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RESEARCH PAPER

STRATIGRAPHIC CORRELATION OF THE SILURIAN-DEVONIAN OF THE AMAZON BASIN (BRAZIL) BASED ON GENETIC STRATIGRAPHIC SEQUENCE APPROACH

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Abstract

The current study consists in the stratigraphic analysis of Silurian-Devonian interval in the Amazon Basin (Brazil) using the concepts of the Modern Stratigraphy, more specifically the genetic stratigraphic sequence, proposed by Galloway (1989), that uses the marine flooding surface as a boundary of sequence. This methodology is since the sediments of studied interval are related to marine transgressions which were part of the basin paleogeographic context. Thus, the maximum flood surfaces, which are presented in four sections (AA', BB', CC' and D-D') throughout the basin, represent chronostratigraphic events, which stand out in gamma ray profiles and are used as correlation data in thirteen exploration wells. Analysis of these sections allowed the identification of four fourth-order sequences (AB, BC, CD and DE) bounded by maximum flooding surfaces on the top and the base. Each sequence consists of asymmetric regressive-transgressive cycles, represented by highstand systems tract and transgressive systems tract. The analysis of these sections integrated with the stratigraphic maps (isopach and isolith) allowed the identification of the depocenter and two main source areas of sandy sediments (west and south). Besides, it was possible to infer that the marine transgression during the Paleozoic induced the deposition of pelitic sediments and followed a trend from northeast to southwest.

Keywords: Amazon Basin. Genetic Stratigraphic Sequence. Silurian. Devonian. Well correlations.

1. Introduction

Initially proposed for marginal basins, the basic concept of the genetic stratigraphic sequence model (Galloway, 1989) was applied in the current study using maximum flooding surfaces (MFS) in correlation and regional stratigraphic analysis. Ramp basins, such as the Amazon Basin, as well as the marginal basins, are characterized by repetitive and intercalated episodes of progradation, transgression and flooding of the depositional platform. In this model, the stratigraphic sequences are bounded at the top and bottom by condensed sections (Galloway, 1989).

The Galloway model is the sedimentary product of a depositional record, in which each sequence is bounded at the top and bottom by a MFS, and among its boundaries may occur progradational, retrogradational and aggradational sedimentary patterns of stacking (Della Fávera, 2001).

The transgressive systems tract (TST), as well as the highstand systems tract (HST) and the lowstand systems tract (LST) are identifiable. However, it is important to highlight the difficulty to determine the LST in intracratonic basins, since these are poorly developed and particularly restricted in this type of environment (Lindsay et al., 1993).

According to Loutit et al. (1988), the condensed sections, which are responsible for defining the boundaries of each depositional sequence, reflect slow deposition rates over time. They are formed during marine transgressions, when the sea reaches its highest level of invasion to the continent, flooding it. Although they are deposited over a long period of time, their sedimentary record is not very thick and presents a predominance of pelagic sediments, generally radioactive shales with a well-developed fossiliferous content, which is easily dating and usually incorporates useful planktonic forms in the high resolution chronostratigraphic correlation.

The surface produced during a maximum flooding period has an easily recognizable, correlated and mappable sea layers, using either well logs, seismic or outcrop data.

There are many similarities between the genetic stratigraphic sequence proposed by Galloway (1989) and the depositional sequence initially defined by Mitchum (1977) and used in most research involving the concepts of modern stratigraphy (Fig. 1). In fact, the concepts involving the genetic stratigraphic sequence are practically identical to the parasequences of Van Wagoner et al. (1988). These models have a conceptual origin inspired by Frazier (1974), but each one emphasizes the most important elements according to the objectives of study.

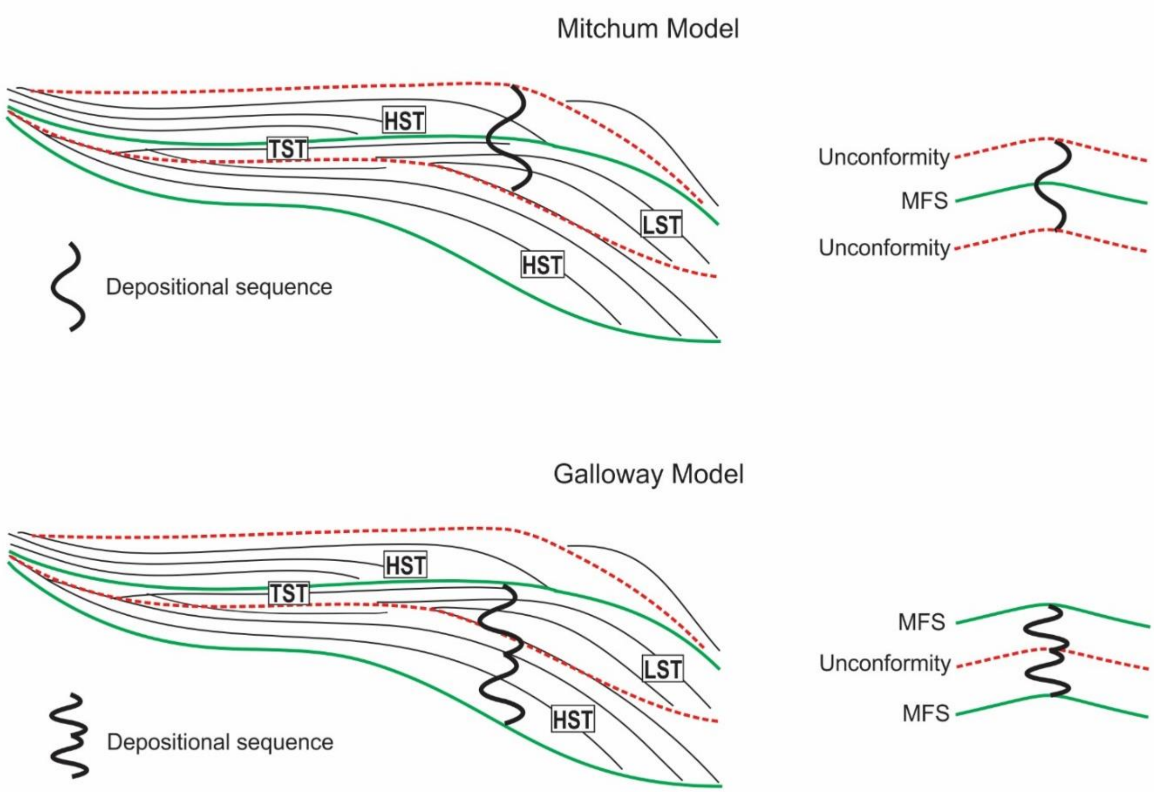

Fig. 1. Comparison between the sequence limits of the models proposed by Mitchum (1977) and Galloway (1989). Modified from Galloway (1989).

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Della Fávera (2001) advises the use of the genetic stratigraphic sequence as the ideal model to delimit stratigraphic sequences in intracratonic basins, mainly in intervals where there is sea invasion over the continent. Regarding seismic analysis in intracratonic basins, it is common the absence of reflection patterns that differ from the plane-parallel pattern, which makes it difficult to differentiate the many subsurface horizons. Thus, the identification of unconformities and paraconformities are generally difficult to perceive. Another problem to be considered is the occurrence of sills and volcanic dikes in the Paleozoic records, which can cause pitfalls once they could be confused with possible seismostratigraphic features. In contrast, Van Wagoner et al. (1990) discourage the use of the genetic stratigraphic sequence, as the authors argue that an unconformity is a real break of a sequence, unlike a maximum flooding surface. However, Catuneanu (2006) argues that during a stratigraphic analysis one should choose the simplest theory, which best applies to the context that basin is inserted.

1.1 The main goals

Therefore, based on the two main methodologies mentioned above, the present study will approach the concepts of modern stratigraphy using the methodology proposed by Galloway (1989) - the genetic stratigraphic sequence, once the time interval studied is characterized by successive events of sea invasion over the continent and, consequently, presents the marine flooding surfaces well developed and easy to be recognized in the gamma rays logs, whereas disagreements could only be inferred or postulated in this almost flat depositional context.

2. Study area

The Amazon Basin has well defined limits in its more than 500,000 km² of area. It is located between the Guianas craton in the north and the Brazilian craton in the south (Cordani et al., 1984). It covers most of the Amazonas and Pará states; it is separated to the west of the Solimões Basin by the Purus Arch and to the east is limited to the Gurupá Arch (Fig. 2). The sedimentary and igneous filling can reach up to 5000 m of thickness and presents deposits from the Ordovician to the Tertiary when the deposition of its great history of sedimentary filling was finished. Its sedimentation is predominantly siliciclastic with carbonate deposition in the Late Carboniferous. Diabases/dolerites representative of magmatic events of the Jurassic and Triassic are also inserted in the basin (Cunha et al., 2007).

According to Cunha et al. (2007) the stratigraphic record of the basin is divided into four Paleozoic tectonic sequences (Ordovician-Devonian, Devonian-Tournasian, Late Visean and Pennsylvanian-Permian) and two Mesozoic-Cenozoic tectonic sequences (Cretaceous and Tertiary). The igneous rocks present in the stratigraphic framework of the Amazon Basin are related to the distensive processes responsible for the opening of the Atlantic Ocean. These igneous rocks are present in the form of dikes and sills of diabase (Thomaz Filho et al., 1974).

The interval analyzed in the current study comprises the Trombetas, Urupadi and Curuá groups, described below:

Trombetas Group comprises the Autás Mirim, Nhamundá, Pitinga, Manacapuru and Jatapu formations. Only these last three formations are inserted in the analyzed time interval. The Pitinga Formation is composed of marine shales and diamictites from Late Ordovician to Late Silurian. The Manacupuru Formation consists of Late Silurian-Early Devonian sandstones and pelitic neritic marine deposits. The Jatapu Formation contains paralic-marine sandstones and siltstones, dated as Lochovian to the Early Emsian based on palynomorph studies (Melo and Loboziak, 2003).

Urupadi Group encompasses the Maecuru and Ererê formations. The first is composed of neritic and deltaic sandstones from Late Emsian/Early Eifelianin age. The Ererê Formation consists of siltstones, shales and sandstones deposited in neritic and paralic environments, dated as Late Eifelian to Early Givetian (Melo and Loboziak, 2003).

Curuá Group comprises the Barreirinha, Curiri and Oriximiná formations. Of these three units, only Barreirinha Formation is addressed in the present study. The radioactive black shales of Barreirinha Formation present high organic matter content and are characterized by geochemical studies as the main source rock of the Amazon basin (Rodrigues, 1973; Triguis et al., 2005).

3. Material and methods

The data used in this work were provided by the *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis ANP* (Brazilian National Agency of Petroleum, Natural Gas and Biofuels), through the *Banco de Dados de Exploração e Produção-BDEP* (Exploration and Production Database). It consists of 13 wells drilled by *Petróleo Brasileiro S.A. (Petrobras)* during its drilling campaign for hydrocarbon exploration in Amazon Basin, which began in the middle of the last century (Table 1).

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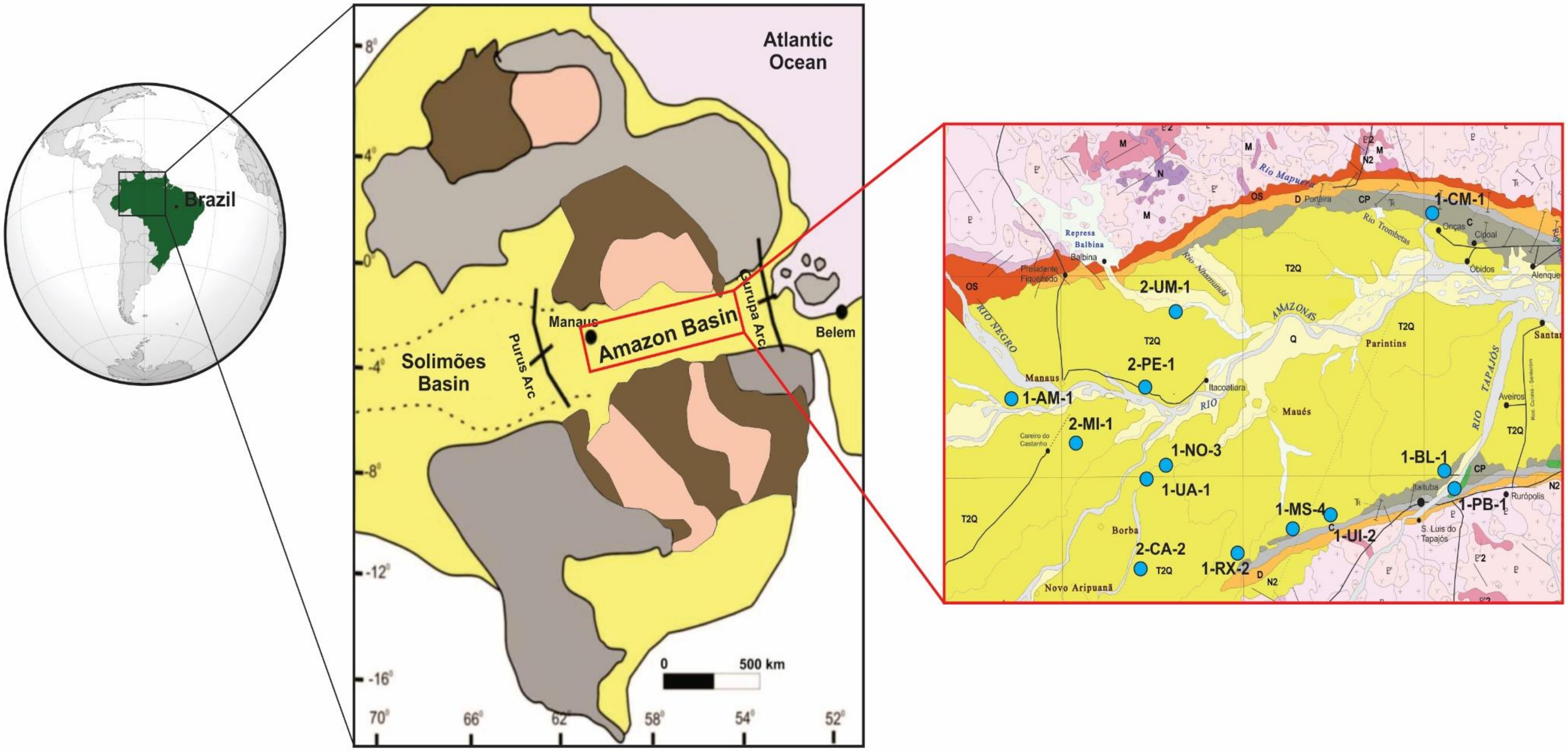

Fig. 2. Location map of the Amazon Basin in the context of the South American Platform. The wells and sections used in the current work are also shown.

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Tab. 1. Summary of all available wells analyzed in the current work.

Well	Latitude	Longitude	Datum	Depth (m)	Type
1-AM-1-AM	-3.285085	-59.873525	SAD-69	2248	Pioneer
1-NO-3-AM	-3.846271	-59.071568	SAD-69	3589	Pioneer
1-UA-1-AM	-3.937807	-58.880623	SAD-69	3767	Pioneer
1-RX-2-AM	-4.596368	-58.195195	SAD-69	2312	Pioneer
1-MS-4-AM	-4353367	-57.595299	SAD-69	1658	Pioneer
1-UI-2-AM	-4.311977	-57.103893	SAD-69	850	Pioneer
1CM-1-PA	-2.415641	-56.048615	SAD-69	1154	Pioneer
1-PB-1-PA	-4.028658	-56.446861	SAD-69	1023	Pioneer
1-BL-1-PA	-3.924866	-56.414856	SAD-69	945	Pioneer
2-PE-1-AM	-3.286008	-58.549823	SAD-69	1987	Stratigraphic
2-UM-1-AM	-2.346253	-58.710454	SAD-69	1858	Stratigraphic
2-MI-1-AM	-3.452095	-59.574705	SAD-69	2195	Stratigraphic
2-CA-2-AM	-4.596368	-58.880623	SAD-69	1881	Stratigraphic

The first step was to identify different sedimentary cycles, based on the natural radioactivity variation of the rocks composition recognized from the interpretation of gamma ray logs. The identified sedimentary cycles were correlated between the wells, and afterwards, it was made the recognition of the genetic stratigraphic sequences based on Galloway (1989), which uses the maximum flooding surface (MFS) as a key element.

The next step was the elaboration of isopach and sand isolith maps, which are essential tools for understanding the modifications in basin geometry, sedimentary filling, as well as providing paleogeographic information.

4. Results

Considering the well locations, it was performed four stratigraphic sections (A-A', B-B', C-C' and D-D') showing the correlation based on gamma ray well logs. From the information obtained in each well, stratigraphic maps (isopach and sand isolith) were elaborated for each recognized genetic stratigraphic sequence.

The studied interval was subdivided into four genetic stratigraphic sequences (AB, BC, CD, and DE) bounded at the base and at the top by MFS, stratigraphically named from the base to the top using the sequence of letters A to E, as shown in the stratigraphic reference section (Fig. 3).

4.1 AB Sequence

The AB Sequence is limited at its base by the typical radioactive shales from the Pitinga Formation (Early Silurian in age) and after that assumes a progradational sedimentary pattern of stacking, ending at the top by the deposition of arenaceous sediments belonging to the Manacapuru Formation, Late Silurian to Early Devonian in age, characterizing the HST.

The uppermost section of this sequence, characterized by paralic marine sediments (Cunha et al., 2007) of the base of the Early Devonian Jatapu Formation, assumes a retrogradational character, typical of a TST. This retrogradational tendency evolves up to the maximum flooding surface (MFS-B), which marks the upper limit of this sequence.

Based on the isopach map of AB Sequence (Fig. 4), it was possible to identify the depositional depocenter at the central-northeast portion of the studied area, while western and southeastern areas exhibit a decreasing thickness of the individual sequences.

The sand isolith map (Fig. 5) shows the progradation of deltaic sandy deposits overlying offshore-marine pelitic deposits from western to eastern, which indicates that the source of the sediments is located in the western region, probably influenced by the Purus Arc.

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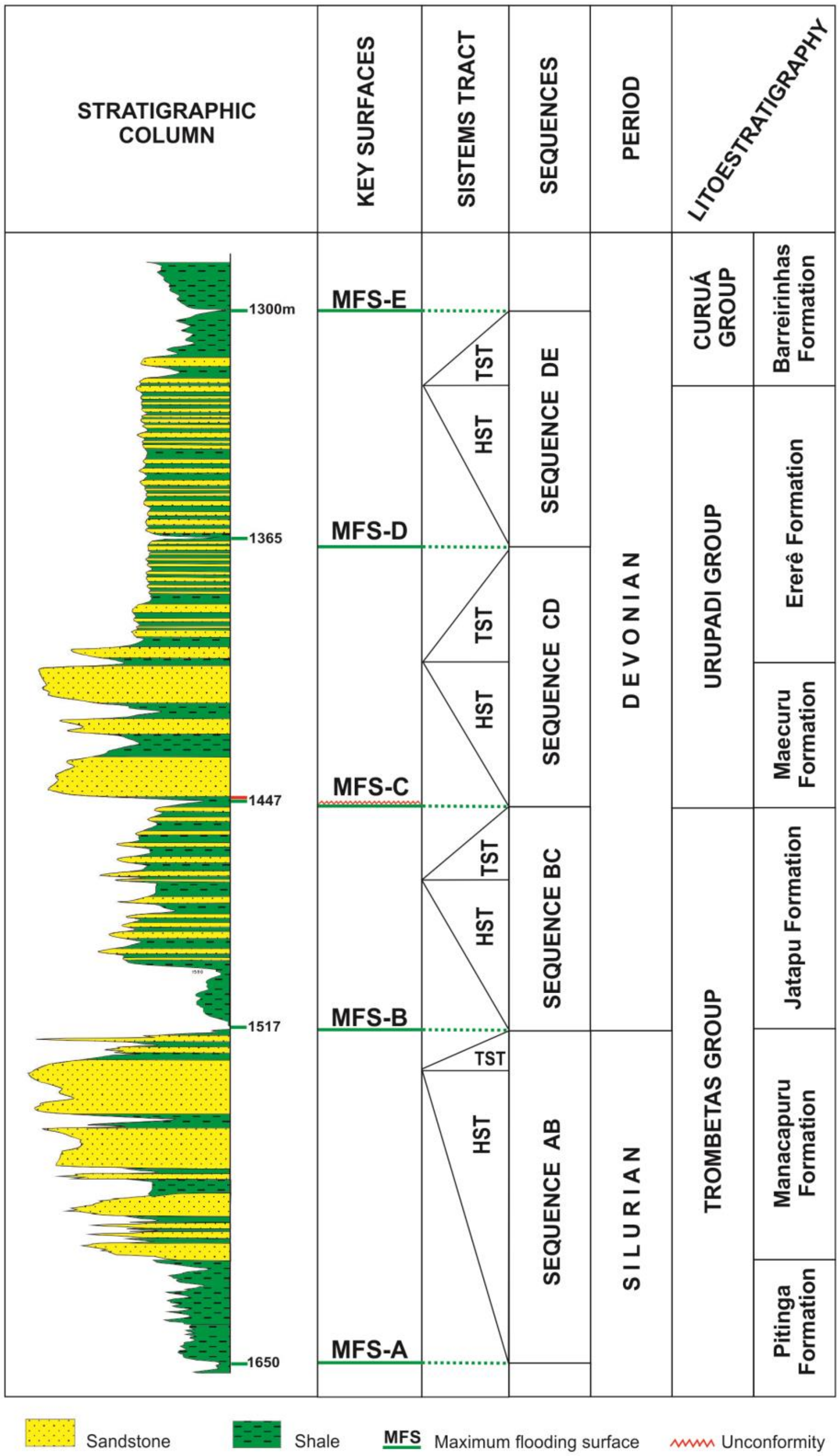

Fig. 3. Stratigraphic reference section. Well 1-AM-1-AM. Modified from Cunha (2005).

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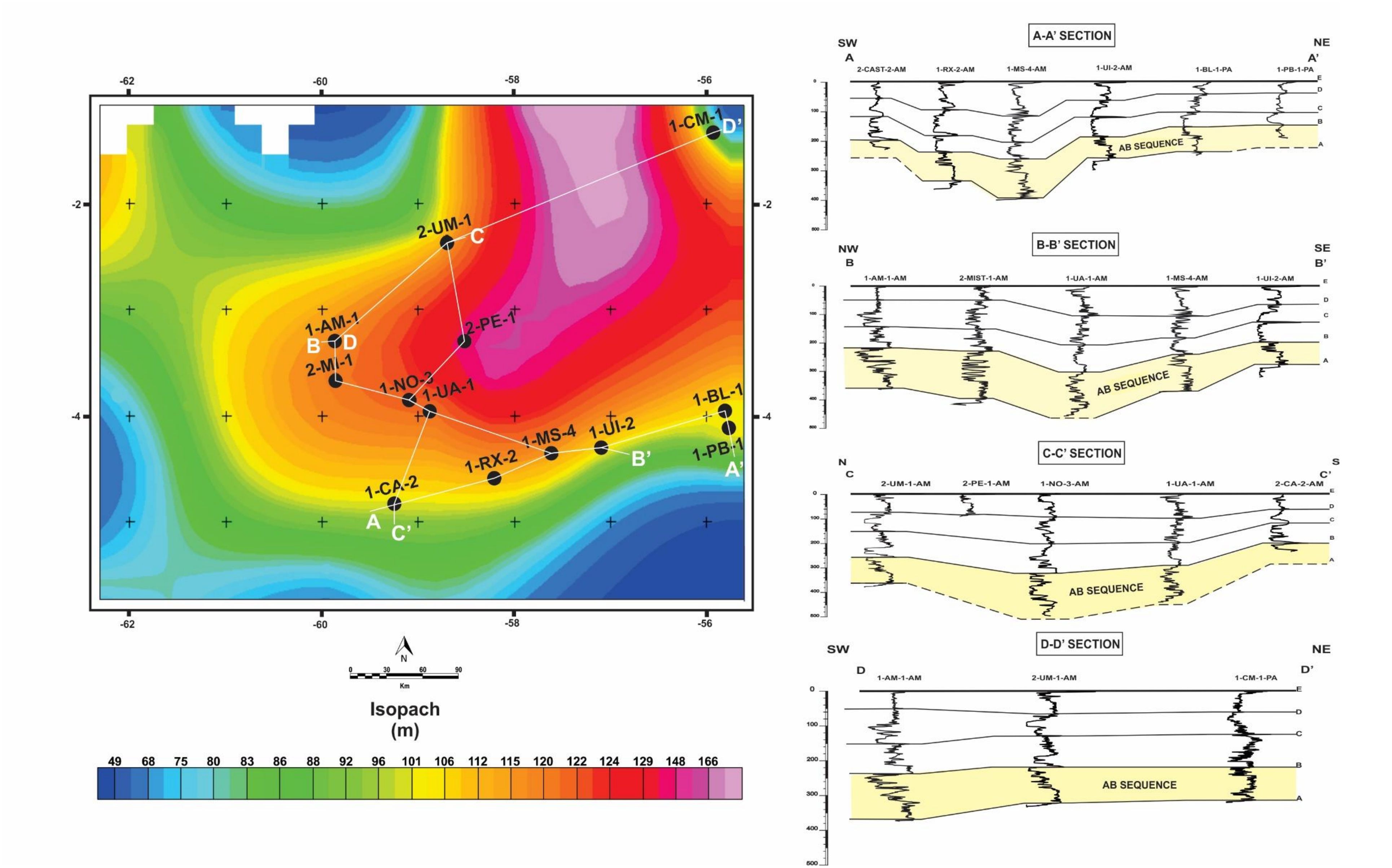

Fig. 4. Isopach map of AB Sequence.

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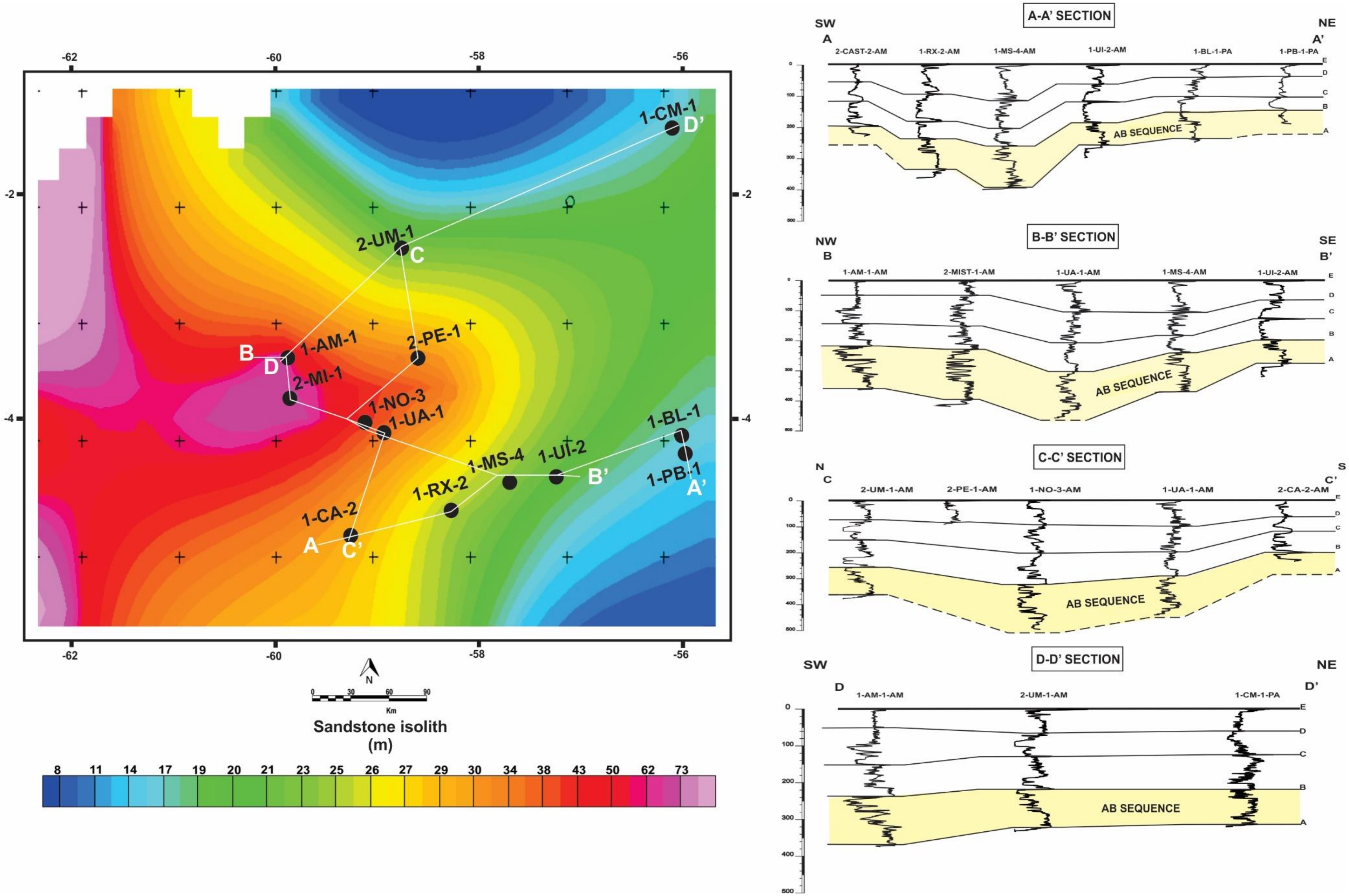

Fig. 5. Sand isolith map of AB Sequence.

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4.2 BC Sequence

The BC sequence is defined below and above by well-pronounced and widely recognizable radioactive peaks in the gamma ray well logs in all analyzed wells. This sequence corresponds entirely to the Jatapu Formation.

The base of this sequence is constituted by the intercalation of fine to medium sandstones, siltstones and bioturbated micaceous shales with sideritic and hematitic levels, passing to progradational tide-dominated deltaic deposits (Cunha et al., 2007). From this progradation, the gamma ray logs show a retrogradational tendency at to top section, which culminates into the C maximum flooding surface (MFS-C). Above it, the sandstones of Maecuru Formation were deposited in unconformity and are part of the overlying sequence (CD). There is a SW-NE trend which marks the thickest part of BC Sequence, while on the western area the mapped section presents smaller thicknesses (Fig. 6). The sand isolith map (Fig. 7) shows that the mainly source area of the sandy sediments was located at the western border of the basin.

4.3 CD Sequence

The fluvial-deltaic sandstones at the base of the Maecuru Formation were deposited sharply on the Jatapu Formation, composing the HST of the CD Sequence. After the deposition of these sandstones, the gamma ray logs display a retrogadational pattern characterizing the TST of this sequence, composed by alternation of fine sandstones, siltstones and bioturbated shales deposited in a shallow-marine depositional environment (Cunha et al., 2007). The upper boundary of this sequence is well marked by thin radiative shale within the Ererê Formation.

From the isopach map of CD Sequence (Fig. 8), it is observed that the depocenter is in the center-northeast region of the basin. The sand isolith map (Fig. 9) indicates the presence of one main source of sand, located at west/northwest. These sands prograded to the center of the basin, where there was more accommodation space.

4.4 DE Sequence

Over the thin radiative shale that represents the maximum flooding surface and the lower boundary of the DE Sequence, the gamma ray log displays a progradational pattern until the thick radiative shale of the Barreirinha Formation, which base corresponds to the upper boundary of this sequence, chosen as stratigraphic datum to the well correlation. This thick radiative shale at the base of Barreirinha Formation reports the higher total organic carbon contents found in the basin and represents the global anoxic event known everywhere in the Upper Devonian (Frasnian) (Rodrigues et al., 2005).

The maximum thickness of this sequence was found at the central-north area of the Amazon Basin. The sand isolith map (Fig. 11) shows a major concentration of pelitic sediments in the northeast of the study area, suggesting a tendency of marine connection to the northeast. The highest sand concentration in center and south areas, suggests an influence of the Purus Arc in west.

5. Discussion

In the Silurian section of the Amazon Basin, the features that stand out in the gamma ray well logs are the condensed section of radioactive shales, related to the MFS. All mapped sequences are constituted by asymmetric cycles, represented by the HST and TST in a regressive (progradational) and a transgressive (retrogradational) context, respectively. In some sections, the transgressive surface coincides with the marine flooding surface, mostly when the latter is located at the base of condensed sections of radioactive shales. In this context, Della Fávera (2001) states that intracratonic successions generally comprise transgressive and highstand staked deposits, separated by unconformities or, more frequently, quasi-planar paraconformities. In addition, MFS commonly coincide with sequence boundaries. Cunha (2000 and 2005) proposed a chronostratigraphic framework for Early to Middle Devonian strata of the western portion of Amazon Basin. In these works, the author identified three fourth-order sequences bounded at the top and bottom by unconformities (Mitchum model). However, the studied time interval presents the MFS well developed, therefore it is easily recognized in the gamma ray logs, whereas unconformities could only be inferred in this almost flat depositional context. Although an unconformity represents a break in the continuity of the sedimentary record (Van Wagoner et al., 1990), such surface was incorporated into the base of the CD sequence. It is understood that soon after the installation of the tide-dominated deltaic system (Sequence BC), the basin has experienced a new stage of marine transgression, very common during the Paleozoic, since there is the signature of the TST well-marked in the gamma ray well logs.

Above the transgressive surface were deposited in discordance the sandstones of the Maecuru Formation, which take part of the overlying sequence (CD Sequence). This gap observed throughout the Amazon Basin would imply a minimum time interval ranging from 7 to 16 million years, according to the geochronologic scale stablished to the Devonian (Gradstein et al., 2004; Kaufmann, 2006). This interpretation is based on palynological data, which point to regional absence of the AB and FD Emsian biozones of Western European miospore zonation, which are equivalent to the international conodont Zones up to serotinus or even costatus patulus (Melo and Loboziak, 2003).

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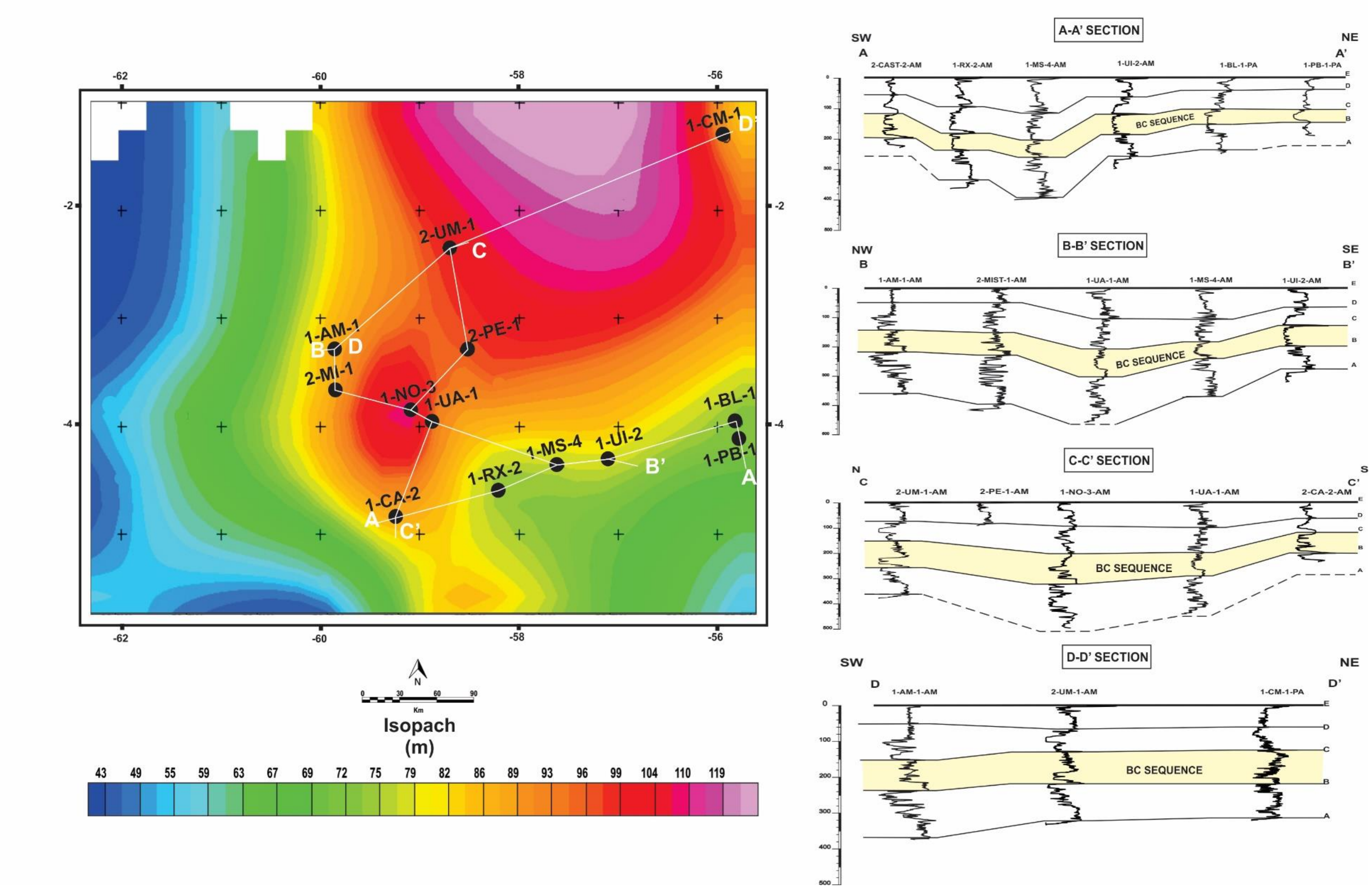

Fig. 6. Isopach map of BC Sequence.

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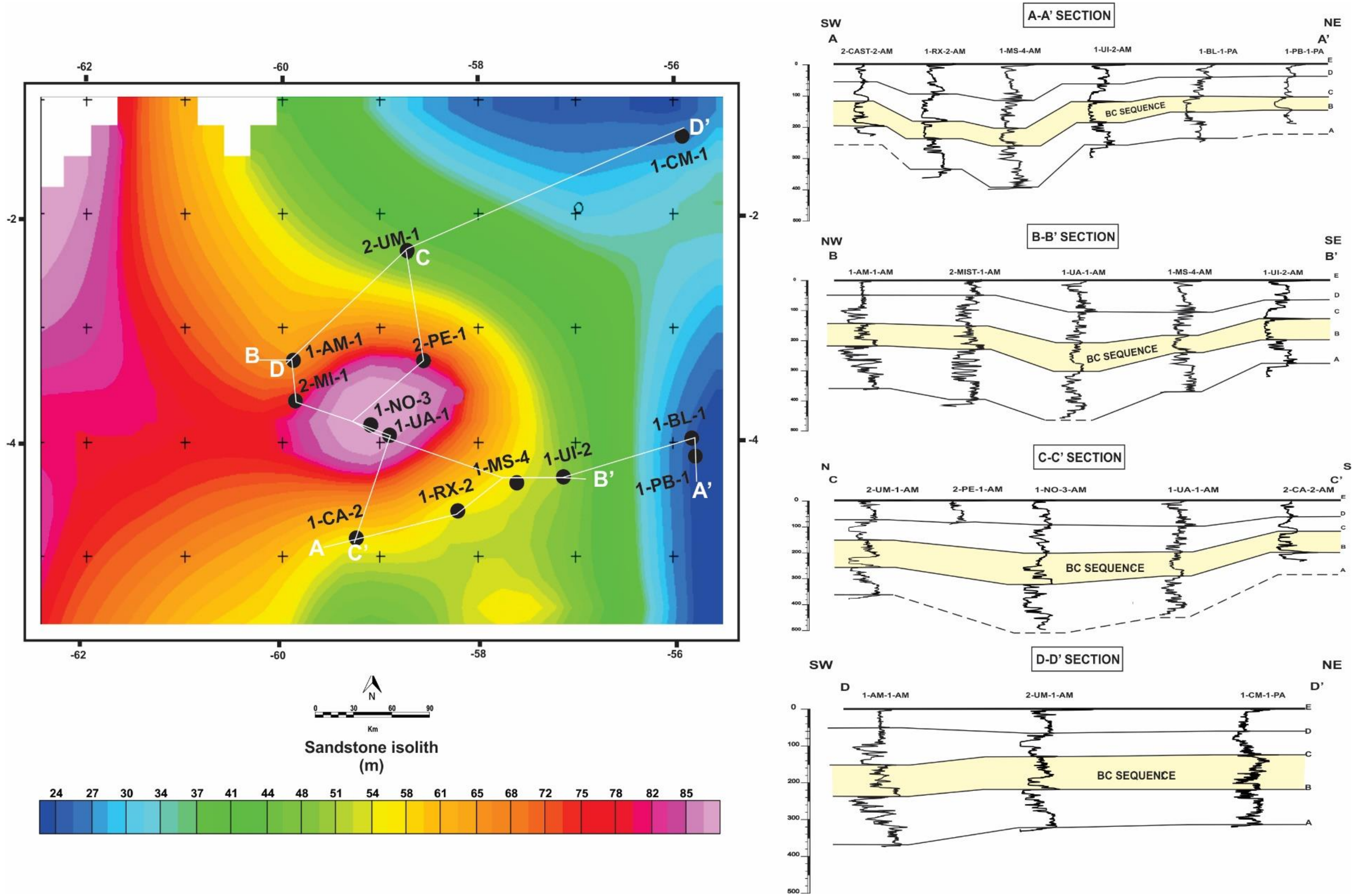

Fig. 7. Sand isolith map of BC Sequence.

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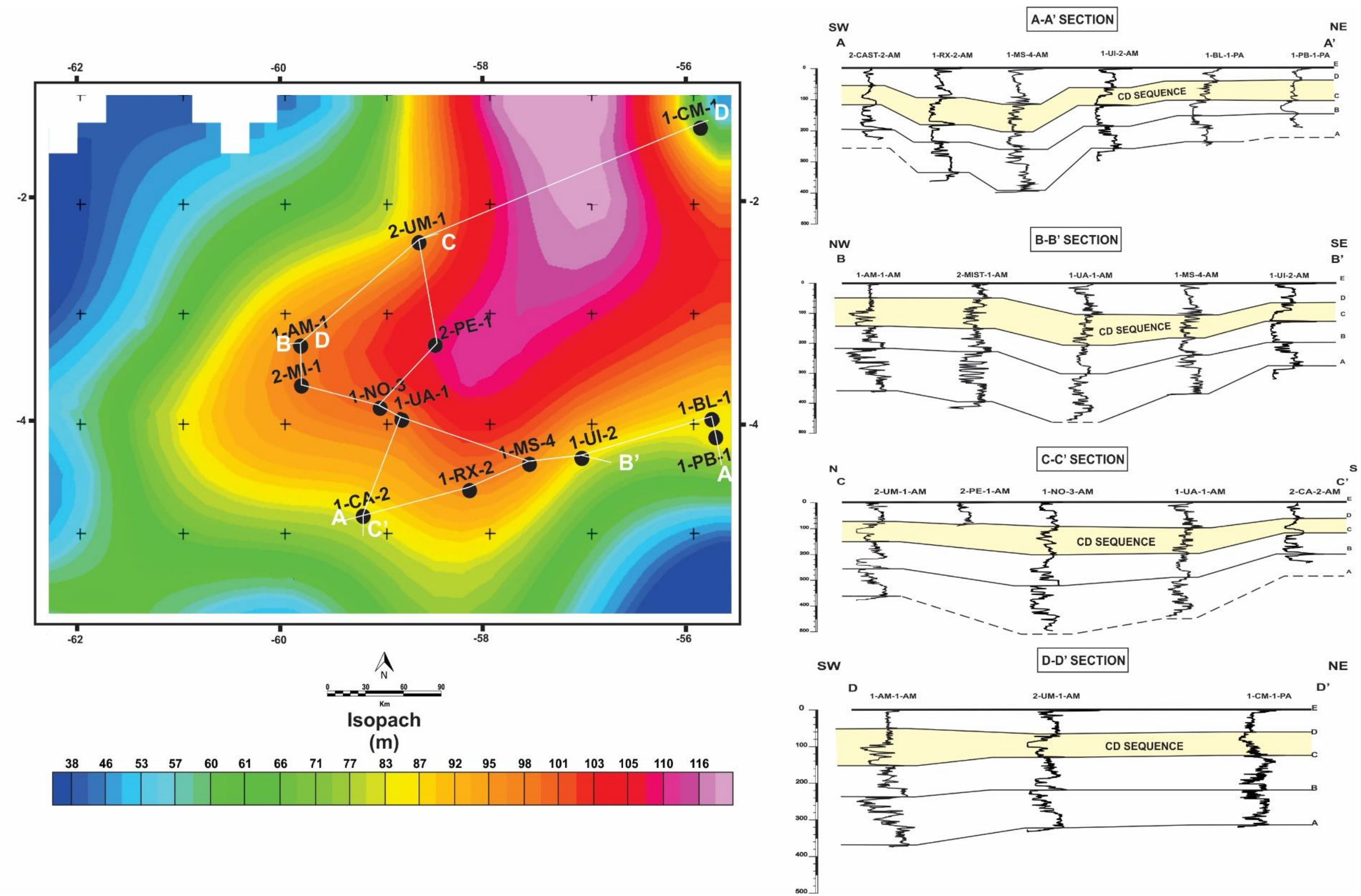

Fig. 8. Isopach map of CD Sequence.

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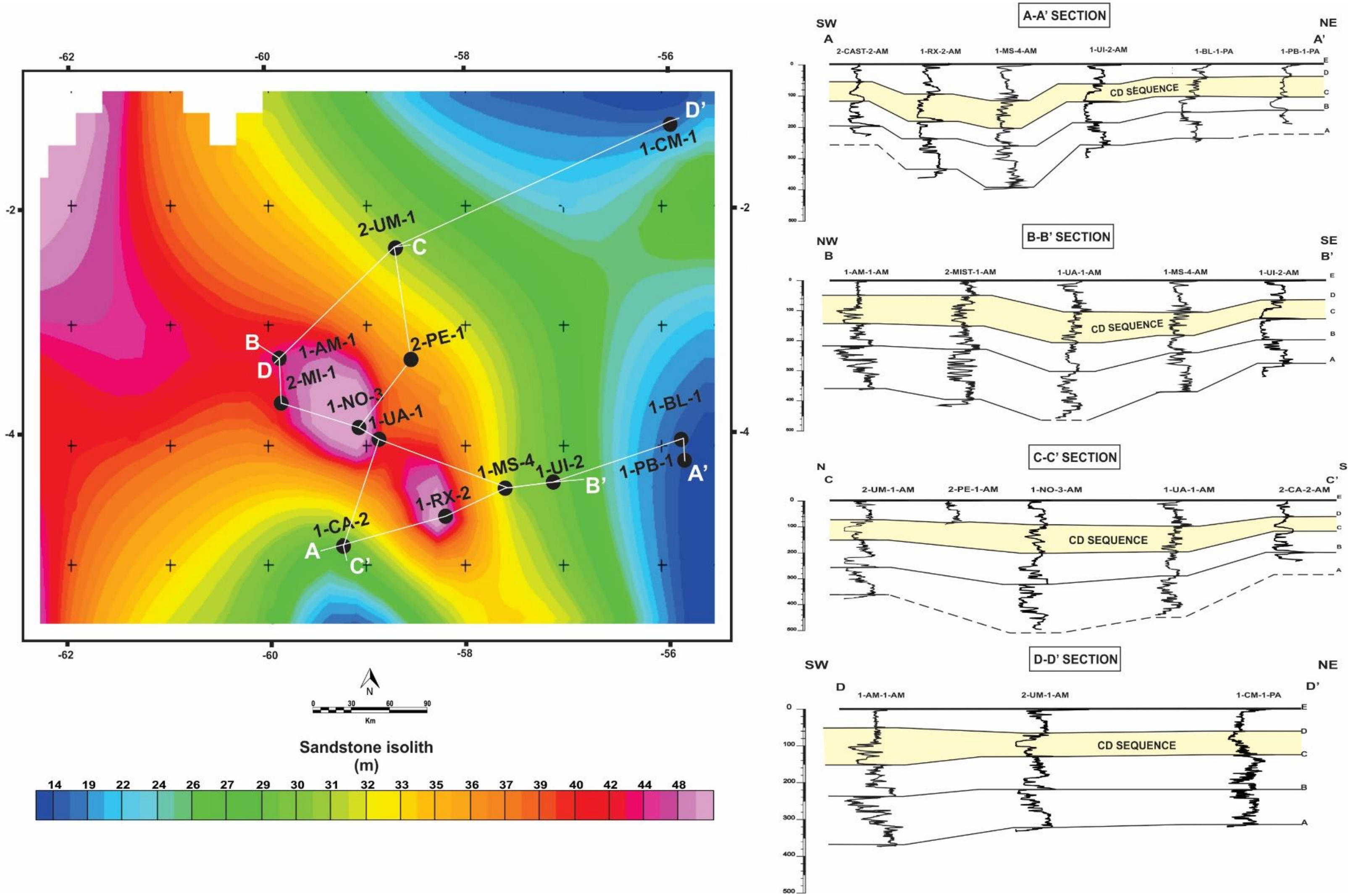

Fig. 9. Sand isolith map of CD Sequence.

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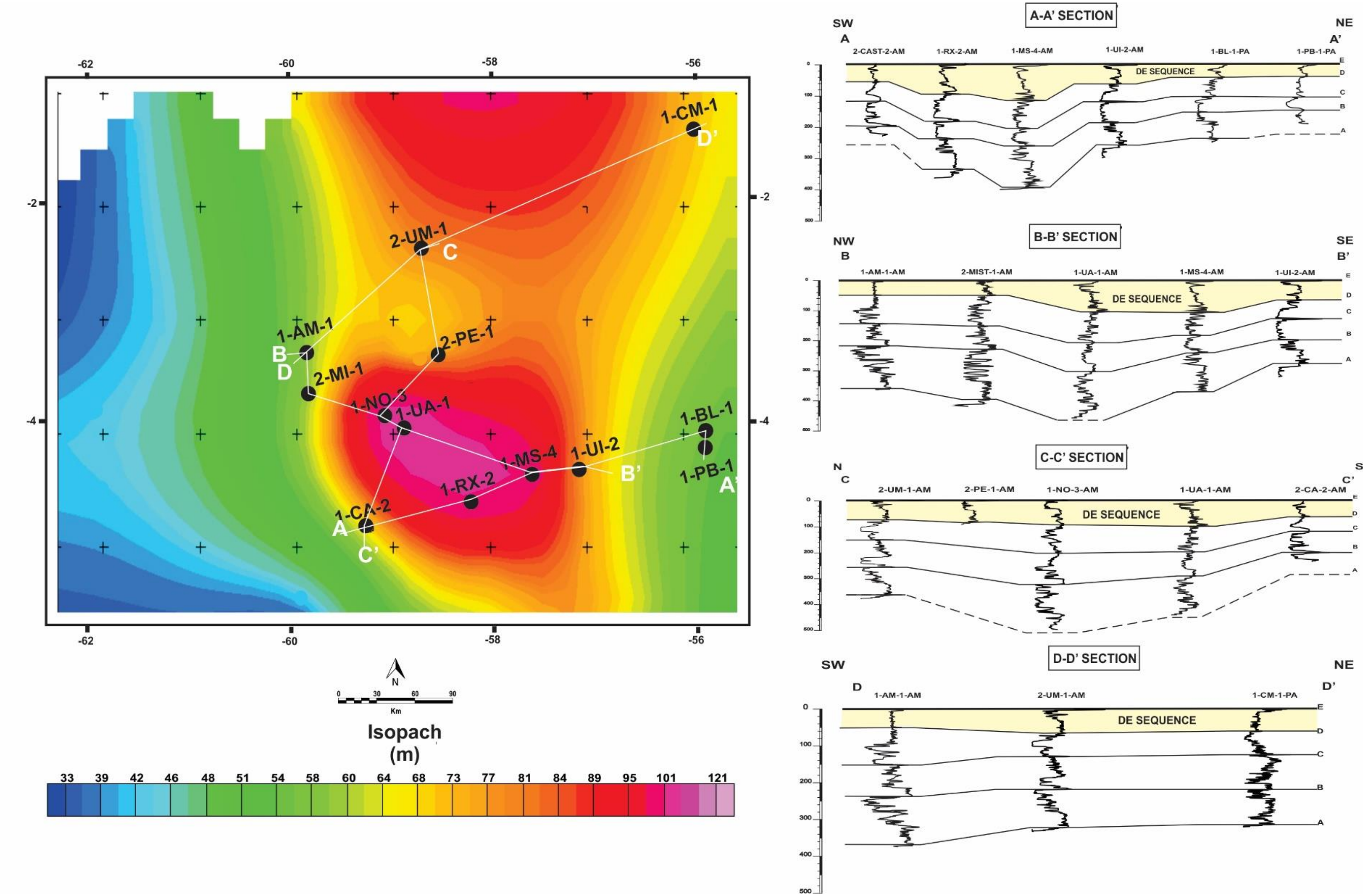

Fig. 10. Isopach map of DE Sequence.

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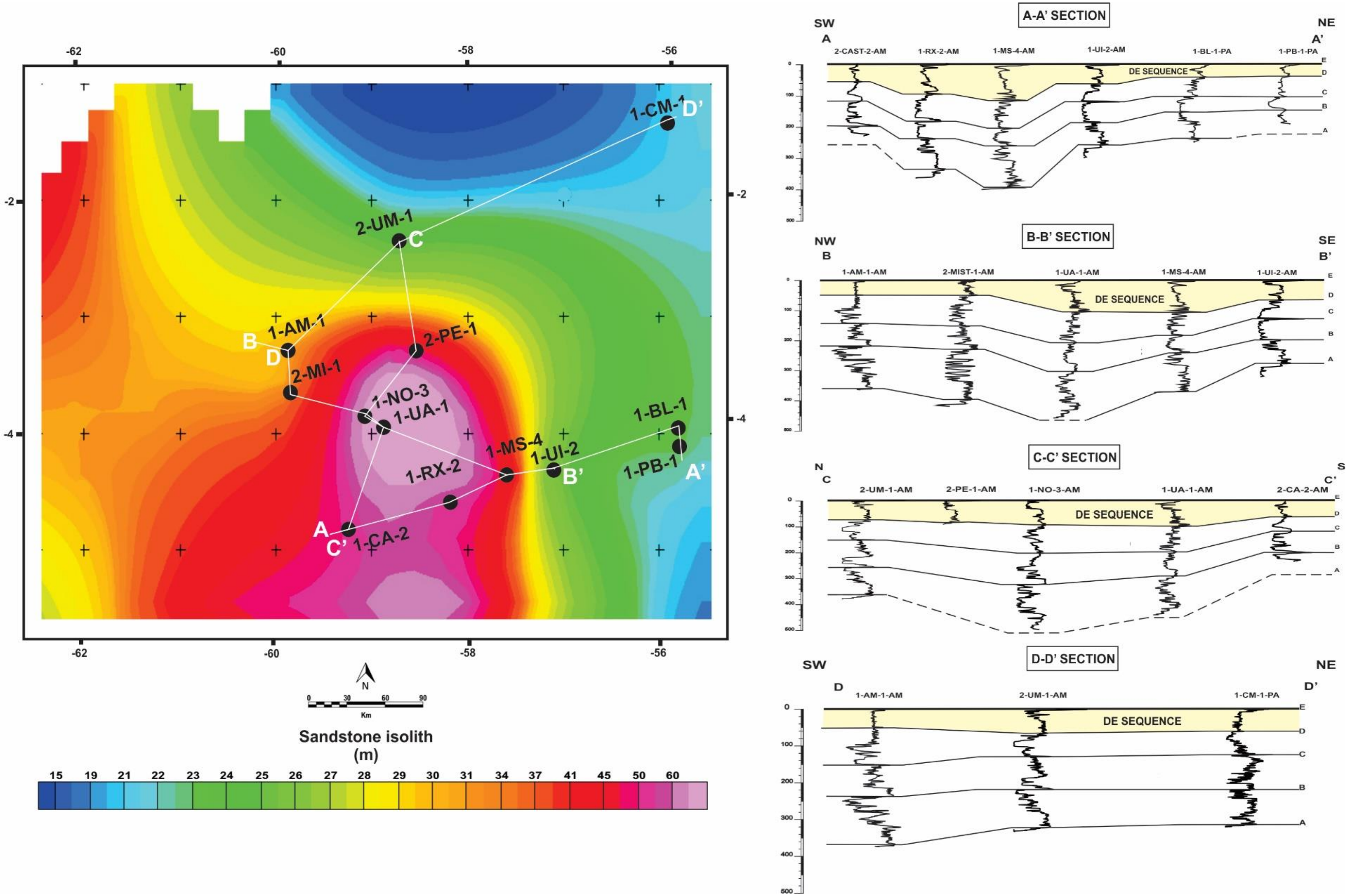

Fig. 11. Sand isolith map of DE Sequence.

The key surfaces that limit the studied time interval (MFS-A and MFS-E) are representative of two most important anoxic events recorded in the Brazilian Paleozoic sedimentary basins (Rodrigues et al., 1995). These surfaces correspond respectively to the MFS events of the Silurian and Devonian and show an excellent chronostratigraphic correlation with the anoxic events of the Paleozoic sedimentary basins of North Africa, Russia, and North America. Its economic importance is related to the fact that approximately 17% of the oil reserves in the world are associated to hydrocarbon generation in Silurian and Devonian sedimentary sequences (Klemme and Ulmishek, 1991). In the Amazon Basin, the time span between these two events extends from the Llandoverian to the Middle Famennian, with a maximum duration of about 70 million years, according to biostratigraphic studies of Melo and Loboziak (2003) and Grahn (2005). Considering the time involved in the sedimentary cycle proposed by Cunha (2005), the total studied interval represents a third-order sequence, while AB, BC, CD and DE sequences are characterized as fourth-order sequences.

6. Conclusion

The methodology based on the concepts of genetic stratigraphic sequence was efficient in the identification of sedimentary cycles in intracratonic marine basins. The use of gamma ray well logs allowed the definition of four fourth-order sequences (AB, BC, CD and DE), bounded by MFS. In general, these sequences are formed by the HST and TST, which are representative of regressive (progradational) and transgressive (retrogradation) events in the basin, respectively.

As a result of the integration of geological sections and stratigraphic maps it was possible to propose two main sand source areas for the basin: one located to the west and other to the south of the studied area. The sand isolith maps also allowed inferring that the Paleozoic transgressions followed a general orientation from northeast to southwest.

Acknowledgment

The authors thank the *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis-ANP* (Brazilian National Agency of Petroleum, Natural Gas and Biofuels), through the *Banco de Dados de Exploração e Produção-BDEP* (Exploration and Production Database), for providing exploratory data of the studied wells.

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