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Triassic synthems of southern South America (southwestern Gondwana) and the Western Caucasus (the northern Neotethys), and global tracing of their boundaries

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ABSTRACT

Global tracing of the key surfaces of Triassic deposits may contribute significantly to the understanding of the common patterns in their accumulation. We attempt to define synthems – disconformity-bounded sedimentary complexes – in the Triassic successions of southern South America (southwestern Gondwana, Brazil and Argentina) and the Western Caucasus (the northern Neotethys, Russia), and then to trace their boundaries in the adjacent regions and globally. In southern South America, a number of synthems have been recognized – the Cuyo Basin: the Río Mendoza–Cerro de las Cabras Synthem (Olenekian–Ladinian) and the Potrerillos–Cacheuta–Río Blanco Synthem (Carnian–Rhaetian); the Ischigualasto Basin: the Ischichuca-Los Rastros Synthem (Anisian–Ladinian) and the Ischigualasto–Los Colorados Synthem (Carnian–Rhaetian); the Chaco–Paraná Basin: the Sanga do Cabral Synthem (Induan), the Santa Maria 1 Synthem (Ladinian), the Santa Maria 2 Synthem (Carnian), and the Caturrita Synthem (Norian); western Argentina: the Talampaya Synthem (Lower Triassic) and the Tarjados Synthem (Olenekian?). In the Western Caucasus, three common synthems have been distinguished: WC-1 (Induan–Anisian), WC-2 (uppermost Anisian–Carnian), and WC-3 (Norian–lower Rhaetian). The lower boundary of WC-1 corresponds to a hiatus whose duration seems to be shorter than that previously postulated. The synthem boundaries that are common to southwestern Gondwana and the Western Caucasus lie close to the base and top of the Triassic. The Lower Triassic, Ladinian, and Upper Triassic disconformities are traced within the studied basins of southern South America, and the first two are also established in South Africa. The Upper Triassic disconformity is only traced within the entire Caucasus, whereas all synthem boundaries established in the Western Caucasus are traced partly within Europe. In general, the synthem boundaries recognized in southern South America and the Western Caucasus are correlated to the global Triassic sequence boundaries and sea-level falls. Although regional peculiarities are superimposed on the appearance of global events in the Triassic synthem architecture, the successful global tracing suggests that planetary-scale mechanisms of synthem formation existed and that they were active in regions dominated by both marine and non-marine sedimentation.

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Palavras-chave:
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RESUMO

A correlação global das superfícies-chave dos depósitos triássicos irá contribuir de forma significativa para a compreensão dos padrões comuns de acumulação. Neste trabalho buscou-se definir sintemas – unidades sedimentares limitadas por disconformidades – nas sucessões triássicas do sul da América do Sul (Gonduana sul-ocidental, Brasil e Argentina) e do Cáucaso Ocidental (Neotethys setentrional, Rússia), e então traçar suas superfícies limítrofes nas regiões adjacentes, e então globalmente. No sul da América do Sul, diversos sintemas foram reconhecidos. Bacia de Cuyo: sintemas Río Mendoza–Cerro de las Cabras (Olenequiano–Ladiniano) e Potrerillos–Cacheuta–Río Blanco (Carniano–Rético). Bacia de Ischigualasto:

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sintemas Ischichuca–Los Rastros (Anisiano–Ladiniano) e Ischigualasto–Los Colorados (Carniano–Rético). Bacia do Chaco–Paraná: sintemas Sanga do Cabral (Induano), Santa Maria 1 (Ladiniano), Santa Maria 2 (Carniano) e Caturrita (Noriano). Oeste da Argentina: sintemas Talampaya (Triássico Inferior) e Tarjados (? Olenequiano). No Cáucaso Ocidental, três sintemas comuns foram identificados: WC-1 (Induano–Anisiano), WC-2 (topo do Anisiano–Carniano) e WC-3 (Noriano–Rético inferior). A superfície limítrofe inferior do Sintema WC-1 corresponde a um hiato cuja duração deve ser mais curta do que anteriormente considerado. As superfícies limítrofes comuns para o sudoeste do Gonduana e o Cáucaso Ocidental estão posicionadas próximo à base e ao topo do Triássico. As disconformidades do Triássico Inferior, Ladiniano e Triássico Superior podem ser traçadas nas bacias estudadas do sul da América do Sul, e as duas primeiras também são identificadas na África do Sul. A disconformidade do Triássico Superior somente pode ser delineada através de outras regiões do Cáucaso, enquanto que todos os limites de sintemas estabelecidos no Cáucaso Ocidental são parcialmente traçados através da Europa. Em geral, os limites de sintemas reconhecidos no sul da América do Sul e no Caúcaso Ocidental são correlacionáveis com limites de seqüência e rebaixamentos do nível do mar. Apesar de que peculiaridades regionais estão superpostas à assinatura dos eventos globais na arquitetura dos sintemas triássicos, a possibilidade de reconhecimento das superfícies limítrofes de forma global sugere que houve mecanismos na escala planetária atuando na formação dos sintemas, tanto em regiões dominadas por sedimentação não-marinha quanto marinha.

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1. Introduction

Synthem stratigraphy is an important stratigraphic tool aimed at defining unconformity-bounded units (Chang, 1975; Salvador, 1987, 1994). It is rarely used as more attention is given to sequence stratigraphy, but synthem stratigraphy was effectively applied to the Cenozoic deposits of some Italian basins (Benvenuti et al., 1998; Zavala, 2000; Benvenuti and Degli Innocenti, 2001), the Pannonian Basin in the Central Europe (Sacchi et al., 1999), the northwestern United States (Hanneman et al., 2002), and Grand Cayman Island (Vezina et al., 1999).

In this paper, we try to explain the definition of synthems in two regions: southern South America (southwestern Gondwana) and the Western Caucasus (the northern Neotethys) (Fig. 1). Another task is to trace their boundaries in both the adjacent regions and globally. This will help to strengthen our knowledge of the inter-regional correlation of the Triassic strata. A comparison between two far-located regions, dominated by absolutely distinct paleoenvironments, may help us to understand whether there were any planetary-scale influences on the regional synthem architecture. In our paper, we prefer the term 'synthem tracing' and not 'correlation', because the latter seems to be more appropriate for detailed biostratigraphic techniques. An additional aim of our paper is to underline the usefulness of synthem stratigraphy, which is very efficient when establishing any regional stratigraphic framework or when attempting inter-regional correlations.

2. Geologic settings

2.1. Southwestern Gondwana

The Triassic deposits of southwestern Gondwana are exposed in southernmost Brazil, western and southern Argentina, and northern Chile (together outlined as southern South America), as well as in southern Africa. The main occurrences in southern South America are the Ischigualasto and Cuyo rift basins (western Argentina) and the intracratonic Paleozoic–Mesozoic Chaco–Paraná Basin, where the Triassic section crops out mainly in the Rio Grande do Sul State of Brazil.

The Triassic sedimentation occurred close to the Gondwanides Orogen, an Andean-type convergent zone on the Panthalassan margin (Figs. 1 and 2) that extended from South America to Australia (du Toit, 1927; Veevers et al., 1994a). Zerfass et al. (2004) suggested that Early Triassic deposition took place in the wide alluvial basin that extended from western South America to South Africa, while the Middle and Late Triassic sedimentation occurred within the tectonically controlled restricted basins such as back-arc rifts (Argentinian and Chilean basins),

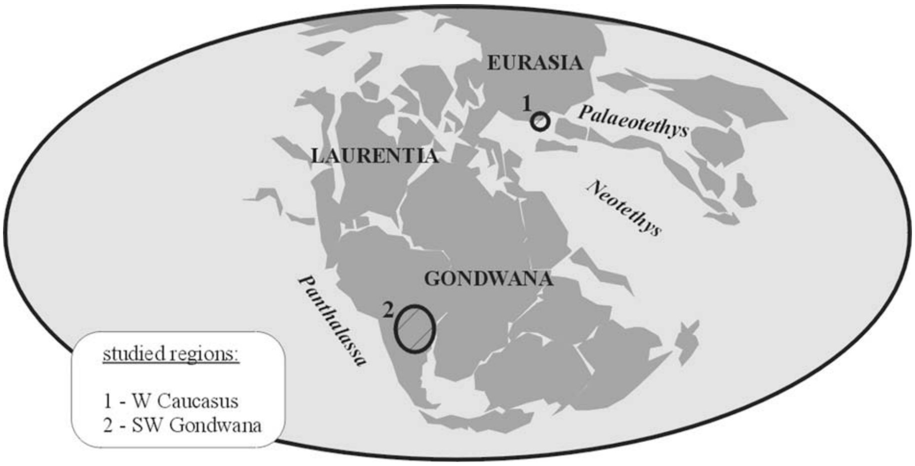

Fig. 1. Location of the studied regions in the Triassic (paleogeographic outline at 210 Ma is simplified from Scotese (2004)).

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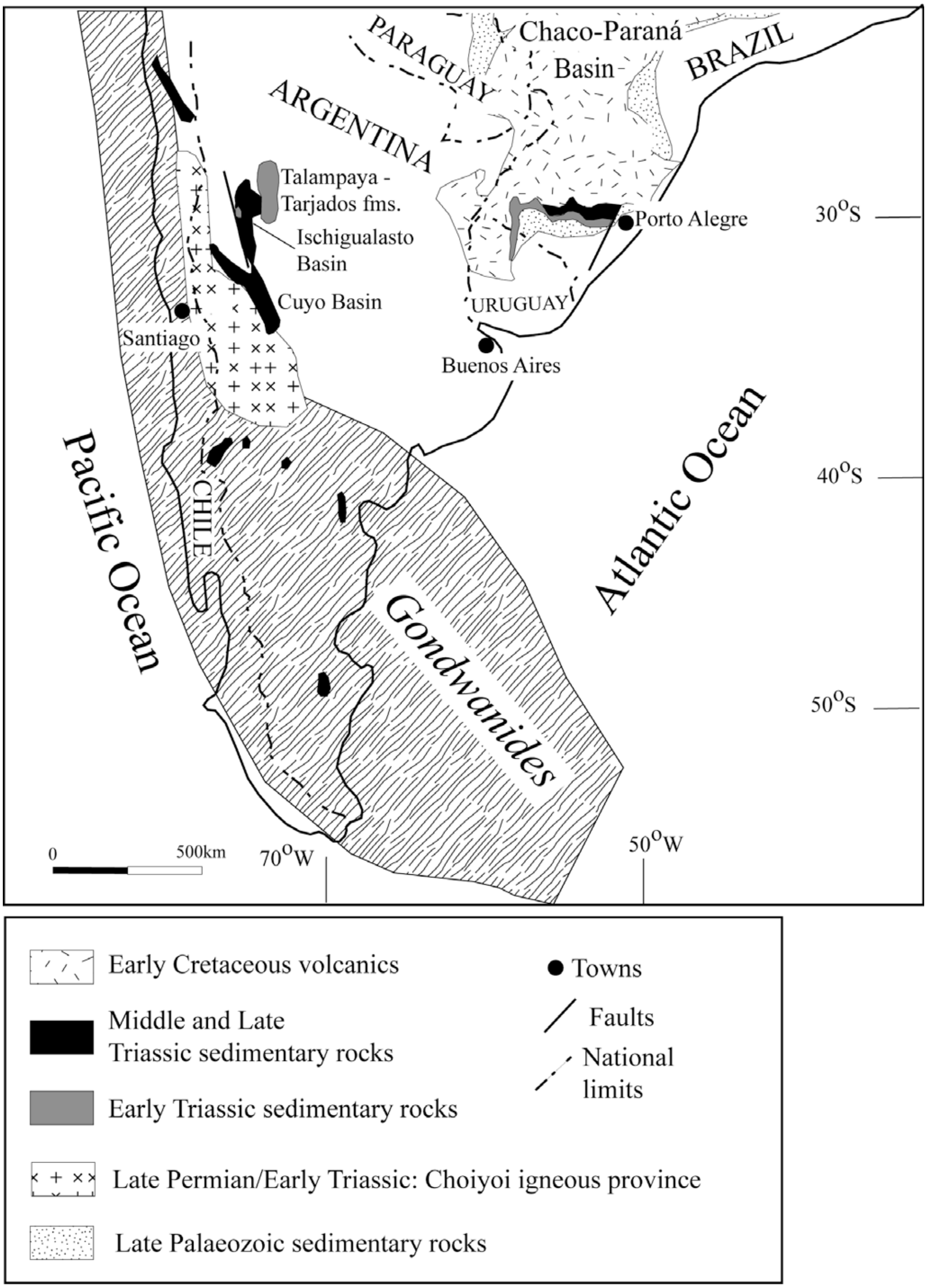

Fig. 2. Location of the Triassic basins in southwestern Gondwana.

intracontinental rifts (basins of southern Brazil and southern Africa), and foreland basins (Karoo Basin). Most of these basins were filled by continental deposits, except for some basins of northern Chile, where marine and continental deposits are interfingered. In southern Brazil and southwestern Africa, the Middle and Late Triassic deposits are distributed within a series of intracontinental rifts generated by reactivation of the Pan-African structures of the Damara Belt (Late Proterozoic) on the African side and their propagation toward the South American counterpart (Zerfass et al., 2005).

The stratigraphic framework of the southern South American Triassic deposits is shown in Fig. 3. The lithostratigraphic units (formations – Fm) comprise the following:

(1) The Cuyo Basin (Mendoza Province, Argentina): Puesto Viejo Fm (González Diaz, 1966), Cerro Cocodrilo Group (Rolleri and Fernández Garrasino, 1976) divided into Río Mendoza Fm (Borrello, 1962), Las Cabras Fm (Rolleri and Criado Roque, 1966), Potrerillos Fm (Biondi, 1931 in Rolleri and Criado Roque (1966)), Cacheuta Fm (Biondi, 1936 in Rolleri and Criado Roque (1966)), and Río Blanco Fm (Rolleri and Criado Roque, 1966).

(2) The Ischigualasto Basin (San Juan and La Rioja provinces, western Argentina): Talampaya Fm and Tarjados Fm (Romer, 1966), Agua de la Peña Group (Bossi, 1971) divided into Ischichuca, Los Rastros, and Ischigualasto Fms (Frenguelli and Ramaccioni in Frenguelli (1944)), and Los Colorados Fm

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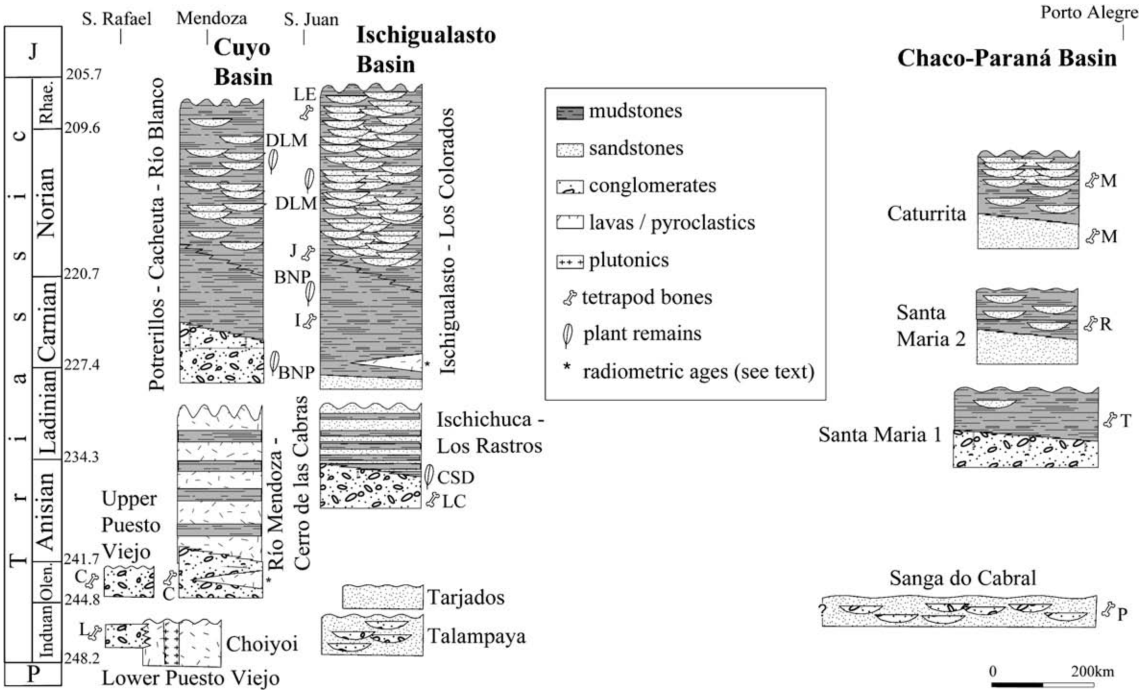


Fig. 3. The Triassic composite sections and synthems of the main basins of southern South America. Synthem names are indicated along each section. Paleovertebrate biozones are abbreviated as follows: C – *Cynognathus* Association Zone, I – Ischigualasto Fauna, L – *Lystrosaurus* Association Zone, LC – Los Chañares Fauna, LE – La Esquina Fauna, M – *Mammaliamorpha* Association Zone, P – *Procolophon* Range Zone, R – *Rhynchosauria* Association Zone, T – *Therapsida* Association Zone. Plant biozones (after Spalletti et al., 1999): BNP – *Yabeiella brackebuschiana*, *Scytophyllum neuburgianum*, *Rhexoxylon piatnitzkyi* Association Zone, CSD – *Dictyophyllum castellanosii*, *Johnstonia stelzneriana*, *Saportaca dichotoma* Association Zone, DLM – *Dictyophyllum tenuiserratum*, *Linguifolium arctum*, *Protocircoporoxylon marianaensis* Association Zone. Absolute ages after Gradstein et al. (2004).

(de la Mota, 1949 in Stipanicic and Bonaparte (1976)). An overview of the lithostratigraphy of this basin was also presented by Stipanicic and Bonaparte (1976).

(3) The Chaco–Paraná Basin (Rio Grande do Sul, southernmost Brazil): Rosário do Sul Group divided into Sanga do Cabral and Santa Maria Fms (Andreis et al., 1980), and Caturrita Member (Bortoluzzi, 1974).

Generally, there were two main phases of sedimentation in southern South America during the Triassic, which were tectonically controlled (Zerfass et al., 2004):

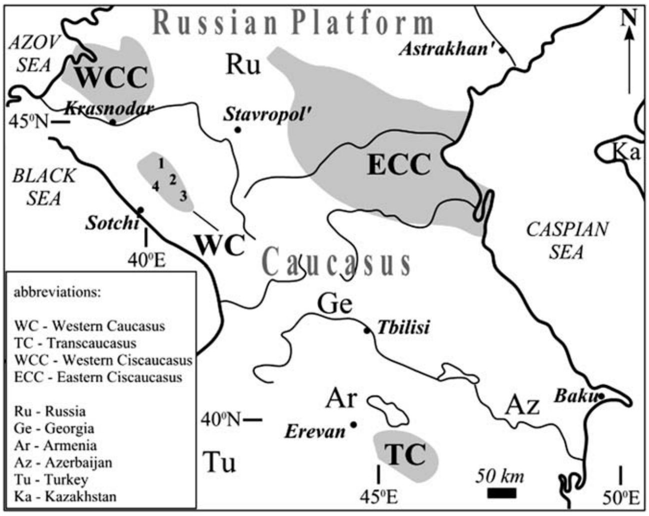
(1) The Early Triassic widespread alluvial sedimentation. The Induan Sanga do Cabral (southernmost Brazil) and the roughly coeval Talampaya and Tarjados deposits (western Argentina) represent a widespread braided fluvial sedimentation related to source area upwelling due to a compressional phase of the Gondwanides orogeny.

(2) The Middle and Late Triassic accumulation in rift basins. The Ladinian to Rhaetian Santa Maria (southernmost Brazil), Ischigualasto and Cuyo basins (western Argentina) were continental rifts related to transtensional stresses in the back-arc and foreland settings that were transmitted to the intracontinental region as strike-slip faults.

2.2. Western Caucasus

In the early Mesozoic, the Western Caucasus was located on the northern margin of the Neotethys Ocean (Fig. 1). Tectonically, this region was situated between the stable Russian Platform and an active subduction zone of the northern Neotethys (Golonka, 2004). Opening of small oceans and development of back-arc basins occurred in the adjacent regions (Stampfli and Borel, 2002). Unfortunately, detailed paleotectonic reconstructions have not been attempted for this region yet, and therefore, it is difficult to justify an exact paleoposition for the Western Caucasus. However, we agree with the suggestion of Gaetani et al. (2005), who suggested strike-slip movements in this region. They might have been related to the activity of the major shear zone located just to the north of the Western Caucasus (Arthaud and Matte, 1977; Ruban and Yoshioka, 2005; Tawadros et al., 2006).

The Triassic deposits are distributed over four Caucasian regions: Western and Eastern Ciscaucasus, Western Caucasus, and



abbreviations:

WC - Western Caucasus
TC - Transcaucasus
WCC - Western Ciscaucasus
ECC - Eastern Ciscaucasus

Ru - Russia
Ge - Georgia
Ar - Armenia
Az - Azerbaijan
Tu - Turkey
Ka - Kazakhstan

Fig. 4. Distribution of the Triassic strata within the Caucasus (after Rostovtsev et al., 1979). Principal areas are highlighted in grey. Areas of the Western Caucasus (after Rostovtsev et al., 1979; Gaetani et al., 2005): 1 – Kamennomostskij, 2 – Tkhatch-Bol'shoj Sakhraj, 3 – Jatyrgvarta-Urushten (Malaja Laba), and 4 – Guzeripl'.

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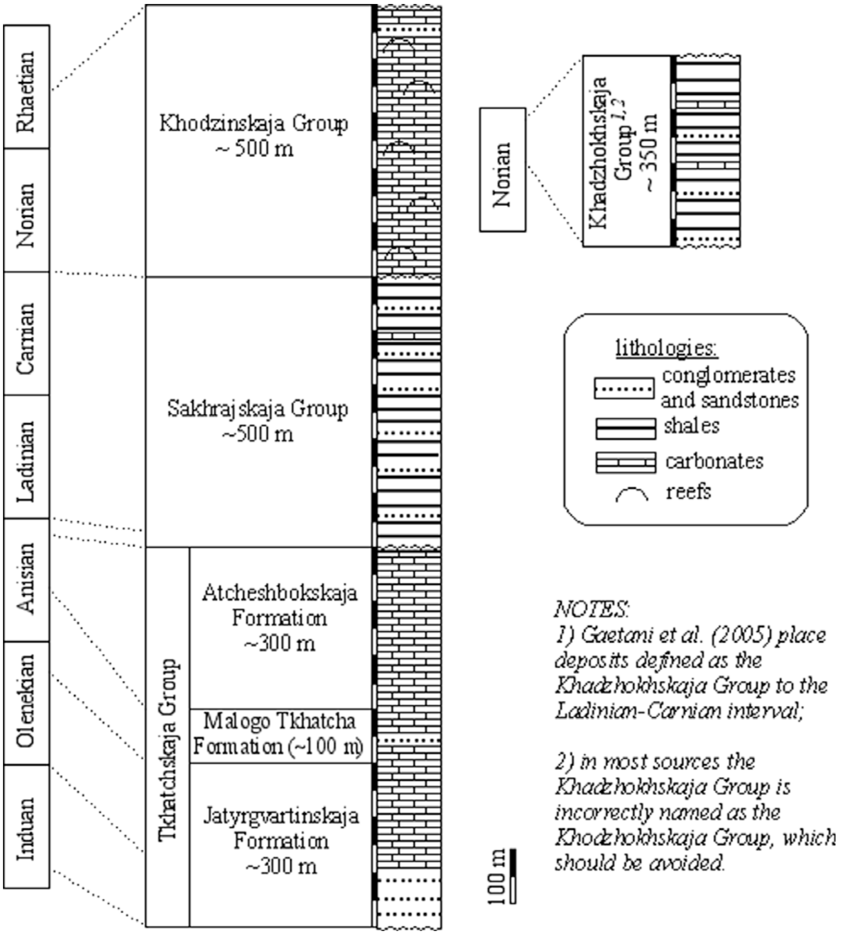

NOTES:
1) Gaetani et al. (2005) place deposits defined as the Khadzhokhskaja Group to the Ladinian-Carnian interval;

2) in most sources the Khadzhokhskaja Group is incorrectly named as the Khodzhokhskaja Group, which should be avoided.

Fig. 5. Triassic composite section of the Western Caucasus (after Ruban, 2006a).

Transcaucasus (Fig. 4). They have been described by D'jakonov et al. (1962), Azarjan and Azizbekov (1973), Dagis and Robinson (1973), Slavin (1973), Jaroshenko (1978), Prozorovskaja (1979), Rostovtsev et al. (1979), and Zakharov et al. (1999). Gaetani et al. (2005) have recently presented their most comprehensive overview, which provides detailed information on the Triassic in the studied region. Ruban (2006a) summarized the available data and presented a composite Triassic section for the Western Caucasus.

The most complete and better-studied sedimentary succession of the Triassic is represented in the Western Caucasus (Fig. 5), where the application of synthem stratigraphy is attempted. The most ancient is the Tkhatchskaja Group (Induan–Anisian) with a total thickness of up to 700 m. Carbonate deposits (wackestones, packstones, mudstones, and calcarenitic limestones), overlying the clastic unit at the base, dominate its composition. The Sakhrajskaja Group (Ansian–Carnian) with a total thickness of about 500 m consists of turbidites. Two upper groups with a total thickness of about 350–500 m were deposited simultaneously. They are the Khodzinskaja Group (Norian–Lower Rhaetian), embracing carbonates, including reefal limestones (packstones in the lower part, overlain by wackestones in the upper part), and the Khadzhokhskaja Group (Upper Norian), encompassing shales with sandstone and carbonate interbeds. Rostovtsev et al. (1979) established a Norian age for the clastic deposits in the Kamennomostskij area with the typical *Monotis* assemblage; however, this age was not confirmed by the studies of Gaetani et al. (2005). In this paper, we prefer to continue the usage of the Khadzhokhskaja Group following the lithostratigraphic framework of Rostovtsev et al. (1979) because of their macrofaunal evidence and our field observations. The upper Rhaetian–lower Liassic interval corresponds to a major regional hiatus. Triassic deposits are known in four areas of the Western Caucasus: Kamennomostskij area, Tkhatch-Bol'shoj Sakhraj area, Jatyrgvarta-Urushten (Malaja Laba) area, and Guzeripl' area (Rostovtsev et al., 1979; Gaetani et al., 2005) (Fig. 4). The differences between these areas were caused mostly by the distinct time spans of the local hiatuses and less by any lithological peculiarities.

3. Synthem stratigraphic approach

The basic principles of synthem stratigraphy are presented in the 'International Stratigraphic Guide' (Salvador, 1994). A synthem is a stratigraphic unit corresponding to a particular unconformity-bounded sedimentary complex. The definition of any synthem is possible only by the analysis of the stratal conformity in the sedimentary succession and the duration of the hiatuses, but always ignoring lithology, thickness, fossil assemblages, and origin. However, although the fossil content is not a criterion for defining synthems, its evaluation is important for characterizing the bounding surfaces in terms of time span. To define synthems we use the regional litho- and biostratigraphic frameworks. Additionally, some considerations additional to those presented in the above-mentioned guide (Salvador, 1994) are proposed below.

(1) It is better to define a synthem as a disconformity- or discontinuity-bounded unit, because the term 'unconformity' may have a more limited sense. It is evident that a synthem may

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be bounded by angular (unconformities) and erosional discordancies as well as 'non-conformities' (parallel disconformities), i.e., by surfaces that coincide with hiatuses of any kind. However, considering unconformity as a general term, which can refer to disconformities, paraconformities, angular unconformities, and non-conformities (Catuneanu, 2006), it would be possible to define a synthem as an unconformity-bounded unit.

(2) As numerous discontinuities are observed in sediments, and as their numbers increase, as one begins to study the succession in more detail, it is necessary to use only those disconformities that are macrostratigraphically significant. This means that the duration of hiatuses, documented by these discontinuities, should be significantly longer than the time interval during which a single bed in a particular succession was accumulated.

(3) Synthem stratigraphy and sequence stratigraphy are somewhat similar. But the degree of their similarity depends on what concept of sequences we prefer. In our own opinion, one fundamental difference between the two stratigraphic approaches is caused by the necessity of facies analysis and paleoenvironmental interpretations for sequence stratigraphy (Catuneanu, 2006), whereas they appear to be insignificant for synthem stratigraphy (Salvador, 1994). Additionally, sequences can be defined not only by unconformities, but also by their correlative conformities (Catuneanu, 2006).

4. Triassic synthems of southwestern Gondwana (the South American Sector)

Available regional litho- and biostratigraphic frameworks are appropriate for identifying synthems (Fig. 3). Because of the occurrence of restricted basins or depocenters separated by hundreds or thousands of kilometers, the synthems proposed herein differ for each basin or region.

4.1. Cuyo Basin

4.1.1. Río Mendoza–Cerro de las Cabras Synthem

Most of the Cuyo Basin rocks occur on the subsurface, and this basin is an important oil producer. The outcrop areas are disconnected and distributed within several thrust blocks in the Andean Precordillera (Mendoza Province, western Argentina). This synthem represents the first syn-rift and sag phase of the Cuyo Rift and lies non-conformably over the rocks of the Choiyoi Igneous Province (Permian–Triassic). It has a maximum thickness of 1000 m in the subsurface (Kokogian et al., 1993). The lower part of this synthem is composed of alluvial fan conglomerates and diamictites, with subordinated tuffs related to the Río Mendoza Fm (Fig. 3). This interval is probably correlated to the upper part of the Puesto Viejo Fm, which crops out further south in a disconnected basin relict. The finding of kanemeyeriid dicynodonts within the lower part of the Río Mendoza–Cerro de las Cabras Synthem, related to the South African *Cynognathus* Zone (Bonaparte, 1982), suggests an Olenekian age for this interval. One tuff level was dated at 243 ± 5 Ma by U–Pb SHRIMP in zircon (Ávila et al., 2003), suggesting the Anisian age. The upper part of this synthem corresponds to the Cerro de las Cabras Fm and is composed of pyroclastic rocks, organic shales and subordinate conglomerates and sandstones, interpreted as a fluvio-lacustrine system with high pyroclastic yield. The hiatus associated with the lower synthem boundary comprises at least some part of the Early Triassic, although the available ages of the underlying Choiyoi rocks are rather variable for defining this boundary more accurately. A disconformity or unconformity, according to its position within the basin, delineates the upper contact with the overlying synthem. This synthem boundary generally corresponds to the Ladinian hiatus.

4.1.2. Potrerillos–Cacheuta–Río Blanco Synthem

This synthem represents the second syn-rift and sag phase of the Cuyo Rift. Its maximum thickness is about 1700 m in the subsurface (Kokogian et al., 1993). The lower succession is composed of conglomerates, mudstones, tuffs, and sandstones, related to a fluvial system with high pyroclastic contribution. It corresponds to the Potrerillos Fm (Fig. 3). Its paleofloristic content suggests a late Ladinian to Carnian age (Spalletti et al., 1999). The intermediate part represents a fining-upward succession of sandstones and tuffs, rhythmites, and organic black shales that are the oil generator. It is interpreted as a transition from a fluvial-deltaic to a lacustrine system and corresponds to the Cacheuta Fm. The upper part (Río Blanco Fm) is composed of a coarsening-upward succession of red shales, sandstones, and mudstones with lateritic levels. This package is interpreted as a succession of shallow lacustrine, deltaic and high sinuosity river deposits, from the base to the top. The plant remains point out to a latest Triassic age (Spalletti et al., 1999). Thus, this synthem was deposited from the late Ladinian to the late Rhaetian. This unit is overlain by either the Jurassic Barrancas Fm or Cenozoic sediments.

4.2. Ischigualasto Basin

4.2.1. Ischichuca–Los Rastros Synthem

From a tectonic point of view, this 1800 m-thick synthem is related to the first syn-rift and sag phase of the Ischigualasto Basin. Its outcrop areas are located in the Peñón River Canyon, Cavallo Anca Canyon, and Valle de La Luna Region (San Juan Province, western Argentina). The lower interval is composed of conglomerates and sandstones related to low sinuosity rivers and it corresponds to the base of the Ischichuca Fm (Fig. 3). This package is succeeded by a 1700 m thick succession of rhythmites and sandstones deposited within a deltaic–lacustrine system. The latter interval corresponds to the Ischichuca and Los Rastros Fms. The fossil content is represented by reptilians in the lower part (Los Chañares Fauna) (Bonaparte, 1982) and plant remains (Spalletti et al., 1999), and it suggests an Anisian–Ladinian age. The lower disconformity corresponds to the hiatus, which comprises the upper part of the Lower Triassic and/or the Anisian. The upper contact of this unit with the Ischigualasto–Los Colorados Synthem is marked by another disconformity.

4.2.2. Ischigualasto–Los Colorados Synthem

The best exposures of this synthem are in the Valle de la Luna Region. This 1600 m-thick unit represents the second syn-rift and sag phase in the Ischigualasto Rift. Its lower interval is composed of up to 10 m of fluvial sandstones from the basal part of the Ischigualasto Fm (Fig. 3). The intermediate part, also corresponding to the Ischigualasto Fm, is composed of mudstones with subordinated sandstones, tuffs and lateritic levels, interpreted as having been deposited in shallow lakes and floodplains. This interval contains remains of reptiles (the Ischigualasto Local Fauna) (Bonaparte, 1982) and plants (Spalletti et al., 1999). An ^{40}Ar–^{39}Ar age of 227.8 ± 0.3 Ma from a tuff level, determined by Rogers et al. (1993), and the fossil content date this interval as close to the Ladinian/Carnian boundary. The upper interval corresponds to the Los Colorados Fm and is composed of fluvial conglomerates and sandstones containing the remains of reptiles and plants. The uppermost strata of this synthem contain reptile fossils of the La Esquina Local Fauna of latest Triassic age (Bonaparte, 1982). Thus, the entire synthem was deposited in a time span from the latest Ladinian to latest Rhaetian.

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According to Stipanicic and Bonaparte (1976), the Cerro Rajado Fm (Early Cretaceous?) lies unconformably over the Ischigualasto–Los Colorados synthem. Conversely, Bracco et al. (1997) considered the contact between these two units as gradational, and suggested that the Cerro Rajado Fm could represent the uppermost strata of the Ischigualasto Basin. Thus, it is possible to conclude that the upper boundary corresponds to a hiatus with a Jurassic age.

4.3. Chaco–Paraná Basin

4.3.1. Sanga do Cabral Synthem

This 100 m-thick unit crops out in Rio Grande do Sul, Brazil, and in Uruguay. It corresponds to the Sanga do Cabral Fm in Brazil, and Buena Vista Fm in Uruguay. In the subsurface, this unit probably reaches the Argentinian side of the basin (the Chaco region). It is composed of intraformational conglomerates and sandstones related to low sinuosity and low gradient rivers (Lavina, 1991; Faccini, 2000; Zerfass et al., 2003). The vertebrate fossils (procolophonid reptiles, amphibians) suggest a Late Induan age.

A disconformity delineates the lower contact with the latest Permian Pirambóia and Rio do Rasto Fms, and the hiatus comprises the lower Induan. The upper disconformity separates this synthem from the Santa Maria 1–2 synthems (Fig. 3) (Middle–Late Triassic) and the Guará-lower Tacuarembó Fms (Late Jurassic or Early Cretaceous). A hiatus embraces the Anisian and/or Ladinian on the eastern outcrop belt. In the western sector, the hiatus comprises the Middle Triassic to Late Jurassic time span. The upper boundary of the Sanga do Cabral Synthem corresponds to the basal boundary of the Guará Fm. This surface cuts different stratigraphic levels. It appears that this surface is the sum of different erosional hiatuses.

4.3.2. Santa Maria 1 Synthem

This synthem crops out in the central region of Rio Grande do Sul and has a thickness of about 150 m. It corresponds to a part of the Santa Maria Fm (Fig. 3). Sandstones, mudstones, and subordinate conglomerates are the main lithofacies, interpreted as low sinuosity river deposits that were succeeded by deltaic and shallow lacustrine systems (Zerfass et al., 2003). Reptile fossils such as dicynodonts, cynodonts and thecodonts suggest a Ladinian age for this unit (Barberena, 1977; Scherer et al., 1995; Schultz, 1995). The unit is overlain by the Santa Maria 2 Synthem, and the bounding surface is a disconformity, which corresponds to a hiatus that embraces the Upper Ladinian.

4.3.3. Santa Maria 2 Synthem

The outcropping area of this 50 m-thick unit is the central region of Rio Grande do Sul. The lower part of the unit is composed of sandstones related to low sinuosity rivers (Zerfass et al., 2003). The upper part is composed mainly of shallow lacustrine mudstones (Zerfass et al., 2003). This synthem corresponds to a part of the Santa Maria Fm (Fig. 3). The fossil content includes reptiles, plant remnants, fish, insects, and crustaceans. The reptiles (rynchosaurs, cynodonts, early dinosaurs) indicate a Carnian to early Norian age (Barberena, 1977; Scherer et al., 1995; Schultz, 1995; Rubert and Schultz, 2004). The upper boundary of this synthem is a disconformity that separates it from the Caturrita Synthem (Norian), and the Botucatu Fm (Early Cretaceous). The hiatus corresponds to the Carnian/Norian boundary.

4.3.4. Caturrita Synthem

The unit crops out in the central region of Rio Grande do Sul and it corresponds to the Caturrita Member (Fig. 3). Its thickness is up to 130 m. The basal portion of this synthem is composed mainly of sandstones rich in silicified logs related to fluvial channels, and rhythmites related to deltaic systems. The upper part is composed of deltaic sandstones, rhythmites and lacustrine mudstones. The sandstones contain fossils of mammal-like cynodonts, dinosaurs, and sphenodonts. The mudstones present dicynodont bones and a rich content of conifer remains. The fossil assemblage suggests a Norian age. This unit is overlain disconformably by the newly recognized Early Cretaceous Paraíso do Sul Sequence (Zerfass, 2006) and the Botucatu Fm. The time span represented by the hiatus probably comprises the Jurassic.

4.4. Other deposits of western Argentina

The Talampaya and Tarjados Synthems share the same depositional locus with the Ischigualasto rift basin, although they are not considered as part of the mentioned basin-fill (cf. Zerfass et al., 2004) (Fig. 3).

4.4.1. Talampaya Synthem

The Talampaya Synthem (corresponding to the Talampaya Fm) crops out in the homonymous river canyon further south (La Rioja Province) and at the Peñón River canyon near Valle de la Luna (San Juan Province). Its maximum outcropping thickness is about 400 m. It is composed of conglomerates and sandstones related to low sinuosity and low gradient rivers (Zerfass et al., 2004). The only fossil remains are ichnofossils related to tetrapod footprints that suggest a Triassic age (Stipanicic and Bonaparte, 1976). Its position within the Induan is suggested by stratigraphic relationships. An unconformity delineates the lower contact of this synthem with the Permian strata of the Paganzo Basin. The related hiatus is located near to the Permian–Triassic boundary although the age uncertainty of the Talampaya Synthem does not allow for a more precise definition. The upper contact with the Tarjados and Ischichuca–Los Rastros synthems is marked by a disconformity. In the region of the Talampaya River canyon the Tarjados Synthem is the overlying unit and the hiatus is minimal, although its time span cannot be defined due to the uncertainty of the Tarjados Synthem age. In the Peñón River canyon the hiatus reaches its maximum.

4.4.2. Tarjados Synthem

This unit crops out in the Talampaya River canyon further south. Its maximum thickness is 385 m (Stipanicic and Bonaparte, 1976). It is dominated by fluvial sandstones. A thin bed of alluvial conglomerate and lacustrine rhythmite occurs at the base. The fossil content is composed of fragments of kannemeyrid dicynodonts of a Triassic age. Zerfass et al. (2004) suggested an Olenekian age. This synthem corresponds to the Tarjados Fm (Fig. 3). Its upper contact with the Ischichuca–Los Rastros Synthem is observed in the Los Chañares region and is delineated by a disconformity. The time span of the hiatus probably comprises the Anisian.

5. Triassic synthems of the Western Caucasus

5.1. Synthem architecture

The regional lithostratigraphic framework summarized by Rostovtsev et al. (1979), Jaroshenko (1978), Gaetani et al. (2005), and Ruban (2006a) may be chosen as a valid base for identifying synthems. An analysis of this framework coupled with field observations were used to define synthems in the Triassic of the Western Caucasus. Three disconformity-bounded units are distinguished (Fig. 6) and characterized below.

5.1.1. WC-1 Synthem

This unit is represented within three areas of the Western Caucasus. It corresponds to the entire Tkhatchskaja Group. The total thickness is estimated as ~700 m, and the age is Induan–Anisian. This synthem is bounded from the underlying Changhsingian deposits by a disconformity, related to the latest? Permian –

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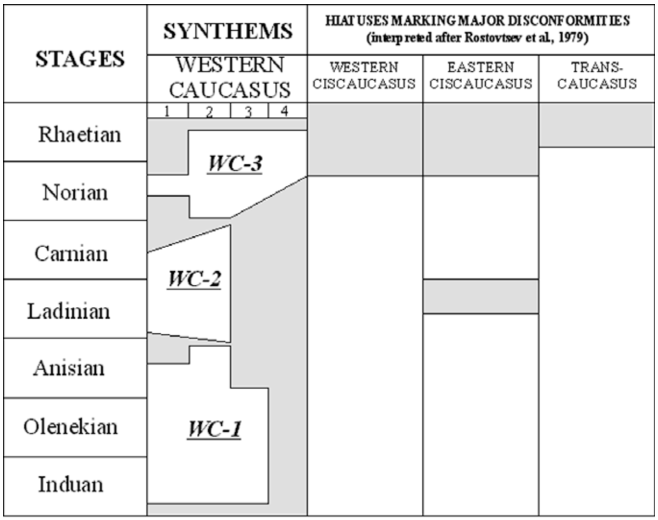

hiatuses are highlighted in grey

Fig. 6. Triassic synthems of the Western Caucasus, and hiatuses in other Caucasian regions (after Rostovtsev et al., 1979). Areas (see Fig. 2 for their location): 1 – Kamennomostskij, 2 – Tkhatch-Bol'shoj Sakhraj, 3 – Jatyrgvarta-Urushten (Malaja Laba), and 4 – Guzeripl'.

earliest Triassic hiatus (see Section 4.2 for more details on its age). The termination of deposition varied within the Anisian. In the Kamennomostskij and Jatyrgvarta-Urushten areas (Fig. 4), this had already occurred in the Early Anisian, while in the Tkhatch-Bol'shoj Sakhraj area, sedimentation was terminated only at the end of the Anisian.

5.1.2. WC-2 Synthem

This unit is represented within two areas of the Western Caucasus only. It corresponds to the argillaceous Sakhrajskaja Group, with a thickness of up to 500 m. The age is Anisian–Carnian. The deposition after a relatively short hiatus, documented by the disconformity, began in the Tkhatch-Bol'shoj Sakhraj area already in the latest Anisian, while in the Kamennomostskij area, this occurred later, i.e., at the beginning of the Ladinian. The upper boundary is disconformity, which marks the termination of the Ladinian sedimentation.

5.1.3. WC-3 Synthem

This unit is represented within all four areas of the Western Caucasus. It includes the argillaceous deposits of the Khadzhokhskaja Group (Fig. 5) and the more widely distributed calcareous deposits with reefs of the Khodzinskaja Group. The thickness of this synthem is up to 500 m, and the age is Norian–Rhaetian. Deposition after hiatus began in the Tkhatch-Bol'shoj Sakhraj area (Fig. 4) already in the earliest Norian, while in the other areas, this occurred later. Particularly in the Guzeripl' area, sedimentation began in the late Norian only. In the Kamennomostskij area, deposition was already interrupted by the Norian. The upper boundary corresponds to a disconformity, which separated the Triassic and Jurassic sedimentary complexes.

5.2. The lower boundary of the WC-1 synthem

The age of the Lower Triassic disconformity, which serves as a lower boundary of the WC-1 synthem, is a subject for special discussion. Recent developments in the stratigraphy of the Permian–Triassic (P–T) transitional interval are connected to the definition of the Global Stratotype Section and Point (GSSP) of the Triassic at the Meishan Section in China (Yin et al., 2001). The Permian/Triassic (P/T) boundary was marked by a mass extinction event (Hallam and Wignall, 1999; Becker et al., 2001; Kaiho et al., 2001; Erwin et al., 2002; Erwin, 2006). In the Western Caucasus, an uncertainty in the regional P–T stratigraphy exists (Miklukho-Maklaj and Miklukho-Maklaj, 1966; Rostovtsev et al., 1979; Gaetani et al., 2005), although influences of the global events, which occurred around the P/T boundary, were evidently documented (Zakharov et al., 1999). The main problem is the lack of representative sections. Some clarification of the P–T stratigraphy in the Western Caucasus is attempted herein.

Three units should be taken into account when considering the P–T transition in the Western Caucasus, i.e., the Urushtenskaja, Abagskaja, and Jatyrgvartinskaja Fms. The Urushtenskaja Fm is represented by reefal limestones up to 200 m thick. It contains abundant and diverse fauna, including foraminifers, bivalves, brachiopods, ammonoids, gastropods, sponges, bryozoans, and trilobites. It is conformably overlain by the limestones of the Abagskaja Fm which is up to 20 m thick (Miklukho-Maklaj and Miklukho-Maklaj, 1966). Rare ammonoids, small foraminifers, and radiolarians have been found in these deposits (Likharev, 1968; Miklukho-Maklaj and Miklukho-Maklaj, 1966; Kotlyar, 1977). The basal conglomerates, sandstones, and limestones of the Jatyrgvartinskaja Fm overlie the Upper Permian strata with an erosional surface (Dagis and Robinson, 1973; Rostovtsev et al., 1979; Gaetani et al., 2005).

It was concluded previously that the beginning of the Triassic was marked by a significant hiatus in the Western Caucasus, which lasted at least until the middle of the Induan (Dagis and Robinson, 1973; Rostovtsev et al., 1979), but this conclusion needs to be verified (Fig. 7). The age of the Upper Permian marine deposits of the Western Caucasus has been recently established as Late Changhsingian (Kotlyar et al., 1999, 2004). The P/T boundary should be located within the overlying Abagskaja Fm, as was previously proposed by Kotlyar (1977). When this formation was deposited, the regional faunas declined catastrophically. This demise may be linked to the global mass extinction, and can be used as evidence for locating the P/T boundary *within* the Abagskaja Fm. As the Late Changhsingian limestones are conformably overlain by the Abagskaja Fm, we may hypothesize that the lack of sedimentation might have occurred only in the earliest Triassic or at least close to the P/T boundary. However, further studies are necessary to examine whether a part of the gap was latest Permian in age.

The *Claraia* assemblage is characteristic of the Lower Triassic Jatyrgvartinskaja Fm (Fig. 7). It includes *C. stachei* Bittner, *C. clarai* (Emmrich), and *C. aurita* (Hauer). In other regions, both Tethyan and Boreal, the poorly faunistic *Claraia*-dominated assemblages are typical of the Lower–Middle Induan (Assereto et al., 1973; Nakazawa, 1977; Taraz et al., 1981; Mandl, 1987; Newell and Boyd, 1995; Davies et al., 1997; Mørk et al., 1999; Tong and Yin, 2002; Benton and Twitchett, 2003; Boyer et al., 2004; Ruban, 2006b). In the Boreal areas, *Claraia* taxa are known even from the Upper Permian (Muromtseva and Gus'kov, 1984). Surprisingly, *Claraia caucasica* Kulikov and Tkatchuk was also found in the Upper Permian of the Western Caucasus (Zakharov et al., 1989), although Kotlyar et al. (2004) reconsidered it as *Claraioides caucasicus* (Kulikov and Tkatchuk). None of the ammonoid taxa found in the Lower Triassic of the Western Caucasus are older than the Dinerian-Smithian (Ehiro, personal communication), but bivalves diversified earlier than ammonoids (Rostovtsev et al., 1979) (Fig. 7). As for brachiopods, *Crurithyris? extima* Grant was found in the lowermost horizons of the Jatyrgvartinskaja Fm (Rostovtsev et al., 1979; Ruban, 2006b). Grant (1970) placed his findings just around the P/T boundary. Summarizing all the above-mentioned evidence, it can be concluded that the hiatus might have already ended by the earliest Induan. If so, it appears to be very short (Fig. 7).

Uplift evidently occurred in the Western Caucasus at the beginning of the Triassic. Conglomerates with plant remains at the base

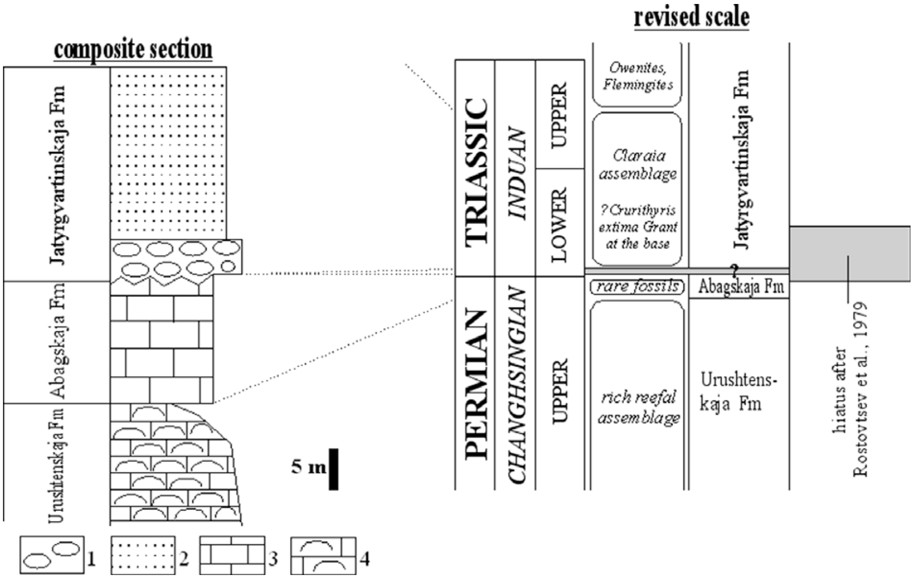

Fig. 7. The Permian–Triassic transition of the Western Caucasus. Lithologies: 1 – conglomerates, 2 – sandstones, 3 – limestones, and 4 – reefal limestones.

of the Triassic succession are the best argument for this (Miklukho-Maklaj and Miklukho-Maklaj, 1966; Kotlyar, 1977; Rostovtsev et al., 1979; Gaetani et al., 2005). The mechanism of this regression is still unclear. One possible explanation is post-orogenic tectonic activity. New ages for the Upper Permian marine deposits (Kotlyar et al., 1999, 2004) suggest a short time interval between the Middle–Late Permian phase of intense tectonic activity and the earliest Triassic regression. Moreover, the presence of red beds among the Chaghsingian deposits (Gaetani et al., 2005) is evidence of local uplift in the latest Permian. Thus, post-orogenic dislocations (local uplifts?) seem to have occurred in the Early Triassic. If so, regional tectonic activity was able to minimize the influence of global transgression established at the P–T transition (Hallam and Wignall, 1997, 1999). The presence of *Claraia* in the Induan may be interpreted as a rapid return to relatively deep-water sedimentation (Taraz et al., 1981; Hallam and Wignall, 1999). In the Eastern and Southern Alps, the Upper Permian–Lower Triassic was a unique sedimentary cycle (Krainer, 1993). In the interim, at the base of the Upper Alpine Buntsandstein Fm (middle Lower Triassic), a significant regression occurred in this region (the so-called 'Campill Event'). It is a matter for further consideration whether it is possible to correlate the Early Triassic regressions between the Western Caucasus and the Alps.

In the Western Caucasus, the Induan/Olenekian boundary was chosen by sharp changes from bivalve *Claraia*-dominated assemblages to those including the ammonoids *Flemingites* and *Owenites*. Global stratigraphic ranges of *Claraia* taxa found in the studied region are limited to the Upper Griesbachian–Lower Dienerian (Nakazawa, 1977; Tong and Yin, 2002). The paleontological record from South China suggests that *Flemingites* began to diversify in the Late Dienerian, while *Owenites* appeared just at the base of the Olenekian. This means that the Induan/Olenekian boundary may be repositioned downwards in the Western Caucasus (Fig. 7).

Such reconsideration of the regional P–T transition is important for precisely placing the lower boundary of the WC-1 synthem. This boundary should be located strictly within the Induan.

6. Discussion

Synthem architecture established in each studied region provides some evidence to trace the principal disconformities (essentially the synthem boundaries) globally. Three main disconformities are established in southern South America: the Lower Triassic, Ladinian, and Upper Triassic disconformities; and four main disconformities are established in the Western Caucasus: the Lower Triassic, Upper Anisian, Carnian/Norian, and Upper Triassic disconformities. Firstly, a comparison of these synthem boundaries between southern South America and the Western Caucasus was attempted. Secondly, we have tried to trace them in the adjacent regions. Thirdly, planetary-scale patterns in regional Triassic stratal architecture have been recognized.

6.1. A comparison of the Triassic synthem architecture between southern South America and the Western Caucasus

The most evident correlative horizon between southern South America and the Western Caucasus is the Lower Triassic Disconformity, which serves as a lower boundary of the Rio Mendoza–Cerro de las Cabras, Sanga do Cabral, Talampaya, and WC-1 synthems (Figs. 3 and 6). It is possible to conclude that the lack of sedimentation in both studied regions was caused by tectonic activity and consequent uplift. However, this was not a world-wide phenomenon. It is already known that on the global scale a remarkable transgression occurred at the Permian–Triassic transition (Hallam and Wignall, 1997, 1999). Moreover, even within some blocks amalgamated into Gondwana, there were no major hiatuses at the Permian–Triassic transition, as was the case in Arabia, where the carbonates of the Khuff Formation were deposited (Osterloff et al., 2004). However, minor disconformities are known there in the Lower Triassic (Sharland et al., 2001; Le Nindre et al., 2003). Thus, this observed similarity of southern South America and the Western Caucasus was not a global feature. The Ladinian Disconformity in southern South America and the Upper Anisian Disconformity in the Eastern Caucasus cannot be related to each other. Something of an analogue of the Carnian/Norian Disconformity, which is a boundary between the WC-2 and WC-3 synthems in the Western Caucasus, is the boundary between the Santa Maria 2 and Caturrita synthems in the Chaco–Paraná Basin (Fig. 3). But there are no such disconformities in the Cuyo and Ischigualasto basins (Bonaparte, 1982; Milana and Alcober, 1994; Zerfass et al., 2004). The Upper Triassic in both studied regions is represented by a disconformity (Figs. 3 and 6). The synthem boundaries

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correspond to hiatuses, which embraced the Rhaetian. This similarity between regions, located so far from each other, seems not to be coincidental, because the global sequence boundary and remarkable sea-level fall have already been established globally (Haq et al., 1987; Embry, 1997; Hallam and Wignall, 1999; Hallam, 2001; Haq and Al-Qahtani, 2005). Moreover, they may be explained by a common cause, i.e., the activity of the mantle plume in the central Atlantic (Hallam, 2001).

6.2. Tracing the Triassic disconformities within Gondwana

In southern South America, the Triassic sedimentation was mainly non-marine, and, in the case of the Middle–Late Triassic interval, it occurred within restricted basins (Figs. 2 and 3). Synthem boundaries may be easily traced between these basins. The common boundaries are those related to the Lower Triassic, Ladinian, and Upper Triassic disconformities (Fig. 3). We have attempted to trace the three above-mentioned synthem boundaries within some parts of Gondwana.

The Lower Triassic Disconformity is related to compressional stresses on the Gondwanides orogen close to the Permian–Triassic boundary (Hälbich et al., 1983; Veevers et al., 1994a; Zerfass et al., 2004). The lack of sedimentation during the Olenekian–Early Anisian occurred just before the first rifting phase on the back-arc and intracontinental rifts as previously discussed by Zerfass et al. (2004). In the African counterpart of southwestern Gondwana, the sedimentation within intracontinental rifts took place already in the Olenekian or even earlier, as suggested by the age of the lower levels of the Waterberg Basin, Namibia (Lower Omingonde Fm, cf. Keyser, 1973; Pickford, 1995; Lucas, 1998; Holzförster et al., 1999). In the main Karoo basins, however, sedimentation did not stop during the Permian–Triassic time interval or it was interrupted for only a short-time interval (Catuneanu et al., 2005). The Permian–Triassic boundary lies within the Beaufort Group there. The Lower Triassic Disconformity is documented in western and northeastern Africa (Bosworth et al., 2005; Guiraud and Bosworth, 1999; Guiraud et al., 2005), but it is not evident in Arabia (Sharland et al., 2001) as already mentioned above.

The Ladinian Disconformity is related to the second syn-rift phase on the South American rifts (Kokogian et al., 1993; Milana and Alcober, 1994; Zerfass et al., 2004). In the Main Karoo Basin of South Africa, the Carnian–Norian Molteno Fm overlies discordantly the Anisian Burgersdorp Fm (Hancox, 1998; Catuneanu et al., 2005). This disconformity is related to tectonic pulses on the Gondwanides (Veevers et al., 1994a), and, therefore, it is somewhat related to the Ladinian Disconformity documented in southern South America. In western and northeastern Africa, there is no evidence of the regional-scale disconformities in the Ladinian, although locally they might have existed (Guiraud et al., 2005). In contrast, the remarkable upper Ladinian hiatus is known in Arabia (Sharland et al., 2001).

Sedimentation within the southern South American Triassic basins ended close to the Triassic/Jurassic boundary. The causes are still controversial, and Zerfass et al. (2004) suggested that there was a time gap related to cratonic stability comprising the Late Triassic and Jurassic, following from the cessation of the Gondwanides orogeny. In the Southern African counterpart, a nonconformity separates the Late Triassic Clarens Fm and the Early Jurassic Drakensberg Fm in the Main Karoo Basin (Visser, 1984; Veevers et al., 1994b; Johnson et al., 1996). However, recent studies suggest that the Triassic/Jurassic boundary lies significantly lower than this non-conformity, i.e., within the Elliot Fm (Catuneanu et al., 2005). Consequently, it seems that there is not a significant end-Triassic disconformity in the Southern African Karoo basins. In contrast, there is no mid-Norian disconformity in the southern South American basins, although it exists in South Africa (Catuneanu et al., 2005). In western and northeastern Africa, a disconformity is established in the uppermost Triassic (Bosworth et al., 2005; Guiraud and Bosworth, 2005; Guiraud et al., 2005). It is also documented in Arabia (Sharland et al., 2001).

6.3. Tracing the Triassic disconformities within the Caucasus and Europe

The only synthem boundary among those established in the Western Caucasus that may be traced in the other Caucasian regions is the upper boundary of the WC-3 Synthem, i.e., the Late Triassic Disconformity (Fig. 6). This disconformity was documented in the Western and Eastern Ciscaucasus, and in the Transcaucasus. These regional Upper Triassic disconformities are explained by the intense tectonic activity at the Triassic–Jurassic transition (Ershov et al., 2003).

In the European Triassic basins, two principal disconformities are established in the Olenekian and at the Norian/Rhaetian boundary (Jacquin and de Graciansky, 1998). In the so-called ‘German Triassic’ numerous hiatuses are concentrated in the Late Triassic, and minor ones in the Early Triassic (Aigner and Bachmann, 1992; Stratigraphische Tabelle, 2002). In the Northern Calcareous Alps (Dachstein, Austria), the hiatuses are observed in the Middle Carnian and end-Triassic (Mandl, 2000). The above-mentioned disconformities and the Western Caucasus synthem boundaries may be partly correlated.

6.4. Global tracing

On a planetary scale, Embry (1997) recognized several sequence boundaries within the Triassic, which may be compared with the

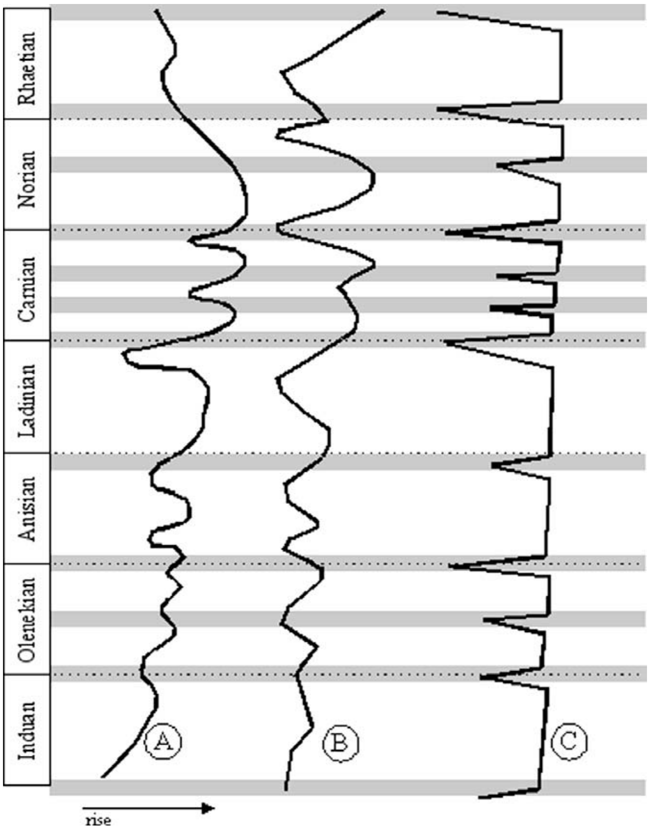

Fig. 8. Global Triassic sea-level changes: A – after Haq et al. (1987); B – after Haq and Al-Qahtani (2005); C – after Embry (1997) (for A, B the amplitudes of sea-level changes are not preserved). Potential global sequence boundaries (after Embry, 1997) are marked by grey lines.

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synthem boundaries established in the two regions studied here. It is evident that the Early Triassic, Ladinian, and Late Triassic disconformities of southern South America have analogues in the global record, and therefore, may be traced globally. They also coincide with the global sea-level falls documented by Haq et al. (1987), Embry (1997), and Haq and Al-Qahtani (2005) (Fig. 8).

The Early Triassic, Carnian/Norian, and Late Triassic disconformities established in the Western Caucasus evidently correspond to the global sequence boundaries recognized by Embry (1997) and sea-level falls of Haq et al. (1987), Embry (1997), and Haq and Al-Qahtani (2005) (Fig. 8). However, as mentioned above, a global transgression has been established for the Permian–Triassic transition (Hallam and Wignall, 1997, 1999), and, therefore, it became impossible to speculate about the global appearance of the base-Triassic disconformity. In contrast, Hallam (2001) suggested the end-Triassic global regression as a reliable event, which resulted from the activity of the mantle plume in the central Atlantic. As for the Upper Anisian Disconformity, established in the Western Caucasus (Fig. 6), it is also linked to eustatic global fall, but of a lesser order. On the contrary, establishing global second-order Olenekian/Anisian and Ladinian/Carnian sequence boundaries (Embry, 1997) and associated sea-level falls (Haq et al., 1987; Haq and Al-Qahtani, 2005) in the Western Caucasus remains doubtful.

7. Conclusions

Our comparative study of the Triassic synthem architecture in southern South America and Western Caucasus allows us to make several conclusions:

(1) In southern South America, the Triassic sedimentary succession consists of two synthems in each of the Cuyo and Ischigualasto basins, and of four synthems in the Chaco–Paraná Basin; additionally two Early Triassic synthems have been recognized in western Argentina.
(2) In the Western Caucasus, the Triassic sedimentary succession consists of three synthems.
(3) In contrast to the previous interpretations, the lowermost Triassic synthem boundary in the Western Caucasus corresponds to a disconformity related to a very short hiatus.
(4) The common synthem boundaries in the studied regions correspond to the disconformities at the base and top of the Triassic succession.
(5) The Early Triassic, Ladinian, and Late Triassic disconformities are the principal synthem boundaries in southwestern Gondwana, and the first two of them are traced in adjacent South Africa.
(6) The Late Triassic Disconformity is unique, and is traced across the entire Caucasus; however, all synthem boundaries established in the Western Caucasus are traced only partly within the European regions.
(7) The synthem boundaries established in both southern South America and Western Caucasus sharply correlate with the global sequence boundaries of Embry (1997) and sea-level falls documented by Haq et al. (1987), Embry (1997), and Haq and Al-Qahtani (2005).
(8) In spite of many differences in the synthem architecture caused by the influence of regional-scale factors, and also in spite of the remarkable paleoenvironmental differences between the studied regions, we may state that there are at least several common patterns in the Triassic global sedimentation, which should be explained in terms of global geodynamics.

Further studies should be aimed at the more precise tracing of the Triassic synthem boundaries, and at the recognition of the global-scale mechanisms that created similar synthem architecture elsewhere.

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