STRATIGRAPHIC SEQUENCES OF THE PARANÁ BASIN

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Summary

Introduction

The Paraná Basin (Fig. 1), a vast sedimentation area located in central-eastern South America, developed during Paleozoic and Mesozoic times and holds a stratigraphic record ranging in age from Late Ordovician to Late Cretaceous times, documenting almost 400 million years of the Phanerozoic geological history for this region of the continent. Six major, second order allostratigraphic units or supersequences (Milani, 1997) are recognized (Fig. 1); three of them correspond to Paleozoic transgressive-regressive cycles, and the others are Mesozoic continental sedimentary units with associated igneous rocks.

The Paraná Basin, due to specific aspects of its actual geotectonic setting and to its general geological characteristics, is considered a typical intracratonic basin. The concept of 'interior cratonic basin' (Leighton & Kolata, 1990) implies a sedimentary region supported by a cratonic basement, i. e., a crustal domain that resists deforming forces originating at plate margins. Nevertheless, the mechanisms of intracratonic subsidence are controversial and still poorly understood. Because intraplate domains of subsidence are situated far away from continental margins and hence disconnected from the tectonic mechanisms originated by plate interactions, the intracratonic basins are frequently explained by poorly constrained and somewhat intangible combination of processes that include 'continental extension, thermal subsidence over a wide area, and later isostatic readjustments' (Klein, 1995).

For a particular basin, however, its present location in the continental interior does not signify that this was a permanent condition during all of its history. This is particularly true for the Paraná Basin. The growth of continental crust along the southern margin of Gondwana has been an important process during Phanerozoic time. Thus the geotectonic context favoured a progressive closure of the continental interior to marine incursions, causing the Paraná Basin, that was born as a gulf (Zalán *et al.*, 1990; Milani, 1992) or sag open to the Panthalassa ocean, to become an intracratonic basin caught inside Gondwana.

The time span of the subsidence cycles of the Paraná Basin compared to those in the adjoining foreland domain served to calibrate the main times of subsidence on a continental scale. Subsidence analysis revealed the existence of notably synchronous episodes of accelerated subsidence in the foreland and in the intracratonic domains, suggesting that such areas might have had a common evolutionary history sharing not only regional sedimentary environments but also major mechanisms of subsidence.

Regional tectonics and subsidence

The southern margin of Gondwana (Fig. 2), particularly the sector that presently corresponds to the Andean border of South America, behaved during almost all Phanerozoic time as an active domain of convergence between the paleocontinent and the oceanic lithosphere of Panthalassa (Bahlburg and Breitkreuz, 1991). A series of terranes reached that region and their accretion to the margin of Gondwana produced important orogenic episodes. The succession of orogenies that marked the Phanerozoic history of southwestern Gondwana, as summarized by Ramos (1988), comprised a series of episodes included in two major tectono-sedimentary-magmatic cycles: the Famatinian (Ordovician to Devonian) and the Gondwanic (Carboniferous to Triassic) cycles. The Famatinian cycle encompasses two pulses of compressional deformation and associated phenomena, the Ocloyic and the Precordilleran orogenies, while the Gondwanic cycle includes the Chanic and the Sanrafaelic orogenies.

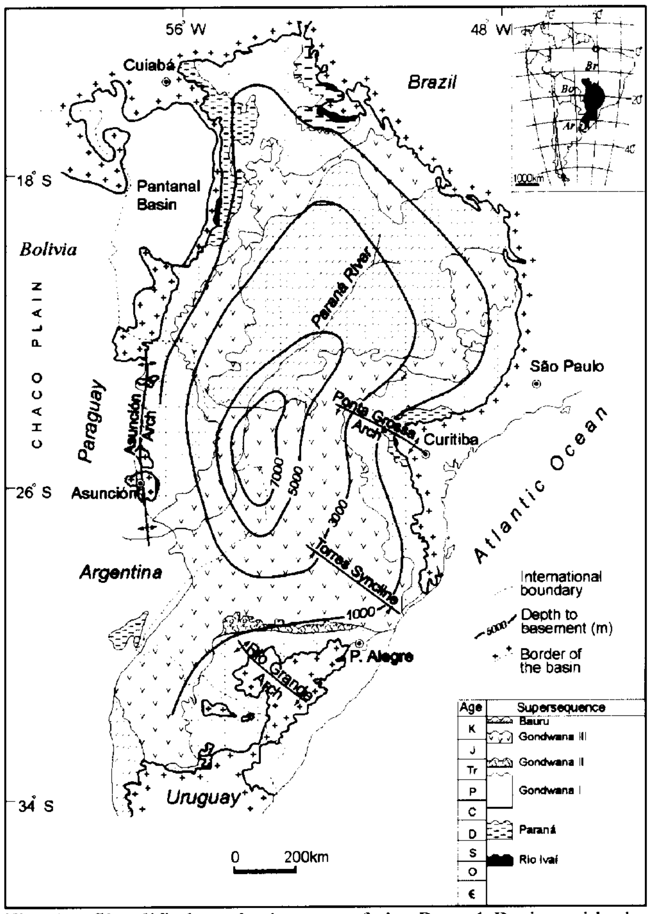

Fig. 1 - Simplified geologic map of the Paraná Basin, with the distribution in time of the major supersequences.

Subsidence plots are useful tools in basin analysis. The shape of a curve, reflecting variations of the subsidence rates with time, reflects a particular tectonic regime at that time that can serve also as an element for interregional correlation. Particularly in the foreland domain, subsidence is induced by the flexural loading of the mountain belt upon the plate margin, so that variations in subsidence rates in terms of acceleration and deceleration can be associated with pulses of compressional deformation along the active continental margin. An idealized orogenic cycle would be recorded in the subsidence history of the adjacent foreland by a complete cycle of growing/peak/falling subsidence rates. This concept was used here as a key to interregional correlation and for the interpretation of the development of stratigraphic sequences in the intraplate domain (Paraná basin).

The subsidence history of southwestern Gondwana Paleozoic foreland basin was summarized by using data from some reference areas (Milani, 1997; Milani and Ramos, 1998). Together with curves already published, computed subsidence plots were combined into a composite subsidence curve, a display of the variation through time of the mean subsidence rate. Average subsidence rates were obtained arithmetically using data from the reference areas, and this computation revealed a succession of cycles representing the subsidence history for the Paleozoic foreland domain as a whole. The changing subsidence rates expressed in such a curve can be interpreted as induced by the varying intensity of tectonic activity along the orogenic belt, and there is a remarkable coincidence in time between the climax of each cycle in the composite subsidence curve and the classical orogenic periods recognized in the geology of southern Gondwana (Ramos, 1988).

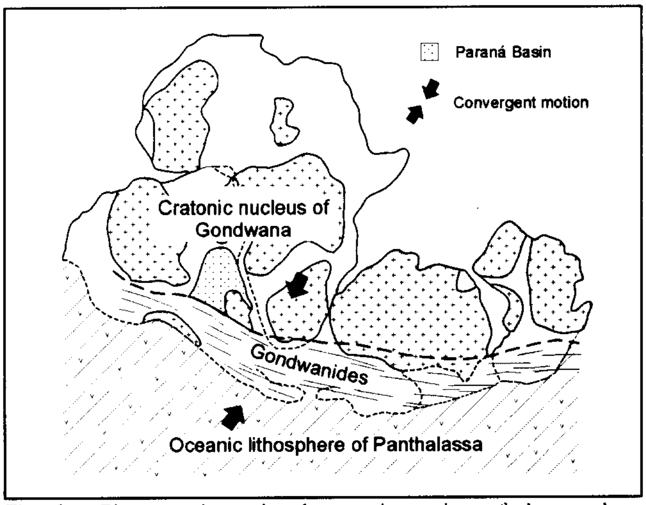

Fig. 2 - Phanerozoic regional tectonic setting of the southern margin of Gondwana. Compiled from Powell (1993), after the conception of Du Toit (1927).

Tectonics and sedimentation in the Paraná Basin

Six supersequences, each one comprising a geological record some tens of millions years long, constitute the stratigraphic framework of the Paraná Basin (Milani, 1997). The overall record spans the range 450-65 Ma, with a much of the time taken up by a series of lacunas that separate the various supersequences (Fig. 1). Rio Ivaí (Caradoc-Llandovery), Paraná (Lockovian-Frasnian) and Gondwana I (Westphalian-Scythian) correspond to major Paleozoic transgressive-regressive cycles of sedimentation, whereas Gondwana II (Anisian-Norian), Gondwana III (Upper Jurassic-Berriasian) and Bauru (Aptian-Maastrichtian) are represented by continental sedimentary packages with associated igneous rocks.

The Rio Ivaí Supersequence, comprising the oldest sedimentary rocks of the Paraná Basin, is particularly significant to the understanding of the inception of the basin because it represents the first cycle of sedimentation in this area that was settled over a consolidated floor, witnessing the establishment of cratonic conditions after the Late Proterozoic/Early Paleozoic Brasiliano Orogeny. Thus the intrinsic characteristics of the Ordovician-Silurian package in terms of occurrence, distribution and geometry of its depocenters, together with sedimentological aspects of this section and its association with magmatic rocks, allow direct considerations on the nature and evolution of the initial subsidence of the Paraná Basin. Rio Ivaí rocks occur widespreadly across the Paraná Basin. Their thickness, however, shows a non-uniform distribution with some elongated depocenters striking SW-NE. There is also a general trend of thickening to the west, with the package reaching about 1,000 m in the Paraguayan portion of the basin. The association of Rio Ivaí sediments with basaltic rocks suggests synsedimentary crustal extension related to some kind of rifting in the inception of the Paraná Basin.

The top of the Rio Ivaí Supersequence is defined by an unconformity surface that had deeply eroded Ordovician-Silurian strata. The blanket-like Devonian Paraná Supersequence rests on the unconformity peneplain, lying over the previous sedimentary package or directly over rocky domains of the basement. The Paraná Supersequence is a complete transgressive-regressive cycle of sedimentation, starting with continental to transitional Early Devonian sandy rocks covered by shaly marine sediments with age ranging from Emsian to Frasnian.

Another basin-scale unconformity surface marks the upper limit of the Devonian package. In fact, the Devonian-Carboniferous boundary is a benchmark of the geology of the Gondwana (López-Gamundí & Rossello, 1993), represented in the Paraná Basin by a lacuna that encompasses almost 55 Ma of the Phanerozoic time, known as the sub-Pennsylvanian unconformity. The Gondwana I Supersequence followed the climax of glacial conditions. Sedimentation was resumed with deglaciation, and an intense sedimentary influx coming from those areas laid open by ice melting allowed depositional processes in which mass flows and resedimentation were important, completely reworking the substratum and defining a singular depositional style for the Westphalian to Sakmarian interval of the Paraná Basin. The 1,500 meter-thick deglaciation-related section is composed dominantly by diamictites intercalated with sandstone packages, having both glacioterrestrial and glaciomarine representatives. The glacial package onlaps the sub-Pennsylvanian unconformity from north to south and extends over progressively wider areas. An important phase of structural rearrangement of the basin geometry followed. The regional sense of onlap of sedimentary beds was inverted by Early Permian time, documented by a northward-wedging retrograding sequence. The overlying package accommodated by a renewed cycle of tectonic subsidence of the basement, being an up to 1,400 meter-thick regressive section that culminates in Early Triassic eolian sandstones.

Sandy deserts covered definitively the entire basin and a wide adjacent region during the Late Jurassic, followed by Early Cretaceous basaltic lavas and intrusives. Subsidence and sediment accummulation in the Paraná Basin had their last stage during the Late Cretaceous with the acommodation of a thin package of continental sandy to conglomeratic rocks.

Discussion

The southern margin of Gondwana was a large domain of sedimentation adjacent to the Panthalassa during Paleozoic times. The persistence of convergent motion between the paleocontinent and the oceanic plate, with occasional collisions of terranes, produced a complex picture of orogenies and sedimentary depocenters close to the active margin, directly related to the dynamics of such geotectonic context. Eustatic variations of the sea level (Vail *et al.*, 1977) also left their imprint on the stratigraphic record of this region. The dominantly marine sedimentation in the southern margin of Gondwana advanced over the cratonic interior of the continent, and the mechanism whereby marine strata occur in the intracratonic basins is one of the important queries on their geology. Two major lines of research are concerned with such question: Sloss (1963) studied the distribution of sedimentary strata over the North American continent and recognized, within a framework of 'cratonic sequences' separated by interregional unconformities, a close relationship between the domains of continental interior (craton) and continental margins (geosynclines). Sloss' conclusion was that the accumulation of sedimentary successions over the cratonic interior and their erosive removal were controlled by epirogenetic fluctuations of the continents. According to this reasoning, the area reached by marine sedimentation at a specific time was a function of tectonically-induced transgressions and regressions. However, if we compare the proposal of Sloss with an analogous picture drawn for South America (Fig. 3), there appears a notable dissimilarity between the two regions in terms of the stratigraphic record in their cratonic interiors. Coincidence is the exception to the rule, suggesting that the temporal amplitude of the units recorded on each continental block was controlled by some kind of a 'local' factor, and this seems to be a strong argument against the extrapolation of Sloss' sequences outside North America.

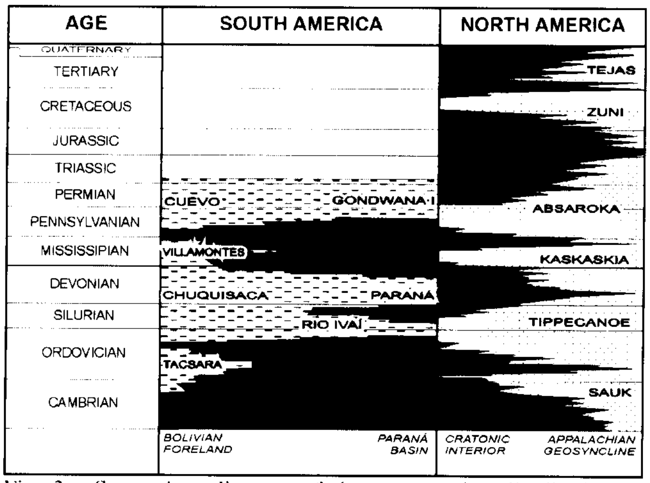

Fig. 3 - Space-time diagram of the comparative distribution of Phanerozoic sedimentary units of western South America and eastern North America, the later after Sloss (1963). Time-amplitude and nomenclature of the stratigraphic record in Bolivia is from Sempere (1995).

Another group of scientists took Suess' eustasy as a tool for stratigraphic studies. Vail *et al.* (1977) attributed the invasion of marine sequences over the continents to large amplitude eustatic fluctuations of the sea level, the tectonics being interpreted as a factor of minor influence on the stratigraphic record. Vail's curve, compiled with data from a series of basins around the world, was published as a reference for synchronous major transgressive-regressive cycles of sedimentation recorded over all the five continents. South America and, of course, the Paraná Basin should be included in this global scheme of stratigraphic correlation. But it does not seems to be the case. Comparing the stratigraphic record of the Paraná Basin to Vail's curve, one can perceive that the best 'global' peaks of correlation defined by the time-intervals of maximum flooding, some of them during Late Silurian, Early Carboniferous and Early Permian times, are not present in this particular basin. 'Local' maximum flooding events developed here, and were preserved, during Early Silurian, Early Devonian and Late Permian times, reflecting relative sea level fluctuations inherent to this portion of the continent that probably responded to a different combination of the movement of basement and absolute (eustatic) sea level variation. Notice that, in this work, basement subsidence of a specific region of the planet, in this case southwestern Gondwana, and eustatic variations of sea level are considered completely independent variables; in other words, if it were possible for one basin to subside at a constant rate the cyclicity of its stratigraphic framework would be constructed only by sea level oscilation. Such eustatic variation, under the perspective of a specific basin, must be regarded as an allochtonous product of a combination of phenomena on a planetary scale, caused outside its limits and independently of its particular tectonic history.

In the development of the Paraná Basin, the geodynamic history of southwestern Gondwana seems to have been of great influence. Stress dissipation along weakness zones and the cratonward propagation of lithospheric foreland flexure are among the main mechanisms that controlled the subsidence and stratigraphic signature in this intracratonic basin (Milani, 1997).

The oldest package in the Paraná Basin, the Rio Ivaí Supersequence, is of Late Ordovician age and its occurrence is controlled by SW-NE weakness zones in the basement. Late Ordovician was also the time when the Precordillera terrane collided with Gondwana (Ramos, 1988). The accommodation of the stresses of the Ocloyic Orogeny in the 'cratonic' region induced the initial subsidence of the Paraná Basin along SW-NE trending transtensional depocenters. The association of this initial sedimentation with intraplate magmatism attests Late Ordovician reactivation of old, deep-seated weakness zones in the basement. A close relationship seems to exist between the subsidence cycle caused by the Ocloyic Orogeny and the temporal range of the Rio Ivaí Supersequence (Fig. 4), such that the maximum flooding of the supersequence nearly coincides with the peak of the orogeny. Also the Devonian record of the Paraná Basin is confined to a subsidence cycle caused by an orogenic phase, in this case the Precordilleran Orogeny. Stable conditions were broken by an accelerated period of subsidence during Praguian-Emsian times, leading to a rapid drowning of the continental to transitional environments of the basal Devonian sandy package. Devonian maximum flooding correlates well with the time when highest rates of subsidence were produced by the apex of orogeny.

The Chanic Orogeny of Late Devonian/Early Carboniferous age produced a renewed cycle of subsidence that was best expressed in the foreland domain (eg. Mississipian Guandacol depocenters in the Paganzo Basin of Argentina; Fernández-Seveso & Tankard, 1995). In the Paraná Basin this was a time of non-sedimentation basically due to the presence of ice caps. Sediment accumulation was resumed during the Westphalian and was continuous up to Early Triassic times. Marine influence on the sedimentation became progressively weaker upwards indicating a gradual closure of the basin. By the end of Early Permian times the morphology of the Paraná Basin was deeply modified, coinciding in time with the climax of the Sanrafaelic Orogeny. The volcanogenic material that occurs in the Lower Permian section of the Paraná Basin (Coutinho *et al.*, 1991) correlates with the Choiyoi event of western Argentina, corresponding there to a large calc-alkaline magmatic arc spanning the 275-250 Ma range (Kay *et al.*, 1989) that acted as an effective, and probably definitive, obstacle to further marine incursions over southern Gondwana.

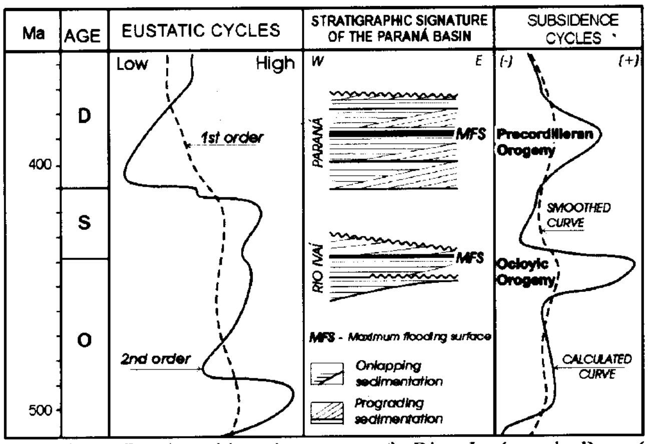

Fig. 4 - Stratigraphic signature of Rio Ivaí and Paraná supersequences of the Paraná Basin and their relationship to the eustatic cycles of Vail *et al.* (1977) and to the subsidence cycles of SW Gondwana.

Conclusions

A close relationship existed between the development of the Paraná Basin in the continental interior and the tectonic regime operating during the Paleozoic along the Gondwanides. The substratum of southwestern Gondwana reacted by flexure under the stresses generated along the collisional margin, and this provided an effective mechanism to recurrently create depositional space also in the cratonic domain. This mechanism of subsidence seems to reflect the cratonward propagation of the flexural bending of the lithosphere that characterizes the foreland domain, so that the Paraná Basin experienced accelerated phases of subsidence that correlate well with those in the adjacent foreland. The temporal amplitude of supersequences and their stratigraphic signatures in the Paraná Basin are clearly confined within the limits of the subsidence cycles caused by Paleozoic orogenic events along the margin of Gondwana.

Neither Vail's global correlation of eustatic highs nor Sloss' cratonic sequences provide the means to elucidate the stratigraphic framework observed in the Paraná Basin. Rather, it seems to be a product of the particular history of subsidence in this intracratonic domain, in close tuning with the Paleozoic development of southwestern Gondwana.

References

Bahlburg, H. and Breitkreuz, C., 1991. Paleozoic evolution of active margin basins in the Southern Central Andes (Northwestern Argentina and Northern Chile). Journal of South American Earth Sciences, 4 (3): 171-188.

Coutinho, J.M.V., Hachiro, J., Coimbra, A.M., and Santos, P.R., 1991. Ash-fall derived vitroclastic tuffaceous sediments in the Permian of the Paraná Basin and their provenance. In: Proceedings of the Gondwana Seven Conference. Universidade de São Paulo, abstracts volume: 147-160, São Paulo.

Du Toit, A.L., 1927. A geological comparison of South America with South Africa.. The Carnegie Institution, publ. 381: 157 p, Washington.

Fernández-Seveso, F. and Tankard, A.J., 1995. Tectonics and stratigraphy of the Late Paleozoic Paganzo Basin of Western Argentina and its regional implications. In: Tankard, A.J., Suárez Soruco, R., and Welsink, H.J. (Eds.) Petroleum basins of South America. American Association of Petroleum Geologists, Memoir 62: 285-301, Tulsa.

Kay, S.M., Ramos, V.A., Mpodozis, C., and Sruoga, P., 1989. Late Paleozoic to Jurassic silicic magmatism at the Gondwanaland margin: analogy to the Middle Proterozoic in North America? Geology, 17 (4): 324-328.

Klein, G.D., 1995. Intracratonic basins. In: Busby, C.J., and Ingersoll, R.V. (Eds.) Tectonics of sedimentary basins. Blackwell Science, p. 459-478, Cambridge.

Leighton, M.W. and Kolata, D.R., 1990. Selected interior cratonic basins and their place in the scheme of global tectonics - a synthesis. In: Leighton, M.W., Kolata, D.R., Oltz, D.F. and Eidel, J.J. (Eds.) Interior cratonic basins. American Association of Petroleum Geologists, Memoir 51: 729-797, Tulsa.

López-Gamundí, O. and Rossello, E.A., 1993. Devonian-Carboniferous unconformity in Argentina and its relation to Eo-Hercynian orogeny in southern South America. Geologische Rundschau, 82: 136-147.

Milani, E.J., 1997. Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica fanerozóica do Gondwana sul-ocidental [unp. Dr.Sc. thesis]. Universidade Federal do Rio Grande do Sul, 255 p., Porto Alegre.

Milani, E.J., 1992. Intraplate tectonics and the evolution of the Paraná Basin, S Brazil. In: De Wit, M.J. and Ransome, I.D. (Eds.) Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of Southern Africa. Balkema, p. 101-108, Rotterdam..

Milani, E.J. and Ramos, V.A., 1998. Orogenias paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. Revista Brasileira de Geociências, 28 (4): 527-544.

Powell, C.M.A., 1993. Assembly of Gondwanaland - open forum, In: Proceedings of the Gondwana Eight Conference. Balkema, expanded abstracts volume: 219-237, Rotterdam.

Ramos, V.A., 1988. Late Proterozoic - Early Paleozoic of South America - a collisional history. Episodes, 11 (3): 168-174.

Sempere, T., 1995 Phanerozoic evolution of Bolivia and adjacent regions, In: Tankard, A.J., Suárez Soruco, R., and Welsink, H.J. (Eds.) Petroleum basins of South America. American Association of Petroleum Geologists, Memoir 62: 207-230, Tulsa.

Sloss, L.L., 1963. Sequences in the cratonic interior of North America. Geological Society of America Bulletin, 74: 93-114.

Vail, P.R., Mitchum, R.M., and Thompson, S., 1977. Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. In: Payton, C.E., ed., Seismic stratigraphy - applications to hydrocarbon exploration. American Association of Petroleum Geologists, Memoir 26: 63-81, Tulsa.

Zalán, P.V., Wolff, S., Astolfi, M.A.M., Vieira, I.S., Conceição, J.C.J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R., and Marques, A., 1990. The Paraná Basin, Brazil. In: Leighton, M.W., Kolata, D.R., Oltz, D.F. and Eidel, J.J. (Eds.) Interior cratonic basins. American Association of Petroleum Geologists, Memoir 51: 681-708, Tulsa.