

New data on depositional environment of Jurua Formation terminal sediments, Solimoes Basin, Brazil

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Abstract. It has been for the first time established on the core taken from two wells that JR10 reservoir sediments (Upper Jurua, Formation Carboniferous) were deposited in the conditions of deltaic and alluvial coast with semiarid climate and in marine-terrigenuous settings. JR10 reservoir differs in its lithological composition and structural architecture from the underlying layers of the Jurua formation and the overlying Carauari formation by the absence of carbonate and sulphate rocks and significant content of carbonaceous terrestrial plant fossils. The change of thickness from the south-east to north-west direction is associated with progradational nature of the deltaic coast evolving to the same direction.

Keywords: Solimoes Basin, Jurua Formation, core, terrigenous sediments, delta front, facies, reservoir, sequences

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Introduction

The Solimoes Basin is located at the upper reaches of the Amazon River, it is classified as an intracratonic sedimentary basin; in the west it is bounded by the Iquitos arch, in the east it is separated from the Amazonas basin by the Purus arch (Fig. 1). In its central part the basin is divided by the Carauari arch into two sub-basins. The total area of the Solimoes Basin is 480 km² (Caputo, 1990). The Jurua Formation (Carboniferous) overlies the marine sediments of the Jandiutuba Formation and is overlaid by the Carauari Formation (Eliras et al., 1994; 2008; Filho et al., 2007). It is subdivided into the upper (Upper Jurua) and the lower (Lower Jurua) subformations (Fig. 2). The lower subformation is mainly formed by clay-terrigenuous sediments, the upper subformation is formed by a mixed complex of clay-terrigenuous, sulphate-carbonate rocks and salts. According to the sedimentological analysis of the cores taken from the upper (terminal) part of the Jurua subformation, the authors interpreted a third-order sequence, JR10 terrigenous reservoir 10 to 50 m thick which is under- and overlaid mainly by carbonates and evaporites.

Factual material and research methods

Sedimentological analysis of the cross-section of the JR10 productive reservoir was performed based on the cores from two wells: the reservoir was fully intersected and cored by Well 1, in Well 2 the core was taken from the lower part. The total meterage of the studied core was 50.87 m with 99% core recovery. Well 1 was drilled in the extreme south-eastern part of the basin; Well 2 was drilled closer to the center of the Jurua sub-basin (well numbers are for reference only). The authors used the lithofacies analysis technique which includes a detailed sedimentological core description, building sedimentological sections in 1:50 scale, selecting reference surfaces and sequences of different order, and building facies profiles and a lithofacies scheme.

When working with core material and interpreting the results of sedimentological analysis, methodical recommendations and works of well-known researchers in the field of facies analysis were used (Alekseev, 2002; Alekseev, Amon, 2017; Leeder, 1986; Einsele, 2000; Nichols, 2012; Reineck, Singh, 1980; Gradzinsky et al., 1980; Bhattacharya, 2006, etc.).

The conceptual lithofacies model of JR10 reservoir was built based on the results of core sedimentological analysis, the hydrocarbon pore volume, well classification (thickness vs. hydrocarbon pore volume cross-plot), and a logging complex (GR, RHOB, NPHI neutron porosity, and DT sonic logs).

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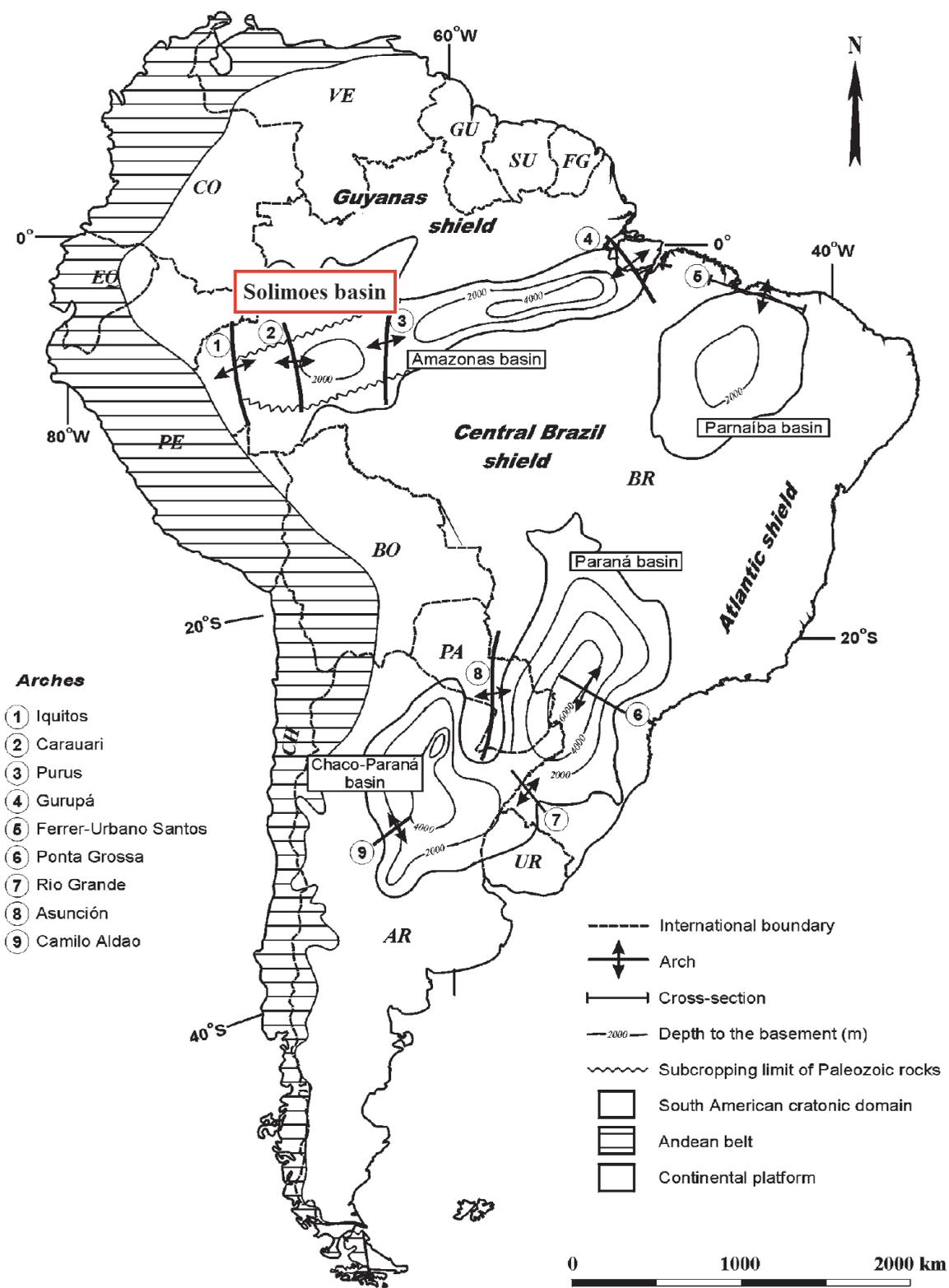


Fig. 1. A layout map of the Paleozoic intracratonic basins of South America (Milani, Zalan, 1998, 1999). States: FG – French Guiana, SU – Suriname, GU – Guiana, VE – Venezuela, CO – Colombia, EQ – Ecuador, PE – Peru, BO – Bolivia, CH – Chile, AR – Argentina, PA – Paraguay, UR – Uruguay, BR – Brazil

Results

The authors divided the Upper Jurua section into three third-order sequences.

Sq1 Sequence is represented by whole terrigenous sediments of the transgressive system tract and the highstand systems tract (TST + HST).

Sq2 Sequence includes the lowstand systems tract (LST) represented by coastal marine terrigenous sediments, the transgressive system tract (TST) composed mainly of marine carbonates, and the highstand systems tract (HST), formed mainly by evaporite facies (Moor, 2001). The central part of the basin contains layers of

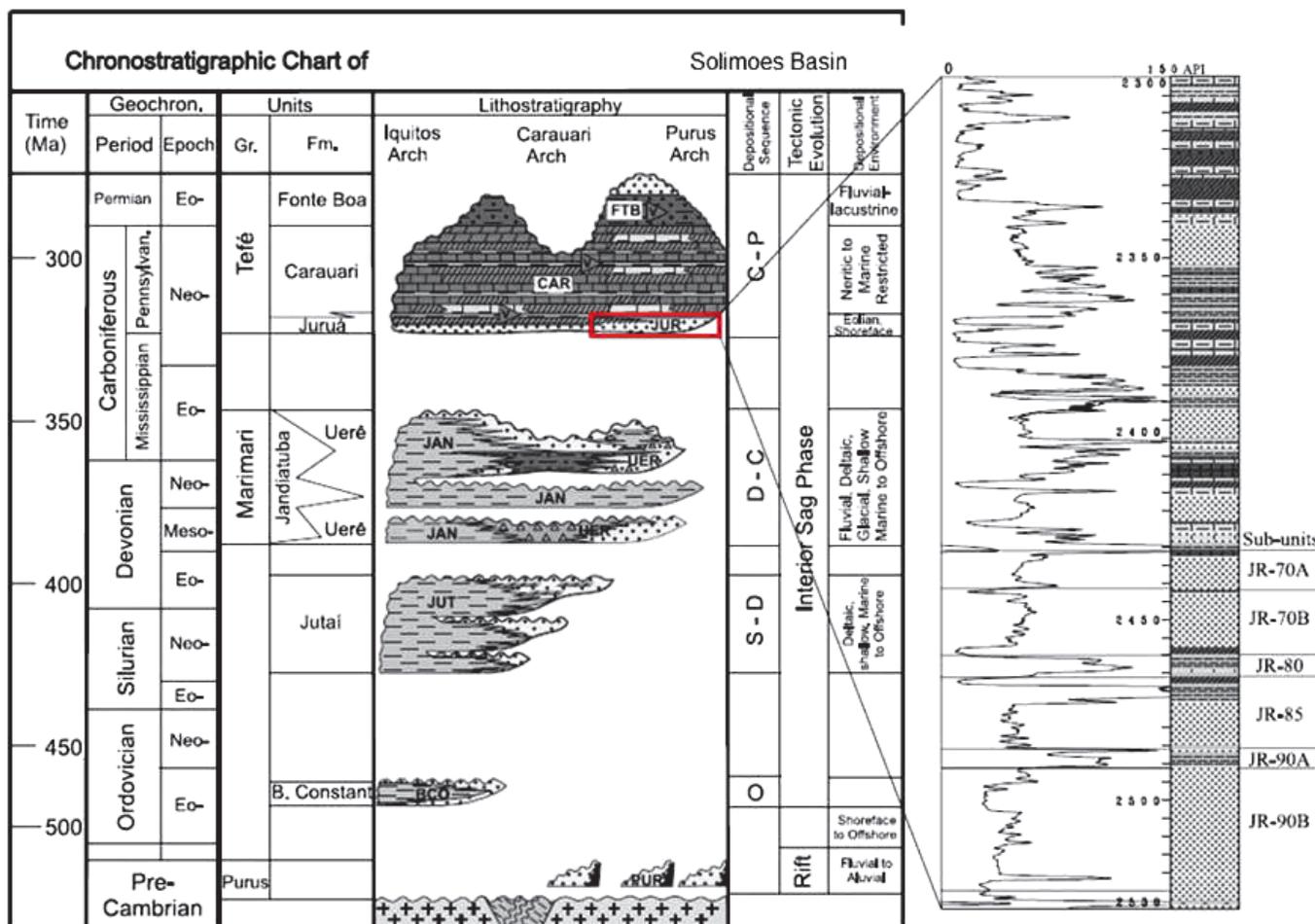


Fig. 2. The litho-stratigraphic structure of the sedimentary cover of the Solimoes Basin (Eliras et al., 2004)

rock salt up to 40 m thick. The Upper Jurua evaporites were formed during a HST period in arid conditions and significant isolation of the basin.

Sq3 Sequence, which includes the studied target, JR10, within the studied territory is formed by the following (Fig. 3-5):

- Black shelf claystones, clay siltstones of the transgressive system tract (TST), everywhere eroded and overlying the evaporite unit (HST Sq2).
- Terrigenous sediments (sandstones, siltstones, and claystones) of the marine, transitional, and continental genesis of the highstand system tract HST to which the JR10 reservoir is confined. The sediments were formed in a more wet, possibly semi-arid climate, as evidenced by numerous clusters of plant detritus and plant roots.

Above the Sq3, there are sandstones, siltstones with inclusions of anhydrites, and dolomites of the Carauari Formation (Fig. 4). Below is a detailed description of the facies forming the deposits in question.

The shelf (Shelf) and the transit zone (TZ) facies are interpreted in the lower part of JR10; they are represented by silty claystones and fine-grained, clayey, thin-bedded, bioturbated siltstones. There are layers of limey marls – dark gray, microcrystalline, thin-bedded, poorly bioturbated. The facies has been interpreted within the

transgressive system tract (TST). The sediment thickness is 2-3 m.

The upper shoreface facies (SF) is represented by light gray, very fine to fine-grained well-sorted sandstones, with flaser and shallow multidirectional cross-bedding, with rare benthos burrows. The sandstones are of arcocic composition with an admixture of volcanic lithoclasts. Accessory minerals include tourmaline and zircon.

Cements are mainly hematite, dolomite, and regenerated quartz.

Open porosity is 12.0%, permeability is 0.34 mD.

The sediments up to 2 m thick were interpreted in the upper part of JR10 (Fig. 4).

The prodelta slope facies (PD) is represented by silty, black, dark gray, brownish-gray claystones, dark gray siltstones, with a greenish tinge, brick-red (hematized), clayey with thin interlayers of sandstones. Claystones and siltstones are fine and micro-layered (Fig. 6A), with rare small plastic deformations, poorly bioturbated, with inclusions of pyrite. The rocks are characterized by a low content of carbonized plant detritus and sludge, Planolites burrows, and small Bivalvia shells.

The thickness of the prodelta slope facies varies from 1.1 to 2.3 m.

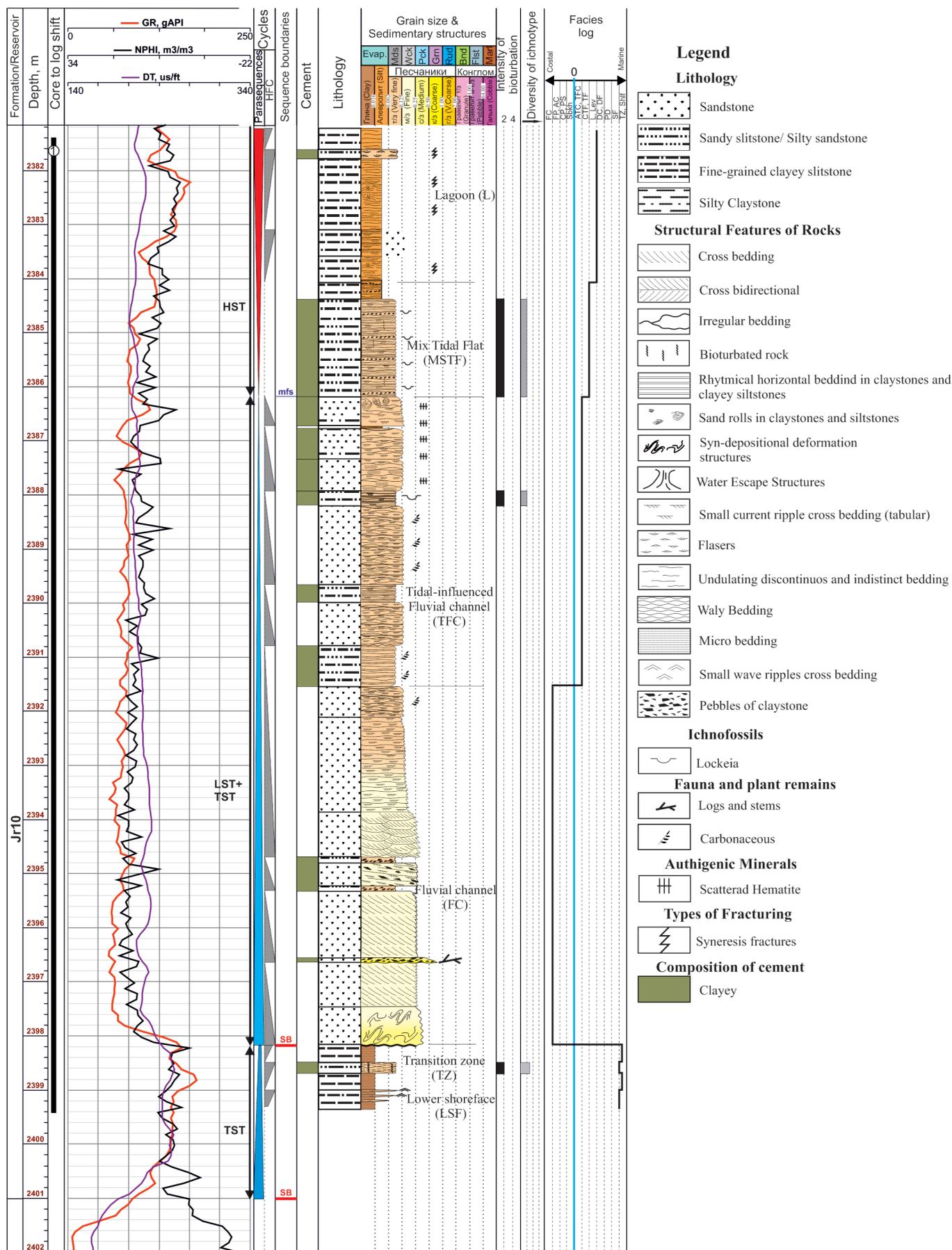


Fig. 5. Sedimentological section of the upper part of Upper Jurassic in Well 2, Solimoes Basin

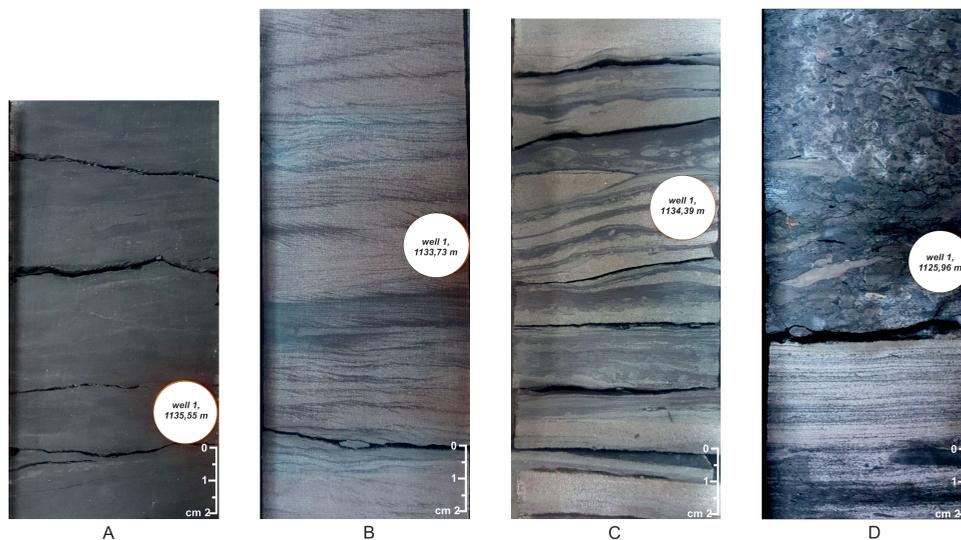


Fig. 6. Structural features of JR10 rocks: A – silty microlayered claystones of prodelta slope; B – fine-grained sandstones, with small multidirectional cross and cross-wave bedding, with rare *Planolites* burrows. Delta front facies; C – interbedded fine-grained sandstones and fine-grained clayey siltstones. Undulating deformational bedding disturbed by *Planolites* and *Palaeophycus* burrows. Delta front facies; D – small and large intraclasts of clayey siltstones in the sand matrix (top of the core) overlying fine-grained sandstones with thin horizontal bedding (bottom of the core). A contact between the delta front and distribution channel sediments.

The **distal delta front facies (DDF)** is represented by gray and brick-red very fine-grained and fine-grained sandstones with flaser and wavy-lenticular bedding, climbing ripples, less often with thin multi-directional cross-bedding (Fig. 6B), with thin interlayers (from 2 to 15 mm) of dark gray fine-grained clayey siltstones (Fig. 6B).

A characteristic feature of delta sediments is an upward increase in grain size, the presence of *Skolithos*, *Palaeophycus*, *Planolites*, an abundance of plant detritus, and the stratigraphic position of sandstones above clay deposits of the prodelta slope.

The delta front sediments are also characterized by a variety of structures of the convolute bedding, gravitational displacement fractures, and intrusion structures along layer contacts.

The cement is predominantly clayey, with a small content of quartz regeneration. The accessory complex is represented by tourmaline and zircon which are resistant to chemical weathering.

The open porosity of sandstones is 11.8%, permeability is 0.023 mD.

The thickness of delta front sandy sediments varies from 1.3 to 4.9 m.

The **facies of delta distribution channel (DC)** is represented by gray very-fine to fine-grained sandstones with gently sloping cross bedding, interlayers with synclinal bedding and climbing ripples. Sand sediments of the distribution channel are eroded and overlie the delta front sediments. At the bottom of the channel deposits there are numerous claystone intraclasts of various shapes and sizes (Fig. 6D), carbonized fragments of plants. The abundance of plant detritus indicates

a relatively wet climate and widespread terrestrial vegetation in the floodplain and delta.

Cement in sandstones is clayey, carbonate-clayey, with regenerated quartz, sideritic.

Open porosity is 9.1%, permeability is 0.016 mD.

The sediment thickness is about 5.0 m.

The **fluvial channel facies (FC)** is represented by gray, fine-grained, medium-fine-grained sandstones with poor and medium sorting, cross unidirectional bedding, less often with convolute bedding. Contact with the underlying layer is sharp, eroded.

The reservoir properties of rocks in the fluvial channel sandstones were studied on 18 cores from Well 2: porosity varies from 9.4 to 12.3%, permeability – within 0.28-2.62 mD.

The thickness is up to 5.0 m.

The **facies of tidal flat channel (TFC)** is represented by gray sandstones with reddish hue, hematized, very-fine to fine-grained, with fine multidirectional cross bedding, double laminae draped with clay material (Fig. 7A, 7B), *Lockeia* burrows, thin layers of silty-clayey material, and carbonized plant detritus. There are numerous clay-silty intraclasts, up to 1.5*4.0 cm in size.

The reservoir properties of rocks were studied on 5 cores from Well 2. The porosity varies from 7 to 12%, permeability is 0.94-2.3 mD.

The **floodplain facies (FP)** is represented by brown, hematized, micro-layered claystones, with thin lenses and gray coarse-grained siltstone laminae and deformational bedding (sliding and crushing structures). There are small shrinkage fractures, carbonized remains of root systems and plant detritus. In Well 2, claystones

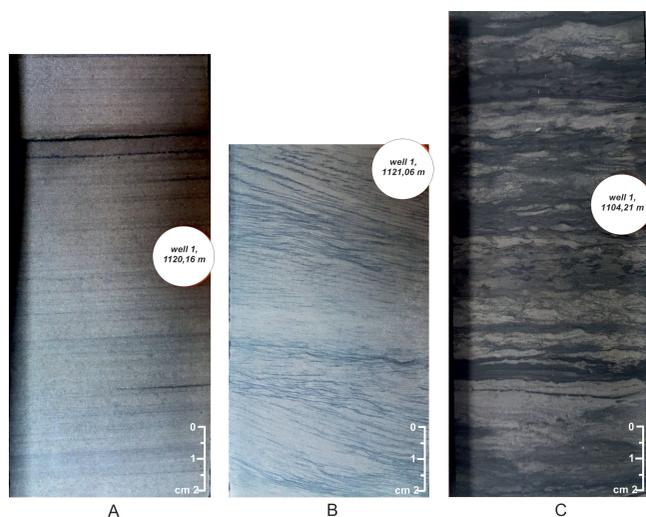


Fig. 7. Structural features of JR10 rocks: A – fine-grained cross bedded sandstones. Tidal flat channel facies; B – cross bedded sandstones with double carbonaceous and clayey laminae. Tidal flat channel facies; C – interbedding of fine-to very fine-grained sandstones and fine-grained clayey siltstones. The bedding is lenticular-wavy, gently-wavy, disturbed by *Planolites* and *Skolithos* burrows. Tidal flat facies.

with a lumpy structure are found and interpreted as paleosols.

The thickness of the floodplain facies is 0.4-1.0 m.

The **tidal flat facies (TF)** is represented by the interbedded claystones, gray very fine-grained sandstones and brick-red clayey siltstones. Depending on the predominance of rocks and their thickness, mixed, muddy, and sandy tidal flats are distinguished. Characteristic features of tidal flats are: multidirectional

small cross/flaser/lenticular-wavy bedding (Fig. 7C), double laminae, syneresis fractures, mono-type composition of ichnofossils, organic remains represented by carbonized detritus of plants and single small bivalve shells.

Paragenesis with fluvial, delta, and lagoon macro-facies.

The sediment thickness is 0.4-2.8 m (Fig. 4, 5).

The **lagoon/bay facies (L)** is represented by claystones, siltstones, and silty sandstones; it is interpreted on the cores from two wells (Fig. 4, 5). Claystones are brick-red, hematized, micro-layered with rare burrows. Siltstones are brick-red (hematized), with indistinct intermittent thin bedding and micro-layered, with rare syneresis fractures healed with dolomitic-sulfate cement, tight. Silty sandstones are reddish-gray, clayey, with flaser bedding, rare syneresis fractures, and tight.

The thickness of the lagoon units varies from 0.8 to 2.3 m.

Figure 8 shows the interpretation of the relationships of the described facies:

1. The transgressive system tract (TST), intersected by Well 1 and 2, is represented by black marine claystones with rare interlayers of clayey limestones.

2. In Well 1, located on the periphery of the basin, the TST is overlaid by a normal sequence of delta-type coastal-marine sediments. Above them lies a series of alternating floodplain, marine, and coastal-marine facies.

3. In Well 2, located in the central part, the same TST is overlaid by alluvial deposits with erosion. Above them lies a series of alternating marine and coastal-marine facies.

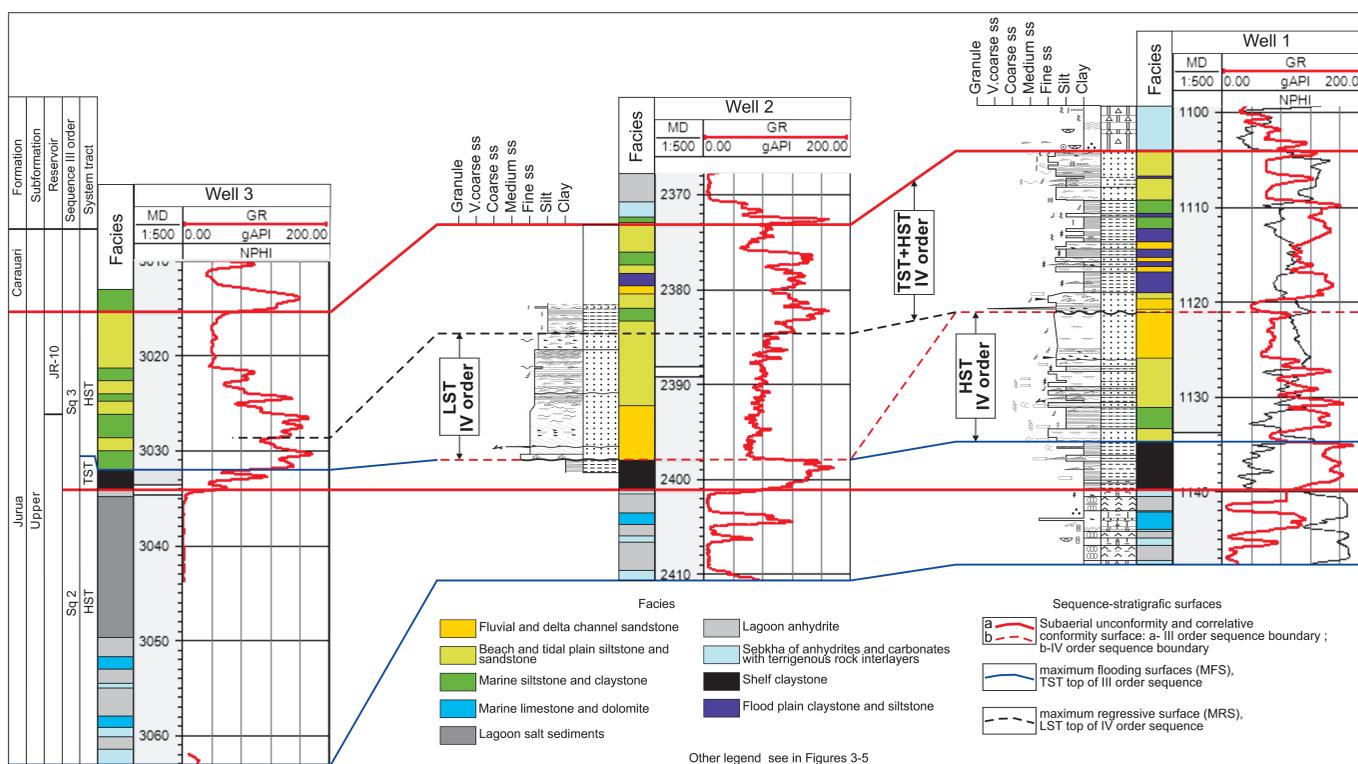


Fig. 8. Comparison of cored sections of JR10

Obviously, the established spatial relationships of the facies contradict the repeatedly tested concepts of facies zones in sedimentation basins (Reineck, Singh, 1980): subcontinental alluvial deposits cannot be replaced by a coastal-sea delta complex toward the land.

This contradiction can be resolved within the new concept which its authors called “high-resolution sequence stratigraphy”, and according to which sequences of different orders (up to order IV and more) with a similar structure can be distinguished in sedimentary basins (Zecchin, Catuneanu, 2013). Apparently, this concept can be considered as a special case of fractality of sedimentary basin models, which in turn is an element of a new non-linear approach to addressing the problems of geology of sedimentary formations (Alekseev, Amon, 2017).

To explain this contradiction within the above concept, the following hypothesis was proposed. A series of alluvial and coastal-marine sandstones in Well 2 overlaying the shelf facies with erosion was interpreted as LST which is part of fourth-order sequence and pinching out toward the paleo land (in Well 1).

In this case, a stratigraphic unconformity – a fourth-order sequence boundary should be assumed between the coastal-marine and continental deposits in Well 1. Therefore:

The coastal-marine delta complex making up the lower part of JR10 is the HST of the preceding fourth-order sequence.

The complex of terrigenous facies of the coastal shallow waters, lagoons, and tidal flats that make up the upper part of JR10 consists of undivided TST + HST deposits of a younger fourth-order sequence.

The conceptual model of JR10 structure is shown in Fig. 9.

The current vision:

First, it is an Sq3 HST which forms the upper part of Upper Jurua

Second, it is a series of progradational fourth-order sequences, each of which is formed by an LST including the alluvial sandstone facies and undivided TST + HST deposits of delta type.

Such a reservoir structure should have determined the distribution of zones with better reservoirs.

A lithofacies map of JR10 is shown in Figure 10. Based on core and logging data, five types of facies zones were conventionally identified according to the southeast-northwest progradation of the delta coast.

Facies zones of type I are found in the southeastern and central parts of the territory. The target is characterized by mottled facies composition, with a significant proportion of sandstones (more than 50%) of delta front and delta distribution channels, as well as river channels. Clay-silty sediments are represented by the deposits of prodelta slope and coastal alluvial-delta plain. The sandstones of distribution channels and mouth bars are well sorted and are good reservoirs. The thickness of JR10 in the southeastern part of the territory is maximum – up to 40-50 m, in the central part it is about 25-30 m.

Facies zones of type II also have a linear distribution in the territory and border type I zones from the northwest. One of them, in the central part of the area, was confirmed by Well 2. The section is composed mainly of clay-silty deposits of the delta, the lower part of the delta front, delta bays, and tidal flat. The sandy

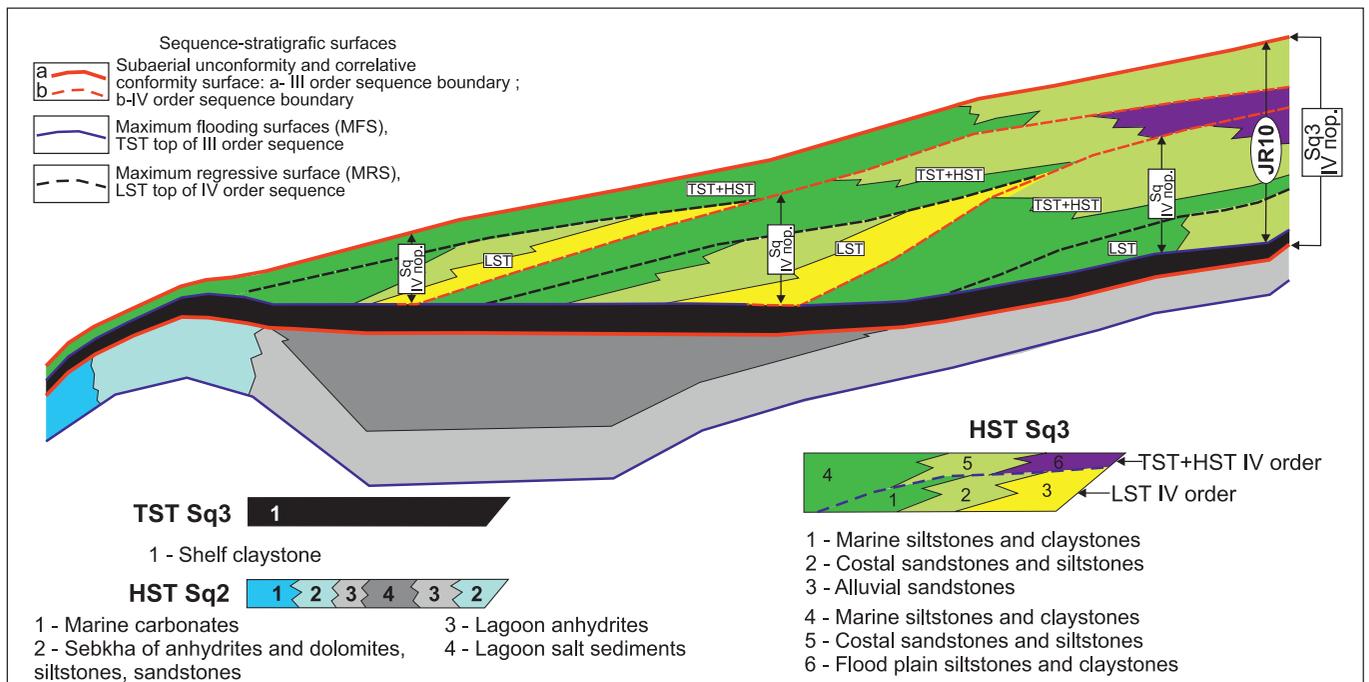


Fig. 9. Conceptual model of JR10

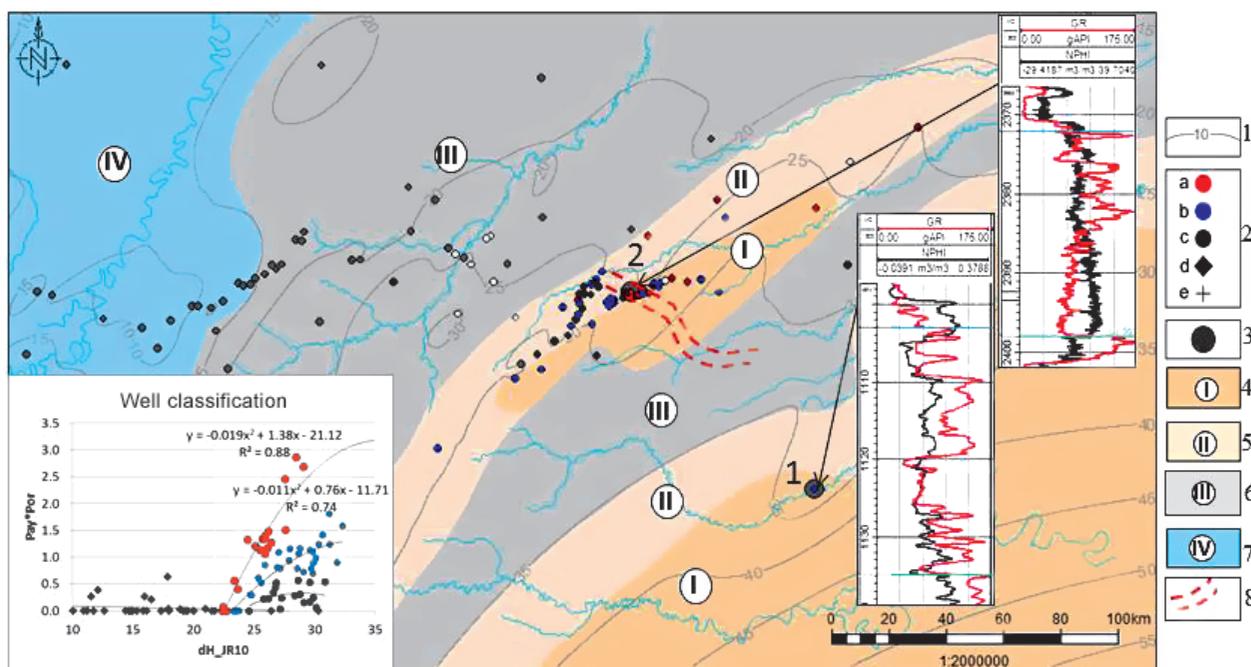


Fig. 10. Litho-facies map of JR10. 1 – isopach lines, m; 2 – wells: a – d – classes, e – no data; 3 – cored wells; facies zones: 4 – delta front, prodelta, distribution channels, coastal plain (sandy sediments > 50%, clay-silty – 25-50%); 5 – delta front, prodelta, distribution channels (sandy sediments – 40-50%, silty and clayey – 50-60%); 6 – prodelta, delta front, marine (sandy sediments – 30-40%, clay-silty – 60-70%); 7 – marine, delta, distal part of the delta front (sandy sediments – 10-20%, clay-silty – 80-90%); 8 – assumed fluvial channel.

facies in the section are subordinate to silty-clay facies: the share of sandy-silty rocks is from 40 to 50%. They are represented by sediments of the upper part of the delta front, distribution channels, and meandering channels. The thickness of JR10 in the southeast zone is about 35 m, in the central part it varies from 25 to 35 m.

Facies zones of type III border type II zones from the northwest. The thickness of the target here varies from 15 to 35 m. The proportion of clay-silty sediments increases (60-70%), the proportion of sandy sediments decreases down to 30-40%. Sandstones are represented by the sediments of delta front and distribution channels. Clay-silty sediments are formed in the environments of the marine terrigenous shallow water, prodelta slope, tidal flats, and lagoons.

In the westernmost part of the basin, a *facies zone of type IV* is distinguished. The thickness of JR10 decreases here down to 10-15 m. The interval was accumulated under conditions of sedimentation “hunger”. The proportion of clay-silty sediments in the cross section increases here up to 80-90%. These are sediments of marine genesis, prodelta slope, and distal part of delta front (Fig. 10).

Since the JR10 sediment complex is progradational in nature, there is a repetition of identified facies zones from south-east to north-west. They become younger in the same direction in accordance with the adopted sequence-stratigraphic model.

Note that the model shown in Figure 10 is a concept which reflects the current state of knowledge. It is quite

possible that new drilling data will help to identify additional zones with increased content of alluvial and coastal-marine sandstones associated with fourth-order sequences.

Inter-basin Correlation

Summing up the review of new data on the features of JR10 sedimentation and its cyclostratigraphic structure, we should dwell on the issue of regional correlation, which has arisen as a result of the studies performed.

The accumulation of prograding clayey-terrigenous complexes of the alluvial-delta coast forming JR10 is a result of certain regional climatic changes that caused an increase in river flow at the boundary of Jurua and Carauari.

It is known that on the Paleozoic supercontinent of Gondwana, which included the ancient South American platform, such changes were controlled by glaciers that occupied significant inland areas (Limarino et al., 2014).

For example, the formation of deltaic coasts, timed to the interglacial period at the beginning of the Early Permian, was identified in the Parana basin (Caputo, 1984; Bernardes-de-Oliveira et al., 2016; Mottin et al., 2018). At the same time, in the Parnaiba basin located to the east of the Solimoes basin (Fig. 1), the activation of alluvial sedimentation with the formation of delta systems takes place during the Late Carboniferous (Barbosa et al., 2016). All these facts testify to the inconsistency

of regional comparisons and the correlation of events caused by seemingly single reasons.

For reliable and reasonable tracking of sedimentation patterns in various South American Paleozoic basins, it is necessary to apply modern methods of zonal biostratigraphic correlation, a palynological analysis in particular. As already noted, various remains of terrestrial higher plants were found in the JR10 rocks during sedimentological analysis. A palynological study of JR10 rocks can significantly clarify the age of the upper part of the Jurua formation and improve the accuracy of both regional intra-basin reconstructions and inter-basin comparisons and correlation of the key events.

Summary

For the first time it was found, based on the core taken from two wells, that JR10 deposits (the Upper Jurua subformation) were formed in the conditions of delta and alluvial coast of the semiarid climatic zone and in marine terrigenous environments. The signs of tidal influence are identified by core in the sediments of the emerged part of the delta.

JR10 differs in its lithology and structure from the underlying Jurua sediments and the overlying Caruari sediments by the absence of carbonate rocks and evaporite layers and high content of carbonized remains of land plants (detritus, sludge, large fragments of leaves and stems).

The abundance of carbonized remains of higher plants is an evidence of semi-arid climate at the transition from the Jurua to the Caruari complex and the spread of terrestrial vegetation at the coast.

To establish the exact age of JR10, we recommend conducting detailed biostratigraphic (palynological) studies of this interval.

Based on the study of core and logging data, it was found that JR10 has a clinoform structure. The south-east to north-west change in its thickness is associated with the progradation nature of the delta coast developing in the same direction.

The sandstones of the delta front, distribution delta channels, and meandering tidal channels facies are characterized by best reservoir properties. The deposits of fluvial channels in JR10 will most likely form lithological-structural traps.

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