K/Ar methodology in the Juruá Mirim Formation. The following section comprises clastics of the Capanaua, Moa, Rio Azul, Divisor, and Ramon formations as old as Aptian to Maastrichtian time. The Cretaceous Divisor Formation is not the same as the Permo–Triassic Serra do Divisor Formation. Peruvian Cretaceous Cushabatay, Agua Caliente, Chonta, Vivian, Cachiyacu, and Huchpayacu formations correlate with the Brazilian Cretaceous formations (Fig. 3). It appears that many Cretaceous formations have disconformable contacts in Brazil. The Cenozoic section consists of the Solimões and Içá formations. The Solimões unit is composed of principally red, green, and gray shale beds (Eocene?–Miocene), and the Içá unit consists of sandstone beds (Pleistocene). The Cenozoic units of the Ucayali Basin consist of the Casa Blanca, Pozo, Pebas, and Ypururo formations.

The stratigraphy of the Solimões Basin is similar to that of the Acre Basin, except for the absence of the Triassic – Jurassic section and small thickness. The Ordovician section shows continuity with the section of the Vaupés – Amazonas Basin of Colombia (Fig. 1). In the Solimões Basin, lava flows are absent, but diabase dikes and sills as old as Late Triassic (~204 Ma) age are thick and abundant.

BASIN TECTONICS

In western South America, the Latest Jurassic time was characterized by strong tectonism related to a change in the orientation of oceanic plate convergence, from nearly southwards to nearly northeastwards, expressed in a magmatic arc and tectonic deformation (Jaillard *et al*. 2000). This major plate kinematics reorganization correlates with important, global-scale, geodynamic changes in the Pacific Ocean and the westward propagation of the Tethyan breakup of Laurasia and Gondwana during the initial opening of the Central Atlantic Ocean in the Late Jurassic time (Jaillard *et al.* 1995). Geological structures were formed coinciding with wide compression and shearing in west-north Brazil and Andean countries.

Brazilian Acre and Solimões basins were inverted in the Late Jurassic time, during the Kimmeridgian Stage (150 Ma), followed by extensive peneplanation before subsidence and deposition of Lower Cretaceous strata (Fig. 4), as observed in seismic lines and wells (Caputo 1991, 2012a; Oliveira 1994; Oliveira *et al.* 1995; Zalán 2004).

These events were followed by a noticeable diachronous marine and continental sedimentation in Subandean countries, from the latest Jurassic period onward. In Peru, a hiatus of approximately 20 M.y., between the top of the Middle Jurassic Pucará Formation and the overlying Early Cretaceous succession, resulted from regional uplift and peneplanation in the Contaya Arch in the Ucayali Basin (Zelasco 2010). The Shira Mountains, which divide the Andean Foreland into two depressions, the Pachitea Subbasin to the west and the Ucayali Basin to the east, are a prominent structural high in the area. Past reconstructions show that the Shira Mountains were an ancestral horst block limited by major normal faults bounding half grabens of a Paleozoic rifting event (Alvarez 2007). The normal faults were reactivated by later compression. In a cross section, through the Shira Mountains, a large-scale deformation of pre-Cretaceous formations (Perupetro 2009) was observed and part of it is here attributed to the Juruá Orogeny. Overlying Early Cretaceous and Cenozoic rocks were later deformed during many Andean deformation phases.

In Argentine, Neuquén, Paganzo, Cuyo, and other basins were affected by widespread inversion, during the Auracan event. An angular unconformity is present in parts of Oxfordian and Kimmeridgian stages. Here the hiatus is approximately 5 M.y. The Late Jurassic age of the Juruá Orogeny, observed in the Solimões Basin and Andean countries, is also supported by the relations of magmatism, seismic surveys, structural interpretation, and sedimentary petrography in the mentioned basins.

MAGMATISM

In the past, based on the K/Ar method, the diabase intrusions of the Solimões Basin were considered as old as 150, 180, and 210 Ma., but $^{40}Ar/^{39}Ar$ dating provided an age of 204 Ma., suggesting a very short igneous event (Wanderley Filho *et al.* 2005). This magmatism belongs to the Central Atlantic magmatic province (CAMP)

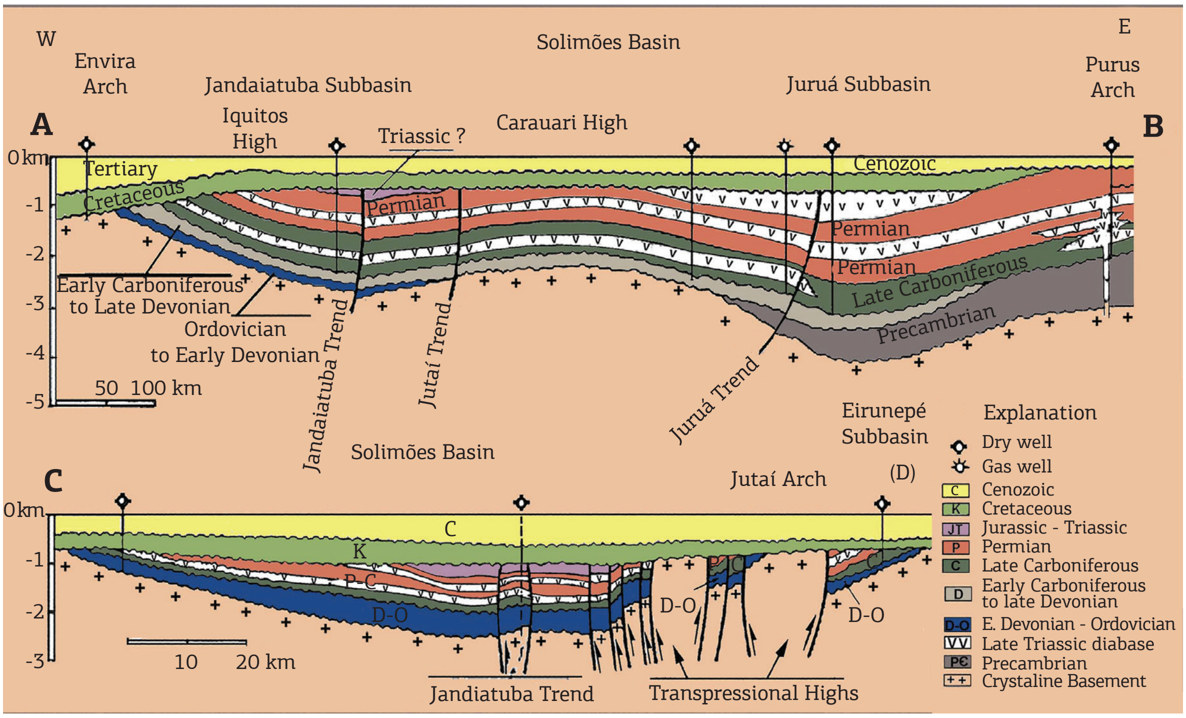

Figure 4. Structural sections along (A–B) and across (C–D) the Solimões Basin (see Fig. 2 for section positioning). Cretaceous and Cenozoic strata were not involved in faulting. Erosion stripped off Paleozoic beds and diabase sills from transpressional highs before the Cretaceous deposition (Caputo 1985a, 1985b, 1991, 2012a).

defined by tholeiitic basalts as old as 200 Ma., which crop out in the once-contiguous parts of North America, Europe, Africa, and South America (Marzoli *et al.* 1999). This Triassic–Jurassic transition magmatism is associated with the initial breakup of Pangea and the tectonic reactivation of the South American Platform.

In the Acre Basin, younger lava flows as old as 177 ± 8 Ma. (K/Ar) indicate an Early–Middle Jurassic age (Cunha 2007) for this magmatic extrusive event. Juruá reverse faults cut these basic igneous rocks in Acre and Solimões basins, as well as Middle to Upper Jurassic beds of the Juruá Mirim Formation in the Acre Basin, so this tectonism should be younger than the Middle Late Jurassic time and older than the Early Cretaceous time when a new deposition cycle started.

SEISMIC AND OUTCROPPING SURVEYS

The boundary between the pre-Andean system rocks (Ordovician to Jurassic) and the Andean system rocks (uppermost Jurassic to Cenozoic) is a regional unconformity that can be traced in seismic sections along all of the Subandean basins of Peru, Ecuador, Colombia, Venezuela, Bolivia, Argentine, and Chile, as well as in Brazil. Seismic lines in the Acre Basin show the Paleozoic – Jurassic sequence well deformed and separated by an angular or parallel unconformity from nondeformed Early Cretaceous strata. The Juruá tectonism affected Middle to Early Late Jurassic strata, indicating a latest Jurassic age for the tectonism. A geological sketch (Fig. 5) of the seismic line 31-RL-183 (Fig. 2 from Zalán 2004), in the Acre Basin shows tectonic deformation of Upper Jurassic beds, made by the Juruá Orogeny before the Early Cretaceous sedimentation. In this figure, the Jurassic faults stop in the Jura–Triassic sequence. The Batã Fault and a parallel fault are related to the Andean Orogeny that reaches the Acre Basin.

The Contaya arch is an elongated geologic high that divides the Huallaga, Marañon, and Ucayali basins in the Peruvian Amazonian plain (Zelasco 2010). It seems to be normal fault-bounded blocks that were active in the Late Permian – Early Triassic time, during rifting and deposition of the Mitu Group. The Contaya High was reactivated by reverse faultings in the Late Jurassic and Cenozoic times. A lower Triassic unconformity, possibly linked to the breakup of Pangea and the opening of the North Atlantic Ocean, is also present in Zelasco's seismic section interpretation. Flattening of the base-Cretaceous

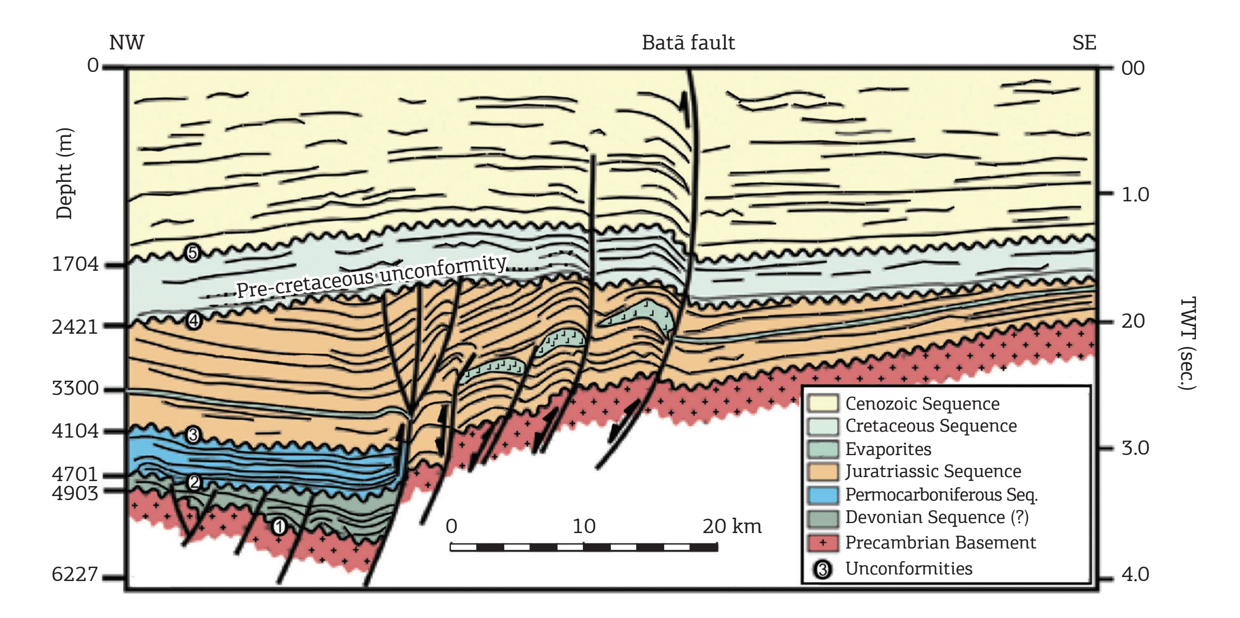

Figure 5. Seismic stratigraphic section of the Acre Basin. Old normal faults were reactivated as reverse faults in the Late Jurassic (Juruá Orogeny) and Cenozoic times (Andean Orogeny) (based on Zalán 2004).

unconformity in the Huallaga Basin (Peru) seismic lines (PARSEP 2001: Figs. 5, 9, and 20) shows the tectonic tilting and the deformation of the Late Jurassic Sarayaquillo Formation below the Early Cretaceous angular unconformity. This Sarayaquillo deformation was caused by Late Jurassic stresses. In the Ene Basin of Peru, the base-Cretaceous unconformity overlies stratigraphic units of different ages, from Devonian to Late Jurassic (Perupetro S.A./PARSEP 2003), suggesting that the same Late Jurassic tectonism affected the basin. The same happens in the seismic–stratigraphic section (Fig. 5) from the Acre Basin (Zalán 2004).

In the Santiago Basin (Peru), the Sarayaquillo Formation contains an internal erosional unconformity, but it is overlain by a large angular unconformity (Abanto 2003), correlated to the Juruá tectonism. In the Oriente Basin (Ecuador), the strongest deformation of the Late Jurassic Chapiza Formation below Cretaceous beds (Baby 2012), as observed in seismic lines, is present. The Chapiza Formation is equivalent to the Sarayaquillo Formation. In Colombia, large tectonism as old as Late Jurassic age was detected in the Middle Magdalena Valley and Vaupés – Amazonas basins under Cretaceous beds (Mendoza & Sanchez 2010). In Venezuela, the Jurassic System belongs to inverted Mesozoic grabens, located along the Mérida and Perijá Andes, where overlying transgressive basal beds of the Cretaceous frequently appear to be unconformable above the Jurassic La Quinta Formation, indicating orogenic movements that occurred after the deposition of the Jurassic La Quinta Formation (Hedberg 1942). In Bolivia, a tectonic event was attributed to the Kimmeridgian age (Late Jurassic) also observed in the Neuquén basin of Argentine and Chile (Sempere 1995). Evident correlation with Peru shows that this tectonism must be associated to the Late Jurassic Orogeny observed in Ucayali and Marañon basins (Sempere *et al.* 1999). In Argentine, this Kimmeridgian deformation is named as the Auracan phase or inversion, and in Peru, it is referred to as the Nevadan Orogeny, which was named in Sierra Nevada and Klamath mountains of Western North America; but it is better to use a South American regional name for the Late Jurassic Juruá Orogeny with its unique characteristics and large extent in western South America.

SEDIMENTARY PETROGRAPHY.

According to Elias *et al.* (2007), based on authigenic illite K/Ar ages, two stages of illite authigenesis (Fig. 6) are observed in Carboniferous oil and gas reservoir beds of the Solimões Basin. The first stage of authigenesis was interpreted as related to thermal effects on reservoirs close to the voluminous Penatecaua Late Triassic basic sills (approximately 200 Ma.), and the second stage to reservoirs far from the basic intrusive rocks, but connected to Juruá pervasive strong stresses at approximately 150 Ma. The time of the second illite formation dates the Juruá Orogeny as old as Kimmeridgian.

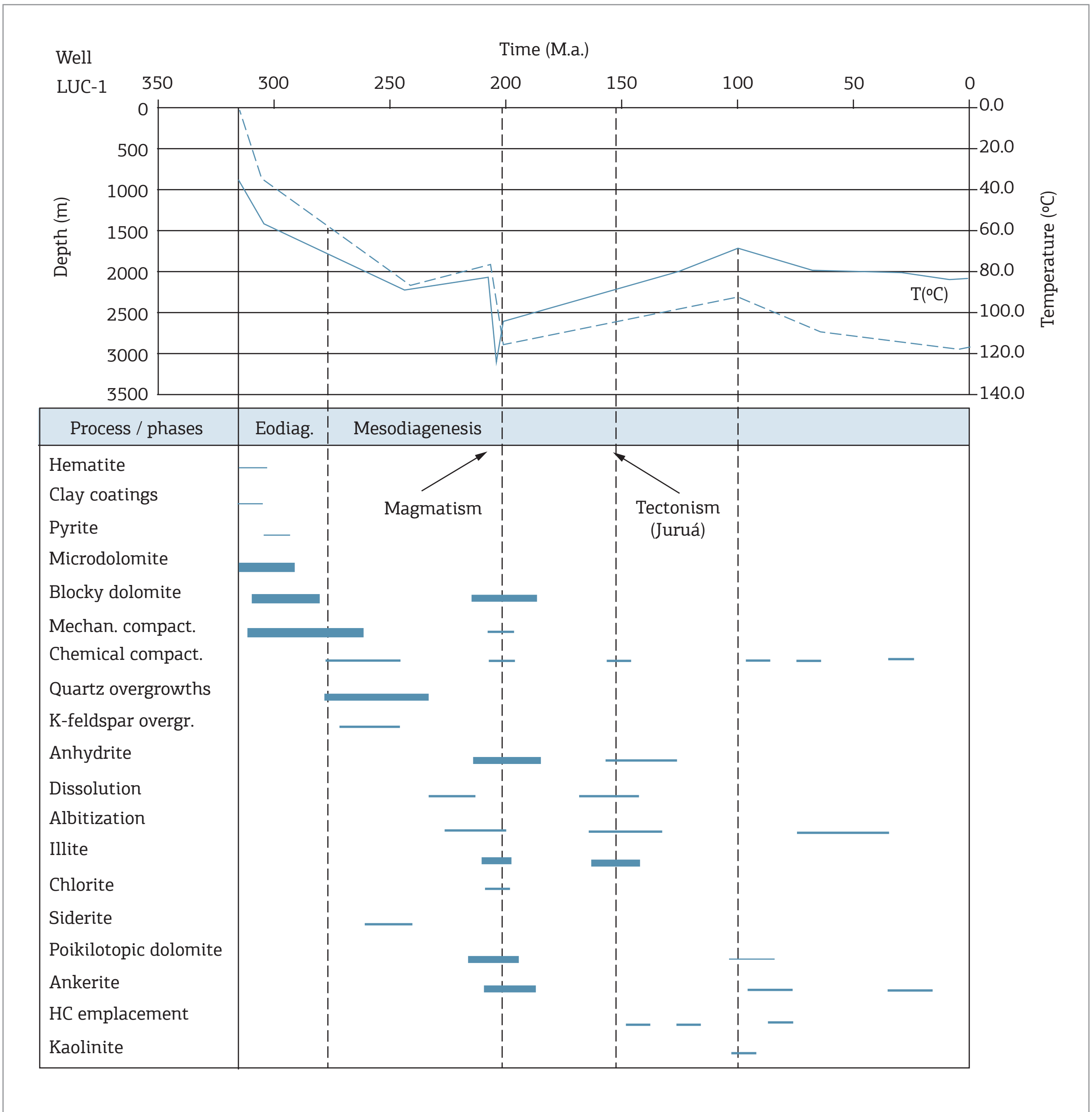

Figure 6. Burial and thermal history of the reservoirs from some oil fields of the Solimões Basin. Authigenic illite K/Ar ages of Carboniferous oil and gas reservoirs are related to the thermal effect of the voluminous latest Triassic basic magmatism (approximately 200 Ma), and to the Late Jurassic Juruá pervasive tectonism in Kimmeridgian time (approximately 150 Ma) (after Elias *et al.* 2007).

CONCLUSIONS

An overlooked strong Late Jurassic (Kimmeridgian) diastrophism is responsible for a generalized structural deformation observed in Solimões, Acre, and Subandean basins of western South America. The several ages for this orogeny proposed by the authors discussed in the text are not appropriate. These authors were referring to generalized ages (Permian, Triassic, Jurassic, and Cretaceous) for this orogeny that now have its dating refined as old as Kimmeridgian.

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