Growth-faults in the Depositional Setting of Gondwanic Coal, Paraná Basin, Brazil

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Manuscript received on June 19, 1997; accepted for publication on February 3, 1998
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ABSTRACT

In the Brazilian territory, the gondwanic coal (Kungurian, Early Permian) of the Paraná Basin, extends in a discontinuous belt parallel to the eastern margin of the basin, from the Rio Grande do Sul to the São Paulo state. Most of the coal beds are in the Siderópolis Member of the Rio Bonito Formation, in a barrier-bar lagoon setting, as seen in the Criciúma area, Santa Catarina state; others are in the deltaic section of the Triunfo Member, at the base of the same formation.

In the Criciúma area, detailed stratigraphic sections were prepared, with the datum chosen in a stratigraphic marker bed above the last coal bed, near the transition Rio Bonito-Palermo formations. These sections show undulating geometries affecting the coal beds. These beds are supposed to be continuous as a result of deposition in a single lagoon where favorable conditions for coal development were attained. At the same time, sand bodies, assumed to be the depositional barrier-bar counterparts of the lagoon, change their thickness across the belt. The only plausible explanation for this configuration is the presence of growth-faults acting during deposition, as shown in modern examples of Niger delta, which presents barrier bar-lagoon settings.

The same is reported in the Figueira area, Paraná state, where the coal beds are situated in the basal member of the Rio Bonito Formation. In this area, coal is associated with deltaic sediments and growth faults, with the characteristic low angles planes, are seen everywhere along an open-pit mine.

Growth-faults are adiastrophic in nature, being mostly due to the sand overload by fluvial-dominated delta deposition or by sandstone lobes exhibiting hummocky cross stratification in barrier bars formed by storm-related processes after marine transgressions in storm-wave-dominated deltas.

Key words: growth-fault, coal, Paraná Basin.

INTRODUCTION

The Paraná Basin (Fig. 1), the largest intracratonic basin in central-southern Brazil, presents a complex filling history, made upon several depositional episodes, or sequences, separated by large hiatuses, when geocratic phases were developed. A large volcanic event is present near the top of the sedimentary pile (Fig. 2, Milani *et al.*, 1994). Sedimentation began in the Cambrian-Ordovician, when the first depositional sequence was formed. The next sequence deposited is from Silurian-Devonian, being separated by an unconformity from the Carboniferous-Permian and this from the Triassic sequence. The Jurassic-Cretaceous sequence

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Fig. 1 — Location map of the studied areas with respect to South America, Brazil and the Paraná Basin. Paraná Basin occupies the central-western and southern regions in Brazil, part of Paraguay, Uruguay, Bolivia and northern Argentina.

encloses a very thick extrusive igneous pile, forming the largest flood basalt area in the world.

The Carboniferous-Permian sequence (Fig. 3) starts with the glacial-derived sediments from the Itararé Group, considered to be mostly Carboniferous in age. This unit is followed by the deltaic to shallow marine Rio Bonito Formation, which is the focus of this paper. The shallow marine Palermo Formation ends a second order sequence, according to Vail *et al.* (1991) criteria. The other Permian units show truly marine conditions towards which are replaced by non-marine conditions towards the top. The uppermost Permian unit, the Rio do Rastro Formation is lacustrine, associated to desertic depositional systems.

In this paper, two areas from the Paraná Basin are examined: one, the Figueira-Sapopema area, in the Paraná state, not only a coal producer but also one of the largest uranium-ore bearing region in Brazil; the other is the Santa Catarina coal district, situated at the southern part of the Santa Catarina state (Fig. 1). Both areas have been studied recently (Della Fávera *et al.*, 1993, 1995, 1996).

SEQUENCE STRATIGRAPHY

The first attempt to apply modern sequence stratigraphy concepts to the Paraná Basin was made by Della Fávera *et al.* (1992, 1993). They visualized a second order sequence (time span greater than 8 Ma) encompassing one part of the Carboniferous and Early Permian. The boundary of the lower sequence coincides with the base of the uppermost diamictites, representing the last glacial stage in the Carboniferous-Permian glaciation. The maximum flood surface is within the Palermo Formation. The upper sequence boundary is still doubfull, considered to be at the base of the Irati Formation, where a former sequence boundary was marked by Soares *et al.* (1978) in a conglomeratic bed found in the São Paulo state. More recently, this boundary is thought to be at the top of the Irati Formation.

A further refinement in terms of sequence stratigraphy was developed recently (Della Fávera *et al.*, 1995, 1996). The second order sequence was divided into two third order sequences (Fig. 2), the first comprising the Rio Bonito Formation (Triunfo and Paraguaçu members) and the second, the Rio Bonito (Siderópolis Member) and the Palermo formations. The lowest sequence boundary remains at the base of diamictites of the Itararé Group. According to Alves (1994), this boundary could be placed at the base of the Rio Bonito Formation itself, assumed to be represented by an unconformity at the Rio Grande do Sul state. In Paraná and Santa Catarina states, the base of the Rio Bonito Formation, although looking like an incised-valley filling, could be explained as growth-faults feature, being the expression of the listric fault planes. The upper boundary of this third order sequence coincides with the top of the Paraguaçu Member, where different bed attitudes can be noted, across the boundary, revealing probably an unconformity.

The uppermost third order sequence upper boundary coincides with that of the second order sequence whereas the maximum flood surface is

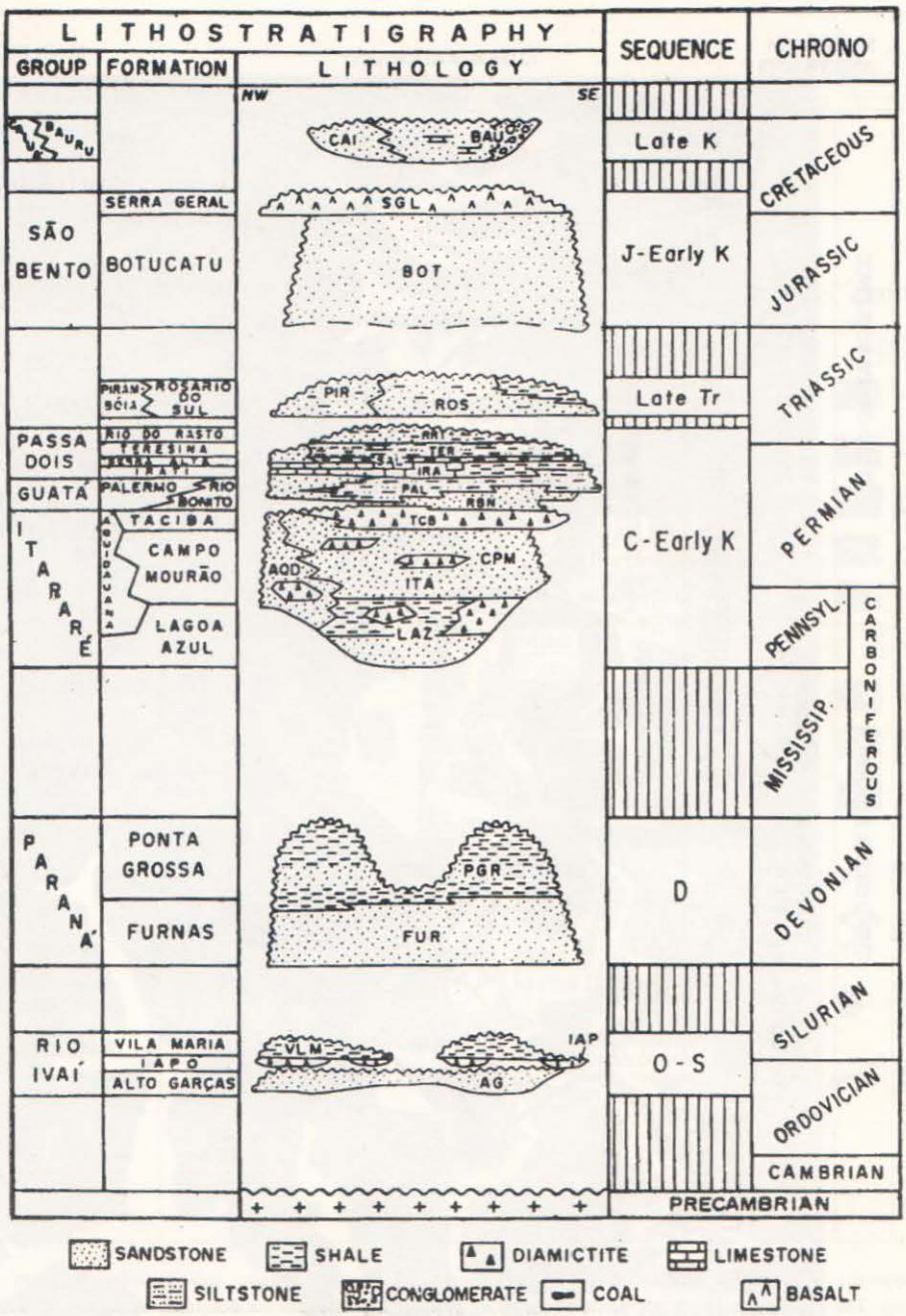


Fig. 2 — Lithostratigraphy of the Paraná Basin (Milani *et al.*, 1994).

within the Palermo Formation (above the section shown in the reference log).

In both third-order sequences, the transgressive system tract predominates over the others, although the basal one presents a clear lowstand systems tract, composed of fluvial-dominated deltas.

STRUCTURE

In the geological map (Fig. 4), faults strike northeast-southeast and northwest-southeast. These orientations are distinctive of the tectonic framework in the Paraná Basin. This faulting framework is believed to be Jurassic-Cretaceous in age, as a

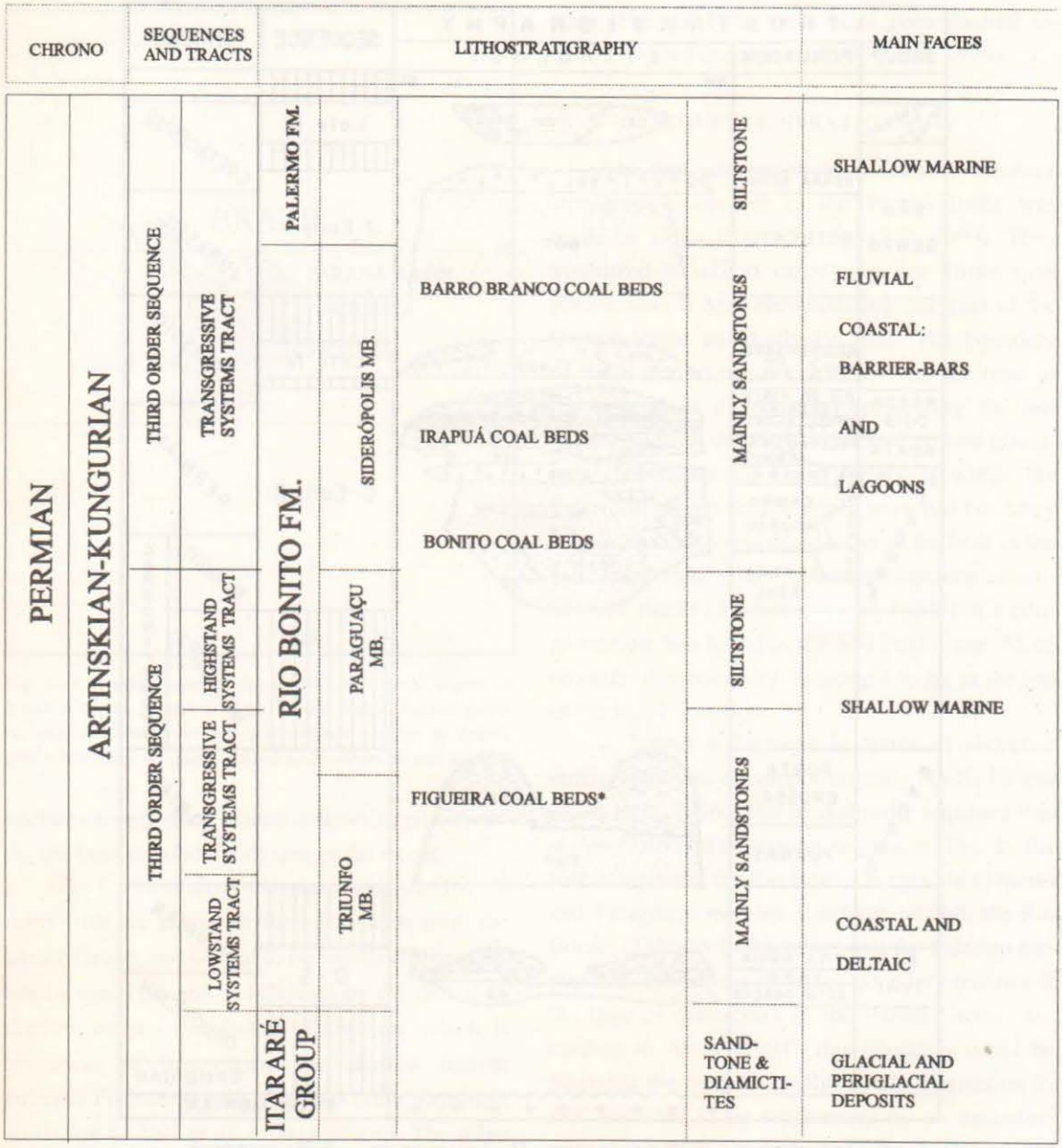


Fig. 3 — Sequence stratigraphy established in the Criciúma area, Santa Catarina, and its relationship to Chrono- and Lithostratigraphy. The Figueira coal beds are indicated in this section although they are not developed in the Criciúma area.

result of the tectonism associated to basaltic magma outpouring that affected the basin at that time.

Other faults, with curved traces, and striking parallel the edge of ancient deltaic lobes mark a different structural behavior. These faults are interpreted as growth-faults, formed contemporaneously with coal deposition. These faults are discussed below.

GROWTH-FAULTS

Growth-faults are common features in deltaic areas of the world like in the Mississipi and Niger deltas.

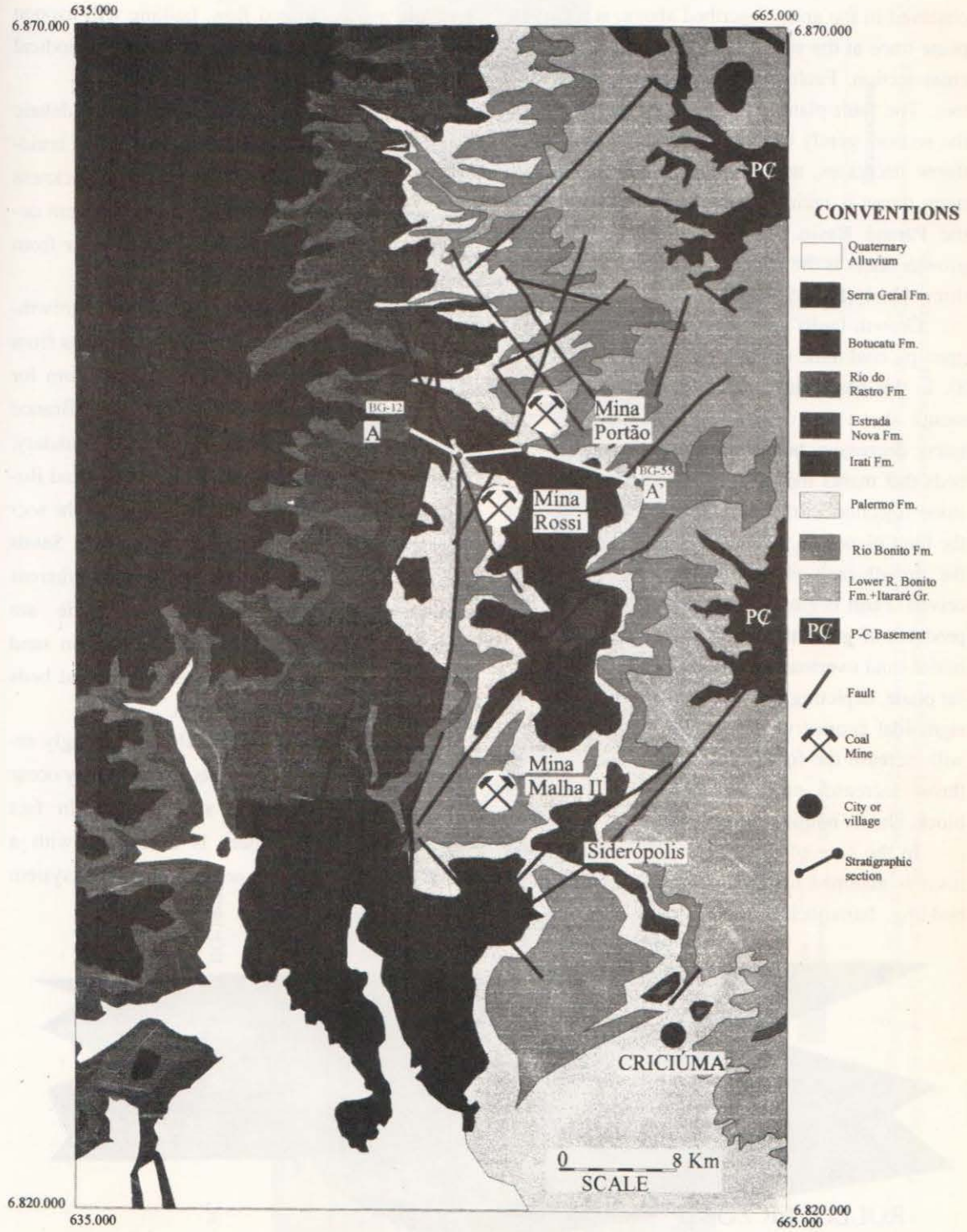


Fig. 4 — Geological map of the Criciúma Quadrangle, Santa Catarina and location of the stratigraphic section. Redrawn from an older map by Petrobrás modified by Geol. Milton Valentini (Cia. Carbonífera Próspera, Criciúma).

The main characteristic of the growth-fault, as observed in the areas described above, is a curved plane trace at the surface and a listric geometry in cross-section. Fault throw decreases towards bottom. The fault plane is steep at the upper part of the section, gently bending towards bottom, as the throw decreases, and becomes horizontal. Maximum throw is variable being around 20 meters in the Paraná Basin. Another common feature of growth-faults is the rollover anticline in the downthrow block (Figs. 5 and 6).

Growth-faults can be seen in outcrops in the open pit coal mine in Figueira, Paraná (Figs. 7 and 8). In this case, faulting affects only deltaic sediments above the coal seams (lowstand systems tract), decreasing tangentially towards the siltstone beds that marks the top of lagoon sediments. Siltstone injection in the deltaic sediments delineates the fault planes. In this area, the very beginning of the growth-fault mechanism can be easily perceived. Fault begins in sigmoidal beds, which are products of gravitational flows. As a result of the initial sand overload, these beds slip along the basal plane, depicting the fault plane according to the sigmoidal geometry or a semi-"s". The next flow will increase the former sliding and thus the fault throw increases progressively. In the upthrown block, almost nothing is deposited.

In the case of barrier bars, a similar mechanism is assumed to happen. Instead of sigmoidal bedding, hummocky cross-bedding (HCS) is the main depositional structure. As this structure is essentially a gravitational flow, faulting will happen near the axis of the hummocky bed by periodical sand overload.

In the Figueira-Sapopema area, the deltaic sediments, interpreted to be derived from braid-deltas entering a lagoon, present variable thickness as a result of growth-faults. Coal development occurs in the lagoon, at the delta margins, far from depocenters where coal beds are very thin.

In the Santa Catarina coal district, growth-faults are interpreted in stratigraphic sections from logs and outcrops (Figs. 6, 8-11). The datum for these sections is at the base of the Barro Branco coal beds near the Palermo-Rio Bonito boundary. Growth-faulting affects both Barro Branco and Bonito coal beds. The coal beds spread across the section and sand thickness varies above them. Sands are interpreted to be barrier-bar deposits whereas coal and associated siltstone and shale are lagoonal. Growth-faults are used to explain sand thickness variation and displacement of coal beds below, as indicated in the section.

In both areas, growth faults are strongly related to lowstand system tracts although they occur also in the transgressive system tract. In fact growth fault development is associated with a large sediment supply no matter which system tract is affected.

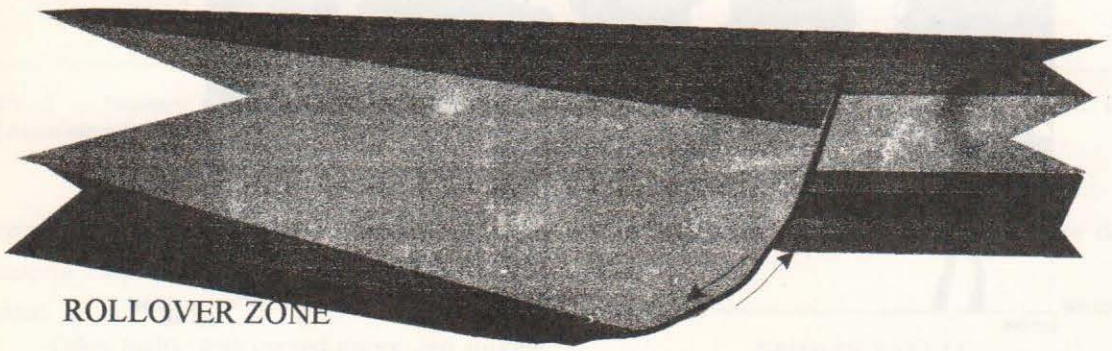


Fig. 5 — Basic geometry and main attributes of a growth-fault affecting the coal section. Main attributes: 1 – Listric Fault plane with no throw in the lower and upper ends of the fault trace. 2 – Beds dip against the fault plane in the downthrown block. 3 – Sandstones thicken in the downthrown block and thin towards the rollover zone. 4 – Sliding surfaces produced in coal or in associated shale and siltstones

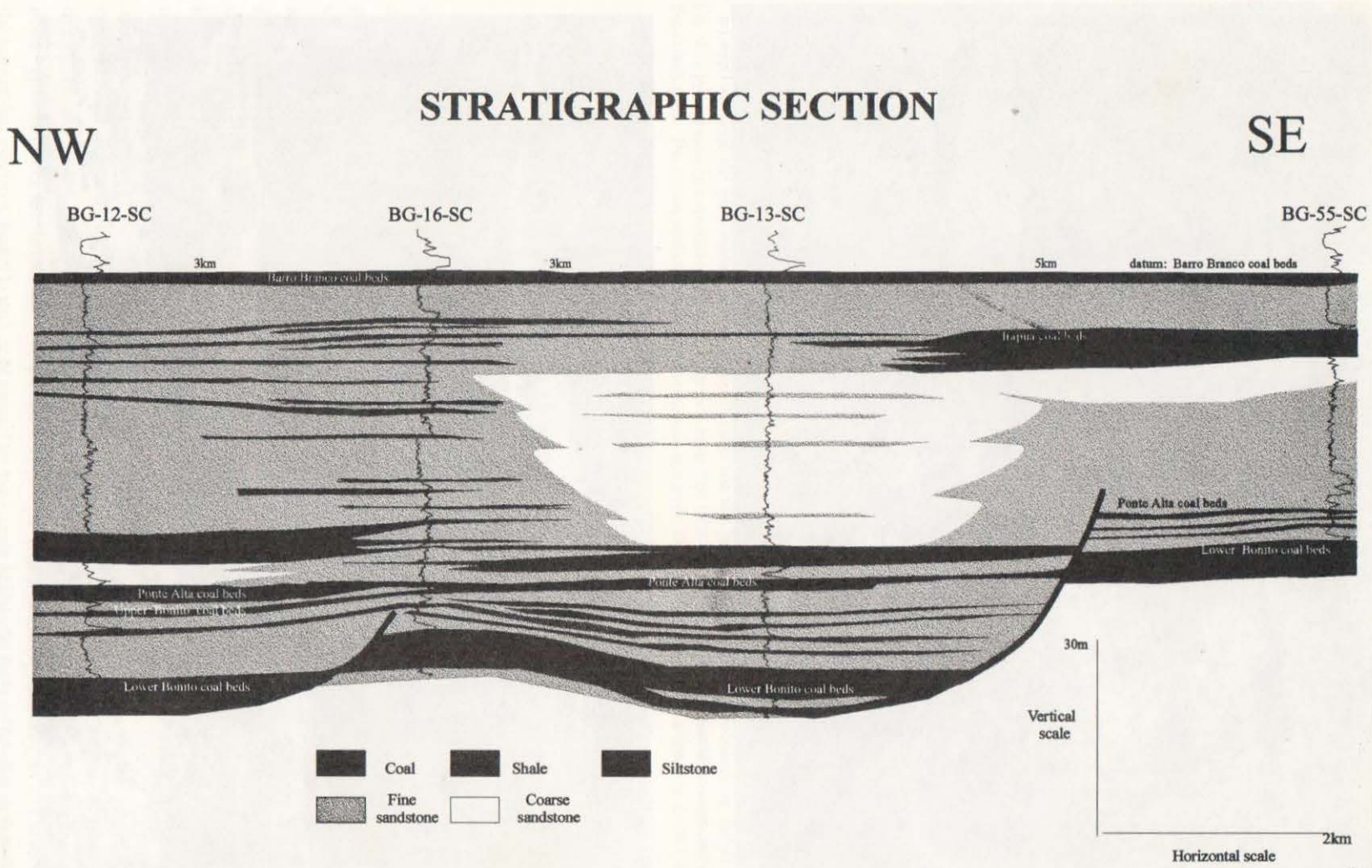


Fig. 6 — Stratigraphic section of the Siderópolis Member, showing two growth-faults, affecting the section above the Bonito coal beds. Location of this section is shown at fig. 3 (A-A'). Coarse sand represents fluvial deposition whereas fine sands are littoraneous deposits, mainly HCS. Boreholes are represented by their gamma-ray curves.



Fig. 7 — Deltaic progradation over lagoonal sediments (silt and coal). Growth-faults are enhanced by silt injection. Open-pit Figueira Mine, State of Paraná.



Fig. 8 — Low-angle growth-fault plane indicated by traces. Open-pit Figueira Mine, State of Paraná.



Fig. 9 — Frontal view of a downthrown block of a growth-fault. The HCS-sandstones are dipping outwards the photograph against a listric fault plane. The gliding surface are the Bonito coal beds at bottom. Open-pit Portão Mine, Criciúma area, Santa Catarina.

CONCLUDING REMARKS

The catastrophic nature of deposition represented both by sigmoidal lobes and HCS sandstones could be pointed to be the cause of growth-faulting in the Permian of the Paraná Basin. These deposits would overload the soft clay- and turf-filled lagoons and promote gravitational glidings, giving rise to growth-faults. This style of deposition and sediment deformation support well-known previous interpretation of deltaic sedimentation for the Rio Bonito formation (Medeiros, 1973). Growth-faults are common features in modern deltaic settings, as the Niger and Mississippi deltas. In the tide- and wave-dominated Niger delta, growth-faults are important components of the barrier-bar environment.

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Fig. 10 — Incipient growth-fault at the contact of a HCS-sandstone with the Bonito coal beds. A rallover anticline can be noted at right. Hammer is pointing to an highly-fluidized HCS sandstone developed at the downthrown block. Open-pit Portão Mine, Criciúma area, Santa Catarina.



Fig. 11 — Large HCS-sandstone wedge developed at the downthrown block of a growth-fault in the contact with the Bonito coal beds. Open-pit Portão Mine, Criciúma area, Santa Catarina.

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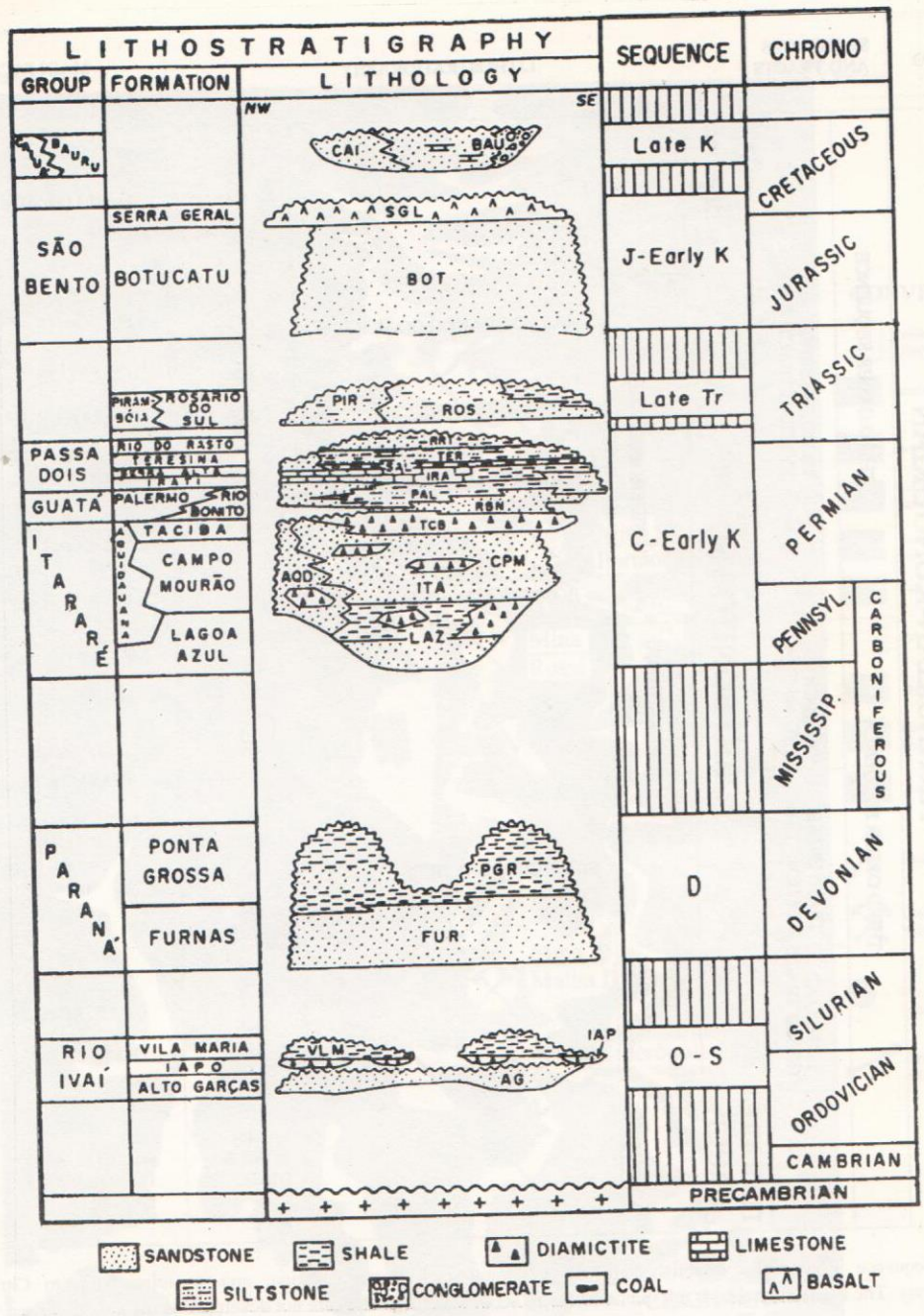


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In the geological map (Fig. 4), faults strike northeast-southeast and northwest-southeast. These orientations are distinctive of the tectonic framework in the Paraná Basin. This faulting framework is believed to be Jurassic-Cretaceous in age, as a

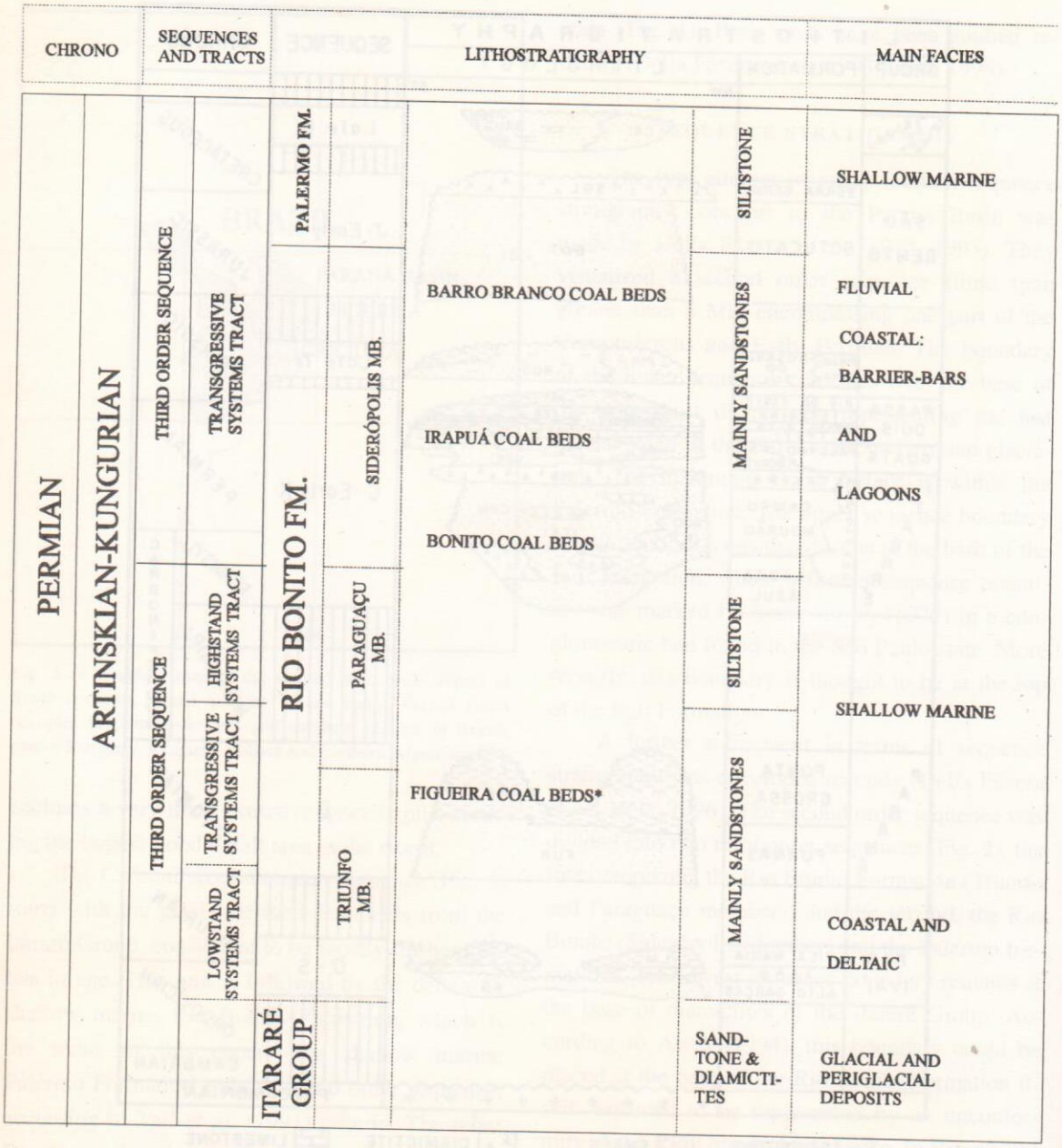


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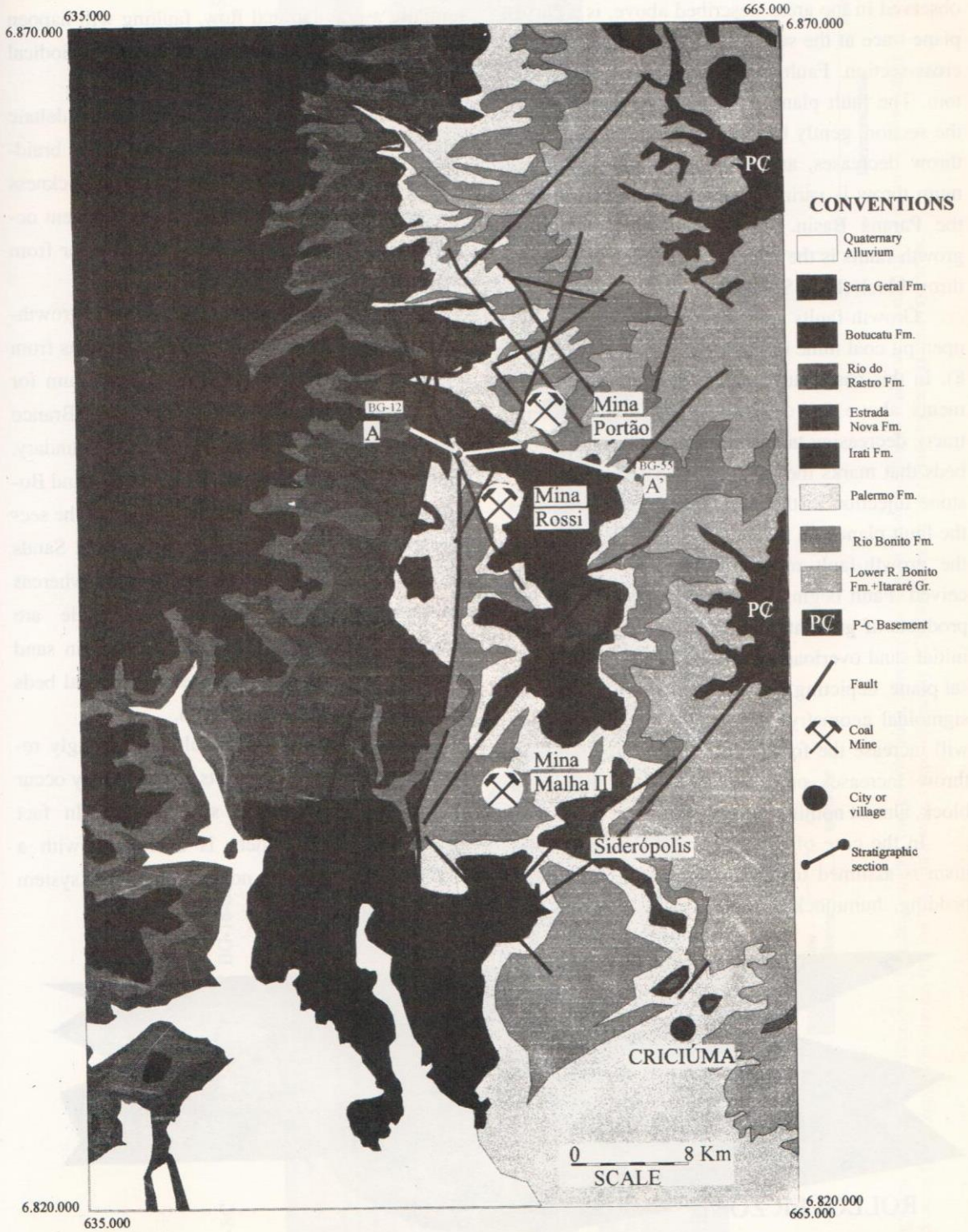


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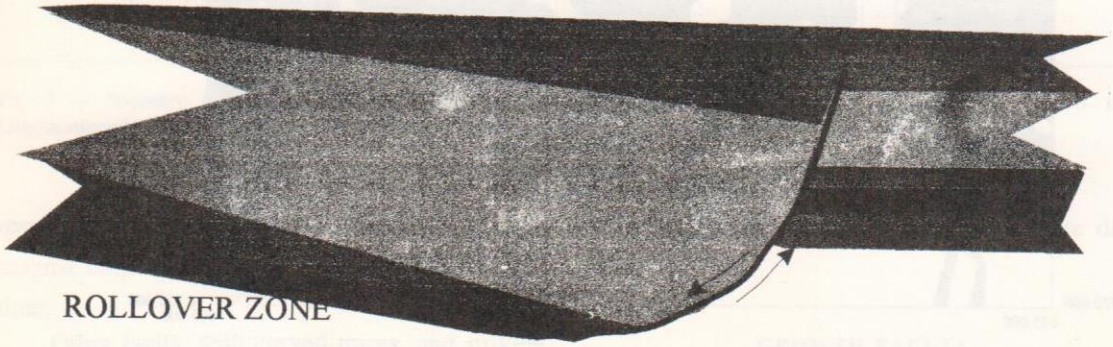


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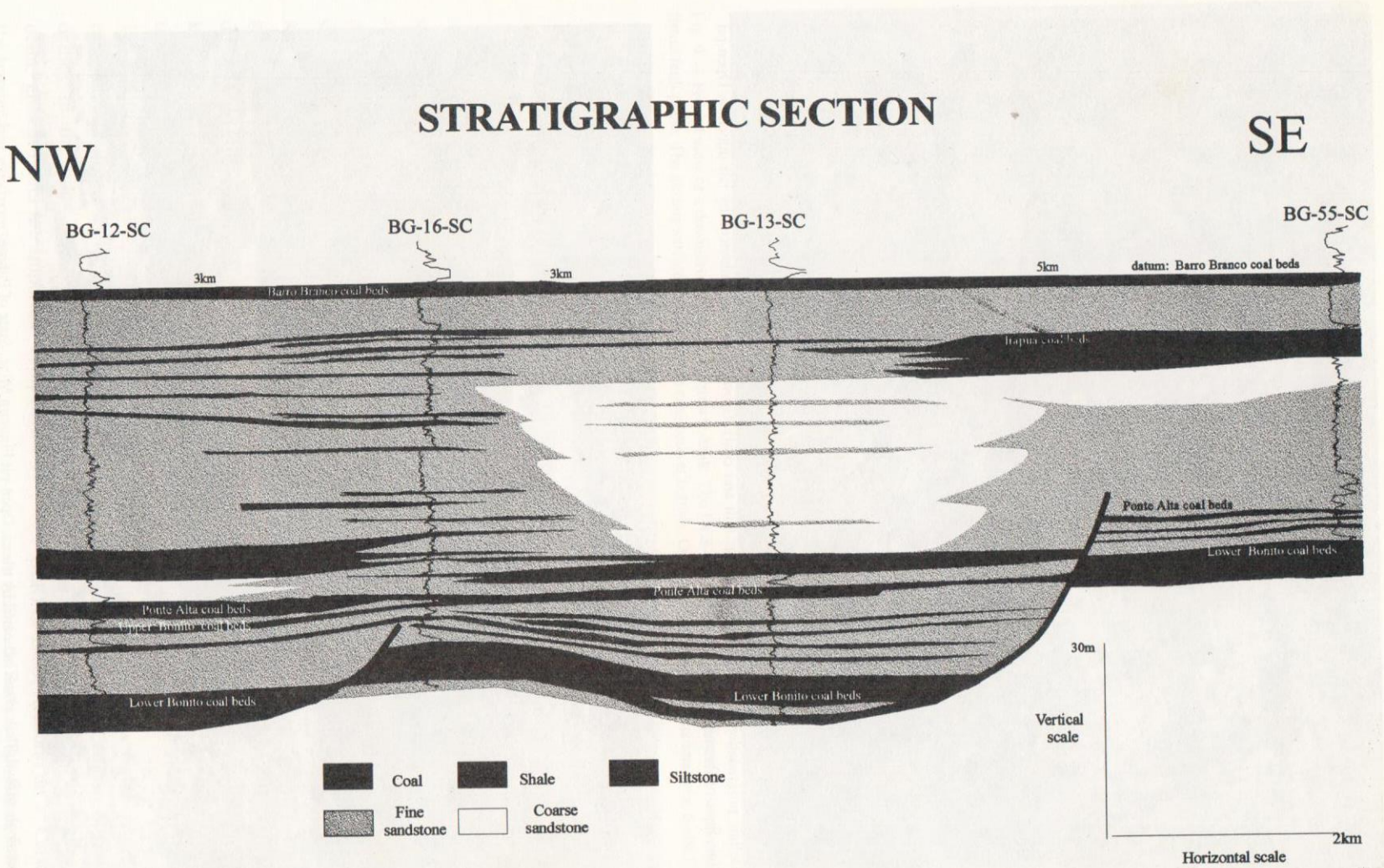


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The catastrophic nature of deposition represented both by sigmoidal lobes and HCS sandstones could be pointed to be the cause of growth-faulting in the Permian of the Paraná Basin. These deposits would overload the soft clay- and turf-filled lagoons and promote gravitational glidings, giving rise to growth-faults. This style of deposition and sediment deformation support well-known previous interpretation of deltaic sedimentation for the Rio Bonito formation (Medeiros, 1973). Growth-faults are common features in modern deltaic settings, as the Niger and Mississippi deltas. In the tide- and wave-dominated Niger delta, growth-faults are important components of the barrier-bar environment.

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Growth-faults in the Depositional Setting of Gondwanic Coal, Paraná Basin, Brazil

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Manuscript received on June 19, 1997; accepted for publication on February 3, 1998
presented by DIOGENES DE ALMEIDA CAMPOS

ABSTRACT

In the Brazilian territory, the gondwanic coal (Kungurian, Early Permian) of the Paraná Basin, extends in a discontinuous belt parallel to the eastern margin of the basin, from the Rio Grande do Sul to the São Paulo state. Most of the coal beds are in the Siderópolis Member of the Rio Bonito Formation, in a barrier-bar lagoon setting, as seen in the Criciúma area, Santa Catarina state; others are in the deltaic section of the Triunfo Member, at the base of the same formation.

In the Criciúma area, detailed stratigraphic sections were prepared, with the datum chosen in a stratigraphic marker bed above the last coal bed, near the transition Rio Bonito-Palermo formations. These sections show undulating geometries affecting the coal beds. These beds are supposed to be continuous as a result of deposition in a single lagoon where favorable conditions for coal development were attained. At the same time, sand bodies, assumed to be the depositional barrier-bar counterparts of the lagoon, change their thickness across the belt. The only plausible explanation for this configuration is the presence of growth-faults acting during deposition, as shown in modern examples of Niger delta, which presents barrier bar-lagoon settings.

The same is reported in the Figueira area, Paraná state, where the coal beds are situated in the basal member of the Rio Bonito Formation. In this area, coal is associated with deltaic sediments and growth faults, with the characteristic low angles planes, are seen everywhere along an open-pit mine.

Growth-faults are adiastrophic in nature, being mostly due to the sand overload by fluvial-dominated delta deposition or by sandstone lobes exhibiting hummocky cross stratification in barrier bars formed by storm-related processes after marine transgressions in storm-wave-dominated deltas.

Key words: growth-fault, coal, Paraná Basin.

INTRODUCTION

The Paraná Basin (Fig. 1), the largest intracratonic basin in central-southern Brazil, presents a complex filling history, made upon several depositional episodes, or sequences, separated by large hiatuses, when geocratic phases were developed. A large volcanic event is present near the top of the sedimentary pile (Fig. 2, Milani *et al.*, 1994). Sedimentation began in the Cambrian-Ordovician, when the first depositional sequence was formed. The next sequence deposited is from Silurian-Devonian, being separated by an unconformity from the Carboniferous-Permian and this from the Triassic sequence. The Jurassic-Cretaceous sequence

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Fig. 1 — Location map of the studied areas with respect to South America, Brazil and the Paraná Basin. Paraná Basin occupies the central-western and southern regions in Brazil, part of Paraguay, Uruguay, Bolivia and northern Argentina.

encloses a very thick extrusive igneous pile, forming the largest flood basalt area in the world.

The Carboniferous-Permian sequence (Fig. 3) starts with the glacial-derived sediments from the Itararé Group, considered to be mostly Carboniferous in age. This unit is followed by the deltaic to shallow marine Rio Bonito Formation, which is the focus of this paper. The shallow marine Palermo Formation ends a second order sequence, according to Vail *et al.* (1991) criteria. The other Permian units show truly marine conditions towards which are replaced by non-marine conditions towards the top. The uppermost Permian unit, the Rio do Rastro Formation is lacustrine, associated to desertic depositional systems.

In this paper, two areas from the Paraná Basin are examined: one, the Figueira-Sapopema area, in the Paraná state, not only a coal producer but also one of the largest uranium-ore bearing region in Brazil; the other is the Santa Catarina coal district, situated at the southern part of the Santa Catarina state (Fig. 1). Both areas have been studied recently (Della Fávera *et al.*, 1993, 1995, 1996).

SEQUENCE STRATIGRAPHY

The first attempt to apply modern sequence stratigraphy concepts to the Paraná Basin was made by Della Fávera *et al.* (1992, 1993). They visualized a second order sequence (time span greater than 8 Ma) encompassing one part of the Carboniferous and Early Permian. The boundary of the lower sequence coincides with the base of the uppermost diamictites, representing the last glacial stage in the Carboniferous-Permian glaciation. The maximum flood surface is within the Palermo Formation. The upper sequence boundary is still doubfull, considered to be at the base of the Irati Formation, where a former sequence boundary was marked by Soares *et al.* (1978) in a conglomeratic bed found in the São Paulo state. More recently, this boundary is thought to be at the top of the Irati Formation.

A further refinement in terms of sequence stratigraphy was developed recently (Della Fávera *et al.*, 1995, 1996). The second order sequence was divided into two third order sequences (Fig. 2), the first comprising the Rio Bonito Formation (Triunfo and Paraguaçu members) and the second, the Rio Bonito (Siderópolis Member) and the Palermo formations. The lowest sequence boundary remains at the base of diamictites of the Itararé Group. According to Alves (1994), this boundary could be placed at the base of the Rio Bonito Formation itself, assumed to be represented by an unconformity at the Rio Grande do Sul state. In Paraná and Santa Catarina states, the base of the Rio Bonito Formation, although looking like an incised-valley filling, could be explained as growth-faults feature, being the expression of the listric fault planes. The upper boundary of this third order sequence coincides with the top of the Paraguaçu Member, where different bed attitudes can be noted, across the boundary, revealing probably an unconformity.

The uppermost third order sequence upper boundary coincides with that of the second order sequence whereas the maximum flood surface is

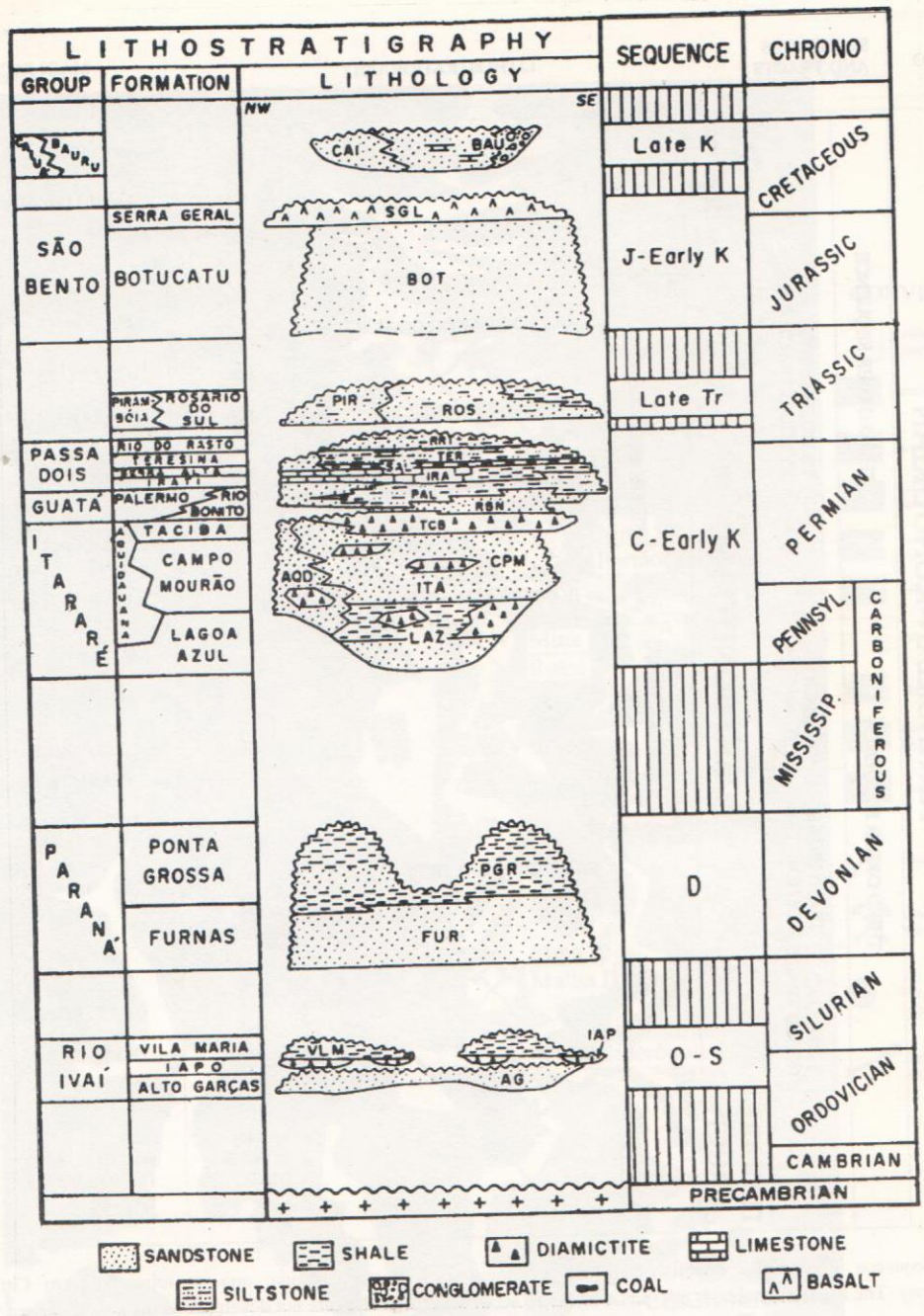


Fig. 2 — Lithostratigraphy of the Paraná Basin (Milani *et al.*, 1994).

within the Palermo Formation (above the section shown in the reference log).

In both third-order sequences, the transgressive system tract predominates over the others, although the basal one presents a clear lowstand systems tract, composed of fluvial-dominated deltas.

STRUCTURE

In the geological map (Fig. 4), faults strike northeast-southeast and northwest-southeast. These orientations are distinctive of the tectonic framework in the Paraná Basin. This faulting framework is believed to be Jurassic-Cretaceous in age, as a

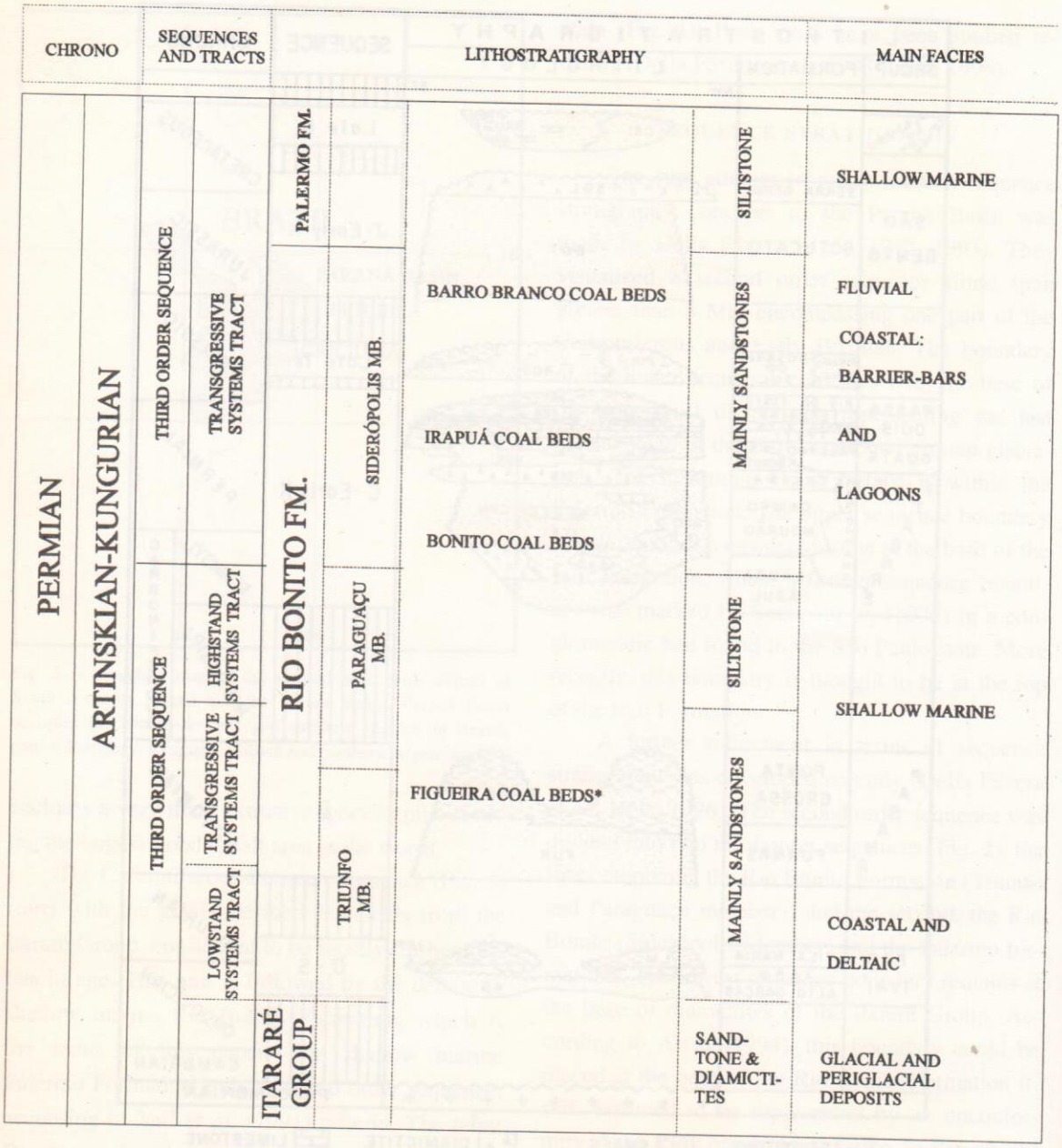


Fig. 3 — Sequence stratigraphy established in the Criciúma area, Santa Catarina, and its relationship to Chrono- and Lithostratigraphy. The Figueira coal beds are indicated in this section although they are not developed in the Criciúma area.

result of the tectonism associated to basaltic magma outpouring that affected the basin at that time.

Other faults, with curved traces, and striking parallel the edge of ancient deltaic lobes mark a different structural behavior. These faults are interpreted as growth-faults, formed contemporaneously with coal deposition. These faults are discussed below.

GROWTH-FAULTS

Growth-faults are common features in deltaic areas of the world like in the Mississipi and Niger deltas.

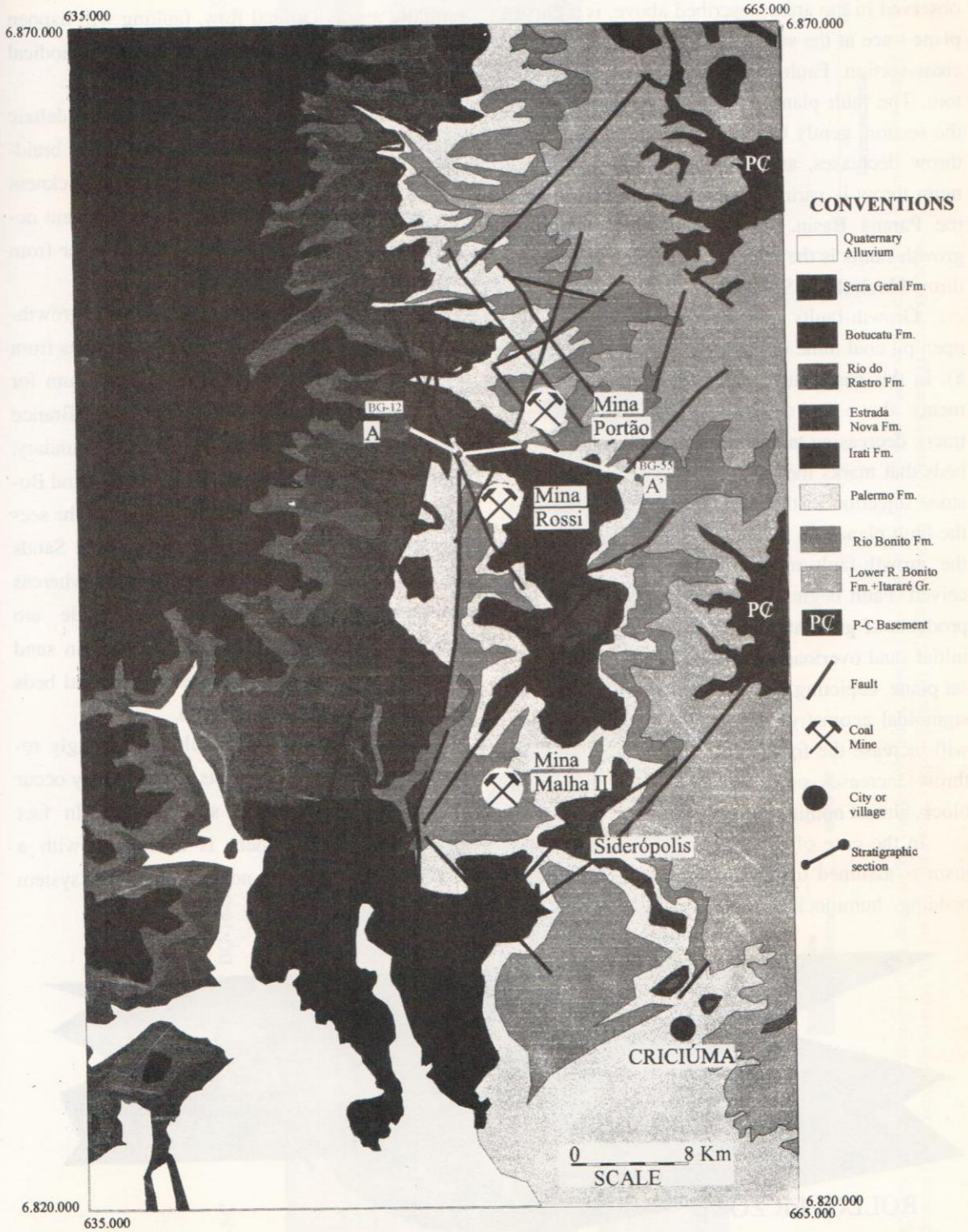


Fig. 4 — Geological map of the Criciúma Quadrangle, Santa Catarina and location of the stratigraphic section. Redrawn from an older map by Petrobrás modified by Geol. Milton Valentini (Cia. Carbonífera Próspera, Criciúma).

The main characteristic of the growth-fault, as observed in the areas described above, is a curved plane trace at the surface and a listric geometry in cross-section. Fault throw decreases towards bottom. The fault plane is steep at the upper part of the section, gently bending towards bottom, as the throw decreases, and becomes horizontal. Maximum throw is variable being around 20 meters in the Paraná Basin. Another common feature of growth-faults is the rollover anticline in the downthrow block (Figs. 5 and 6).

Growth-faults can be seen in outcrops in the open pit coal mine in Figueira, Paraná (Figs. 7 and 8). In this case, faulting affects only deltaic sediments above the coal seams (lowstand systems tract), decreasing tangentially towards the siltstone beds that marks the top of lagoon sediments. Siltstone injection in the deltaic sediments delineates the fault planes. In this area, the very beginning of the growth-fault mechanism can be easily perceived. Fault begins in sigmoidal beds, which are products of gravitational flows. As a result of the initial sand overload, these beds slip along the basal plane, depicting the fault plane according to the sigmoidal geometry or a semi-"s". The next flow will increase the former sliding and thus the fault throw increases progressively. In the upthrown block, almost nothing is deposited.

In the case of barrier bars, a similar mechanism is assumed to happen. Instead of sigmoidal bedding, hummocky cross-bedding (HCS) is the main depositional structure. As this structure is essentially a gravitational flow, faulting will happen near the axis of the hummocky bed by periodical sand overload.

In the Figueira-Sapopema area, the deltaic sediments, interpreted to be derived from braid-deltas entering a lagoon, present variable thickness as a result of growth-faults. Coal development occurs in the lagoon, at the delta margins, far from depocenters where coal beds are very thin.

In the Santa Catarina coal district, growth-faults are interpreted in stratigraphic sections from logs and outcrops (Figs. 6, 8-11). The datum for these sections is at the base of the Barro Branco coal beds near the Palermo-Rio Bonito boundary. Growth-faulting affects both Barro Branco and Bonito coal beds. The coal beds spread across the section and sand thickness varies above them. Sands are interpreted to be barrier-bar deposits whereas coal and associated siltstone and shale are lagoonal. Growth-faults are used to explain sand thickness variation and displacement of coal beds below, as indicated in the section.

In both areas, growth faults are strongly related to lowstand system tracts although they occur also in the transgressive system tract. In fact growth fault development is associated with a large sediment supply no matter which system tract is affected.

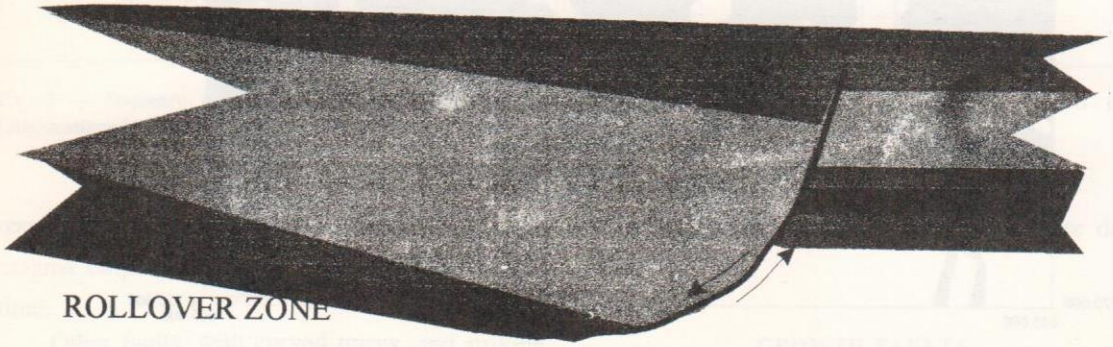


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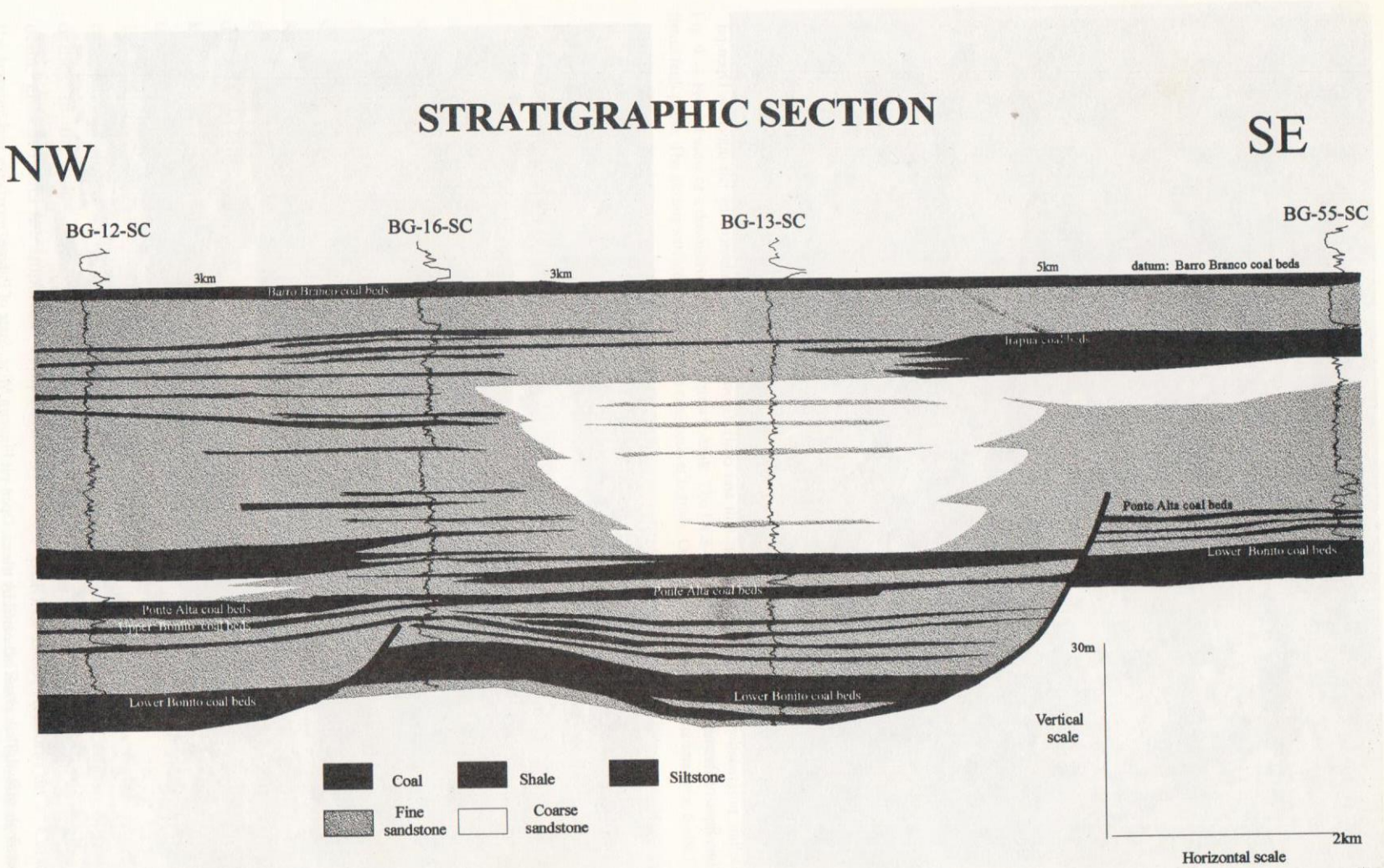


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