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Sequence stratigraphy and sedimentology of the late Triassic TAG-I (Blocks 401/402, Berkine Basin, Algeria)

P. Turner[a,*], D. Pilling[b], D. Walker[b], J. Exton[c], J. Binnie[c], N. Sabaou[a]

[a]*School of Earth Sciences, The University of Birmingham, Birmingham B15 2TT, UK*
[b]*PM Geos, 24 Market Street, Aberdeen AB11 5PH, UK*
[c]*BHP Petroleum, Neathouse Place, Victoria, London SW1V 1LH, UK*

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Abstract

The Berkine Basin is an intra- or pericratonic basin that developed during the Middle to Late Triassic on the margin of the Saharan platform. The basin lies to the east of the north–south trending Hassi Messaoud Ridge which separates it from the Oued Mya Basin to the west. These Algerian basins lie to the south and east of the network of rift basins that developed in the Iberian peninsular and along the margins of the North Atlantic seaboard.

The principal hydrocarbon reservoir is the Upper Triassic Argilo-Gréseux Inférieur (TAG-I) which, in Blocks 401a and 402a, is Carnian to Norian in age. Elsewhere in North Africa, especially to the south and east, there are older Triassic formations. For example, in Zarzaitine in the extreme south east of the Triassic Algerian outcrop, Anisian vertebrates are documented.

The TAG-I sits unconformably on Palaeozoic basement rocks and with the basal Lower Carbonate comprises a laterally and vertically variable sequence which has been sub-divided into four depositional sequences: Sequence 1, an unconformity-bounded, ephemeral fluvial interval that fills palaeorelief on the Hercynian unconformity; Sequence 2, an initially upward-fining, and subsequently upward-coarsening package of perennial fluvial sandstones and floodbasin shales with thin crevasse splay elements and interfluve palaeosols; Sequence 3, an erosively based, fluvio-lacustrine section characterised by fluvial sandstones with associated crevasse sandstones and floodbasin/lacustrine shales. This sequence is the main hydrocarbon reservoir section and is divided into two main packages 3A and 3B; the base of 3B is distinguished by basin-wide fluvial incision and the widespread channel sand deposition; Sequence 4 (Lower Carbonate) is a coastal plain and shallow marine system comprising shales, sabkha-type evaporites and bay-fill sandstones.

The four depositional sequences reflect differences in depositional style resulting from base level shifts, tectonics and climate throughout TAG-I times. The overall increase in relative sea level was interrupted by periods of incision, which may relate to periods of rifting and erosion of the rift shoulders of the Berkine Basin. The initial valley fill (Sequence 1) was deposited under relatively arid or semi-arid conditions. During Sequences 2 and 3A, perennial fluvial systems with anastomosed channels and floodplain lakes became dominant and the climate increasingly humid. At this time a major longitudinal drainage, divide developed due to intrabasinal rifting. The basin was ultimately flooded by the transgressive systems tract of Sequence 4. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: TAG-I; Algeria; Berkine; Triassic

This paper presents the results of a regional study of the Triassic Argilo-Gréseux Inférieur (TAG-I) and basal Trias Argilo-Carbonaté of the Berkine Basin, eastern Algeria. The stratigraphy of the TAG-I is further refined and the stratigraphical evolution of the Berkine basin discussed. We present for the first time a rigorous classification of the TAG-I in sequence stratigraphic terms and clearly define the boundary with the overlying Trias Argilo-Carbonaté. The results are presented in a series of correlation diagrams based on core and wireline log data along with palaeogeographical maps which illustrate the evolving gross depositional environment (GDE), major facies belts, and their changing geometries throughout the basin evolution (Carnian to Norian).

1. Regional setting

The Berkine Basin is an intra- or pericratonic basin which developed during Middle–Late Triassic times on the northern margin of the Saharan platform (Busson, 1971a,b). It forms part of the autochthonous basin system

* Corresponding author. Tel.: +44-121-414-6139; fax: +44-121-414-4942.
E-mail address: p.turner@bham.ac.uk (P. Turner).

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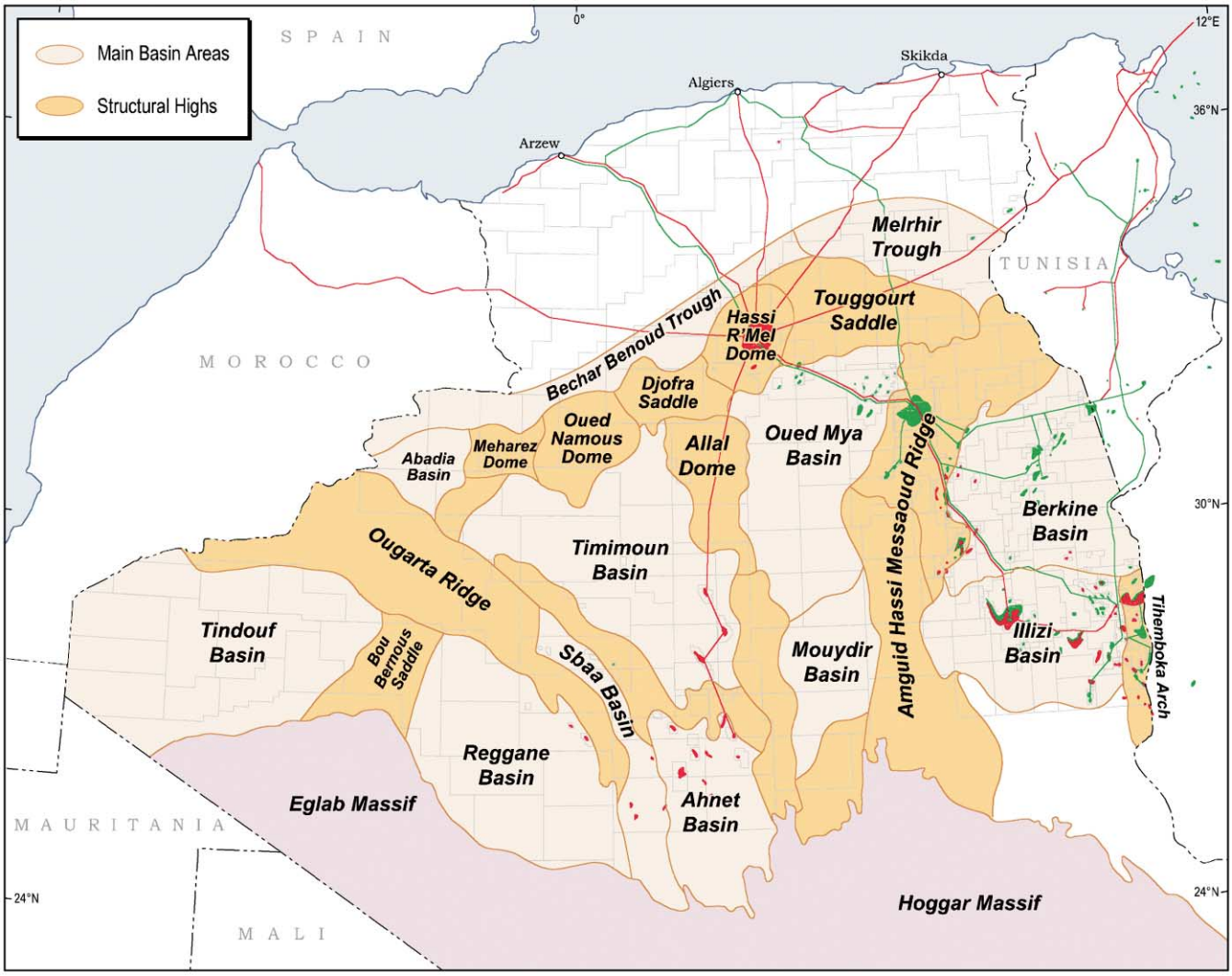


Fig. 1. Map showing the location of the Berkine Basin on the northern flank of the Saharan Platform, related structural highs and the main oil (green) and gas (red) fields of Algeria.

which is part of the network along the margin of the Atlantic and western Mediterranean borders formed as part of the synrift phase immediately prior to the Atlantic and Tethyan sea floor spreading (Fig. 1). It is bounded to the north by the Saharan flexure and the allochthonous units of the Saharan and Tellian Atlas Mountains (Guiraud, 1998). The Berkine Basin lies to the east of the Hassi Messaoud Ridge (HMR) a N–S fracture zone extending between Hassi Messouad and El Biod (Aït Salem, Bourquin, Courel, Fekirine, Hellal, Mami et al., 1998) and to the north of the Illizi basin which lies south of the Saharan Front. The area of investigation is in the order of 400 000 km^2, mainly within the Algerian sector of the Berkine Basin with some additional Tunisian data (Fig. 2). The dataset comprises wireline logs, constrained by recent cores from the ROD, BSF and SFNE Fields (Block 401a/402a), and supplemented by additional core data from other areas including the El Borma field. In total, 62 wells have been evaluated at the TAG-I and basal Trias Argilo-Carbonaté levels within the constraints of the core-based lithostratigraphy.

The structure of the Triassic basins is largely controlled by reactivation of NE–SW, NW–SE, Panafrican and late Palaeozoic basement lineaments (Nedjari, 1994). The Middle Cretaceous extensional reactivation of the NW–SE cross-cutting faults play a key role in the formation of a number of giant TAG-I reservoir oil fields (Pink, Carney, Drumheller, & Okbi, 1999). Late Cretaceous/early Tertiary compressional inversion accounts for a number of other fields including RDB/RSR/RERN and El Borma. A key question concerns the extent of Triassic extension in the Berkine Basin. Although seismic sections indicate that Triassic intrabasinal faults are rare or absent, the presence of syndepositional volcanics to the east and west of the HMR shows that contemporaneous rifting was active in this area.

The Zarzaitine outcrops which are situated at the extreme

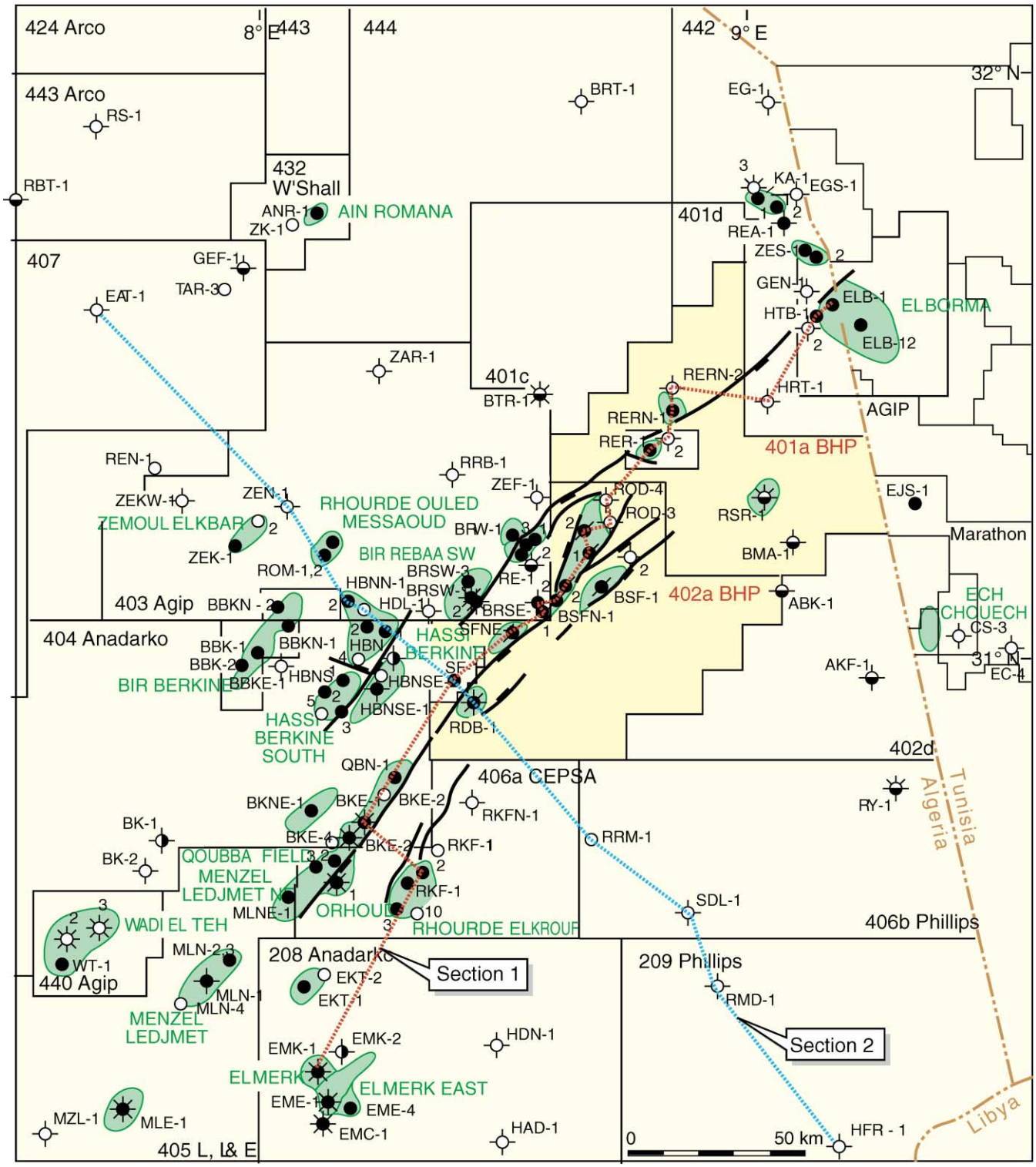


Fig. 2. Berkine Basin hydrocarbon accumulations, regional correlation lines and well locations used in the study. The lines indicated as Sections 1 and 2 are shown in Figs. 9 and 10 respectively.

south of the Illizi basin provide, along with the Kirchaou Sandstone of Tunisia, the nearest surface outcrops of the TAG-I and its equivalents. Here the Triassic overlies a sequence of Carboniferous shales (Stephanian-Autunian, Tigentourine Red Shales) and is exposed in a 150 km E–W cliff. The thickness increases from the Tinhert Hamada (subsurface) in the north towards the outcrops to the south and decreases from the east of the cliff section towards its western part. The overall succession comprises The Lower Zarzaitine (Zarzaitine Inférieur) of supposed Upper Triassic

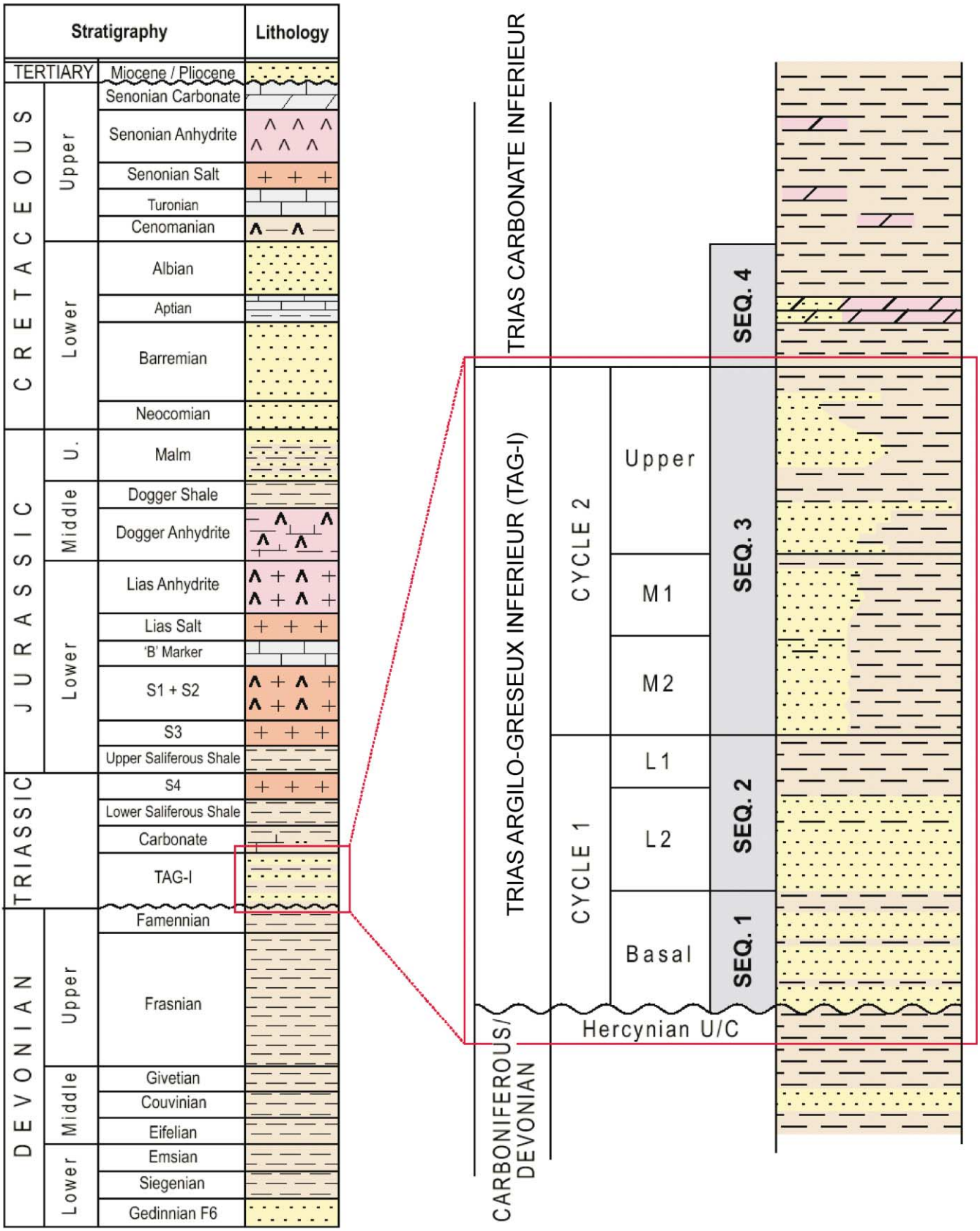


Fig. 3. Generalised stratigraphy of the Berkine Basin and the different units which make up the TAG-I. Previous terminology, and that used by other authors (Cycle 1 and L1, M1 etc., is shown for comparison.

and the Upper Zarzaitine (Zarzaitine Supérieur) of probable Liassic age (Eschard, Desaubliaux, Bekkouche, & Hamel, 1999; Lapparent, de Claracq, & Nougarade, 1958; Lehman, 1957, 1971)).

The maximum thickness of the Triassic is about 150 m. Jalil (1999) confirmed the presence of Middle Triassic (Anisian–Ladinian) dinosaur remains within the basal sandstones and divided the Zarzaitine Triassic into two units: Middle Triassic (50 m) and Upper Triassic (110 m).

The Middle Triassic Unit (maximum thickness: 50 m) directly overlies the carboniferous Tigentourine Shales although there is no marked angular unconformity. It is consists of two members, Member 1 is separated from Member 2 by a relatively mature palaeosol. The Zarzaïtine outcrops have yielded a rich vertebrate fauna of early Anisian age (Capitosaurids, Trematosaurids and Brachyopoids) and a younger Carnian to early Norian assemblage with *Aetosaurus* and *Phytosaurus* (Jalil, 1999; Jalil, Lucas, & Hunt, 1995). It is this upper sequence, which is time-equivalent the bulk of the TAG-I in the Berkine Basin.

These sandstones are known as 'Grès à Stégocephales' (Jalil, 1999). The sandstones are fine to coarse-grained, well to poorly-sorted, friable and occasionally pebbly. Planar and trough cross-bedding are common in upwards-fining sequences with northerly flowing palaeocurrents. The lower sandstone is interpreted as braided fluvial channel deposits but fish remains (*Ceratodus* and *Hybodus*) are observed suggesting a possible marine influence (Busson, 1971a; Busson & Comee, 1989.

This Member is separated from the overlying Upper Triassic sandstone by a supermature palaeosol which marks a regional disconformity. The Upper Triassic Unit (maximum thickness: 110 m) overlies the supermature palaeosol along an erosive contact. The sandstone series are subdivided into the middle and upper sandstone member and are separated by a thick red/green floodplain shales and immature palaeosols. These sandstones differ from the lower sandstone member, as they are consolidated, more coarse-grained, thick-bedded and constitute the main part of the cliff. Planar and trough cross-bedding, overturned bedding and ripple cross-laminations are common as well as roots; rootlets and allochthonous silicified tree trunks. Several erosive surfaces are observed within these members which are characterised by large intraformational mudclasts up to 12 cm in diameter. These upper sandstones were deposited in a braided fluvial depositional environment Within the upper part of the series and just below the Liassic lagoonal silty dolomite, another mature palaeosols is present, characterised by a root network indicative of mangrove-like environmental conditions.

2. Stratigraphic framework

The lithostratigraphy of the Triassic is complicated and in the past a variety of different classification systems have been used. More recently Aït Salem et al. (1998) recognised seven stratigraphic cycles (I–VII) between the Hercynian unconformity and the base of Jurassic in the area. A summary of the nomenclature and stratigraphy used by us in the Berkine Basin is shown in Fig. 3. In general, the TAG-I comprises two megasequences, which are bounded by unconformities or their conformable equivalents. These megasequences correspond to the Anisian–Ladinian and Carnian–Norian time intervals. These are exposed in the southern Algerian sections around Zarzaitine and in south-western Tunisia around Tataouine.

3. Depositional framework

3.1. Description

The TAG-I of the Berkine Basin is represented by a wide range of sedimentary facies. A total of 23 lithofacies

Table 1
Lithofacies

Conglomerates	
1	Intraformational conglomerate
2	Extraformational conglomerate
Sandstones	
3	Very poorly sorted, medium-coarse grained, kaolinitic sandstones
4	Upward-fining, buff/purple mottled, fine–coarse sandstones with planar tabular and trough cross stratification and extraformational clasts
5	White-buff fine-medium sandstones with scattered intraclasts and massive bedding or feint parallel lamination but no primary current lineation
6	Micaceous, green/buff carbonaceous fine sandstones with primary current lineation
7	Upward-fining, buff, cross-stratified fine sandstones with intraclasts and includes inclined heterolithic cross-stratification
8	Green/buff, fine grained, cross-stratified sandstones with green clay drapes on foreset laminae
9	Thick ripple cross-laminated fine sandstones
10	Thin-thickly flaser bedded very fine-fine sandstones
11	Thickly interbedded, fine sandstones and black siltstones in upward-fining and upward-coarsening elements
Mudrocks	
12	Grey and grey-green silty claystones sometimes with mm-scale pinstripe lamination
13	Thin(<5 cm), black to green and grey-green claystone
14	Black–green carbonaceous shales
15	Red, purplish-red and green homogeneous silty mudstones
16	As 15 but with glaebular calcrete or dolocrete
17	Sideritic palaeosols
18	Red, green, purple vertisols with listric surfaces
Marine carbonates and evaporates	
19	Thin, phosphatic bone beds
20	Brown, sulphurous and pyritic bioturbated fine sandstones
21	Algal laminites
22	Dolomite
23	Bedded and nodular anhydrite

Table 2
Facies associations

F	Fluvial channel
F1	Primary anastomosed channels
F2	Lenticular (ribbon) channel sandbodies
F3	Sheet-like channels sandstones
F4	Channel plug (avulsion) deposits
S	Splay deposits
S1	Proximal crevasse splay (upwards-coarsening)
S2	Distal sheet-like splay deposits
P	Palaeosols and floodplain
P1	Immature and unmodified floodplain
P2	Mature palaeosols
L	Lacustrine
L1	Lacustrine basin shales
L2	Lacustrine delta fill
M	Transgressive systems tract

(Table 1) and five main facies associations (Table 2) have been interpreted based on core descriptions of the wells used in this study. The main facies associations are fluvial channel sandstones, floodplain silts and palaeosols, crevasse splay deposits, lacustrine sediments and shallow marine transgressive deposits.

The fluvial channel deposits are erosively-based, commonly with intraformational conglomerate lags of green siltstone clasts and wood fragments. The sandstones are almost exclusively fine to medium grained and well sorted (Fig. 7A). Bedforms include plane bedding, small scale ($<$25 cm) planar tabular and trough cross-stratification and ripple lamination. Some of the larger scale cross-sets, particularly in the El Borma area have foreset drapes of thin green mudstone suggesting the possibility of some tidal influence in the channels. Similar deposits have been observed in the upper part of the middle sandstone member of the Zarzaitine outcrops suggesting the possibility of an easterly opening to Tethys. In all the cores examined by us, there has been no evidence of aeolian strata. The plane bedded units are frequently rich in micaceous or carbonaceous material and sometimes show primary current lineation. In some cases transitions from clean, massive medium grained to plane bedded micaceous sands are observed suggesting that the plane bedded sands may be the deposits of falling flood stage conditions (Fig. 7B).

The thickness variation of the fluvial channels is a particular feature of the TAG-I and sandbodies range from $<$2 to 30 m. The thicker sandbodies normally comprise at least four or five stacked individual channel deposits. In SFNE-2 (Fig. 4) a major stacked channel complex is made up of five erosively-based units. This channel complex spans the whole of Sequence 3a and 3b and when traced SW and NE passes laterally into thinner channels (e.g. BRSE-2, ROD-2) separated by floodplain deposits with palaeosols. Well-to-well correlation shows that these channel sandstone have a ribbon-like geometry; internally they are variable, some are cross-stratified intraclast-rich horizons (e.g. BRSE-2); others are clean with dominantly plane bedding (e.g. ROD-1, Fig. 5). Other sandbodies, particularly those in Sequence 3b (e.g. ROD-4) are clearly lenticular or highly sinuous in geometry since they cannot be identified in adjacent wells. A common feature of the TAG-I is the presence of erosively-based, intraclastic horizons with clay or sand plugs which are interpreted as basal channel lags of abandoned channels (e.g. the conglomeratic unit between 2950 and 2955 m in SFNE-1, Fig. 4).

Splay deposits comprising upwards-coarsening siltstones and sandstones are also prominent within the TAG-I. These include ripple-laminated and cross-stratified fine sandstones interbedded with floodplain and lacustrine deposits (cf. Smith & Pérez-Arlucea, 1994). The lacustrine units include two distinct facies: finely laminated shales, often rich in well-preserved plant fragments and ripple laminated or flaser-bedded coarse siltstones and sandstones. A significant lacustrine development is present within the BSFN area (Fig. 6) with ripple-laminated very fine and fine-grained sandstones interbedded with thin claystones displaying abundant soft sediment deformation structures. The splay sandstones are sometimes laterally extensive. Some of the key lithofacies in the TAG-I are illustrated in Fig. 7.

A variety of palaeosols are present in the TAG-I sequence which can be classified into two broad facies groups, namely P1 (immature palaeosols) and P2 (mature palaeosols). The immature palaeosols (P1) are present in all the sequences, are characteristic of channel-proximal settings and may be developed on floodplain sediments or on channel sandstones. The pedogenic horizons are typically not well developed and in some cases, sedimentary structures are preserved indicating rapid deposition with relatively little time for pedogenesis. As a result, the P1 palaeosols are weakly developed. They include (1a) *Red/Brown palaeosols* showing abundant listric surfaces and green mottles that may represent the original colour of the sediments. Rhizoconcretions and sphaerosiderites are common. These palaeosols are associated with floodplain settings and formed under oxidising conditions; (1b) *Green/Grey palaeosols* are similar to (1a) but contain burrows and more abundant rhizoconcretions. This facies is associated with more proximal floodplain and avulsion/crevasse splay facies. Pyrite, red mottles and calcareous nodules are common. They occur in highly reducing settings and are considered as a waterlogged or gleyed soils (hydromorphic); (1c) *Yellowish/Orange palaeosols* occur within Sequence 4 (Well SFNE-1). They are rare and thin (1–6 cm), overlie an estuarine facies and represent a short lived events of subaerial exposure within a coastal plain setting.

Mature palaeosols (P2) occur in the upper parts of Sequence 2 and 3 (see Fig. 7G). These palaeosols are characterised by their purple or very dusky brown colour, iron oxide nodules, root hairs, and breccia-like fabric (interpreted as peds). Three kinds of palaeosols are present: (2a) *Blackish-red palaeosols* occur only in mid-Sequence 3 in ROD-2. The colour is very dusky, and comprises coarse angular blocky peds (3 cm max) and cutans. Roots are rare;

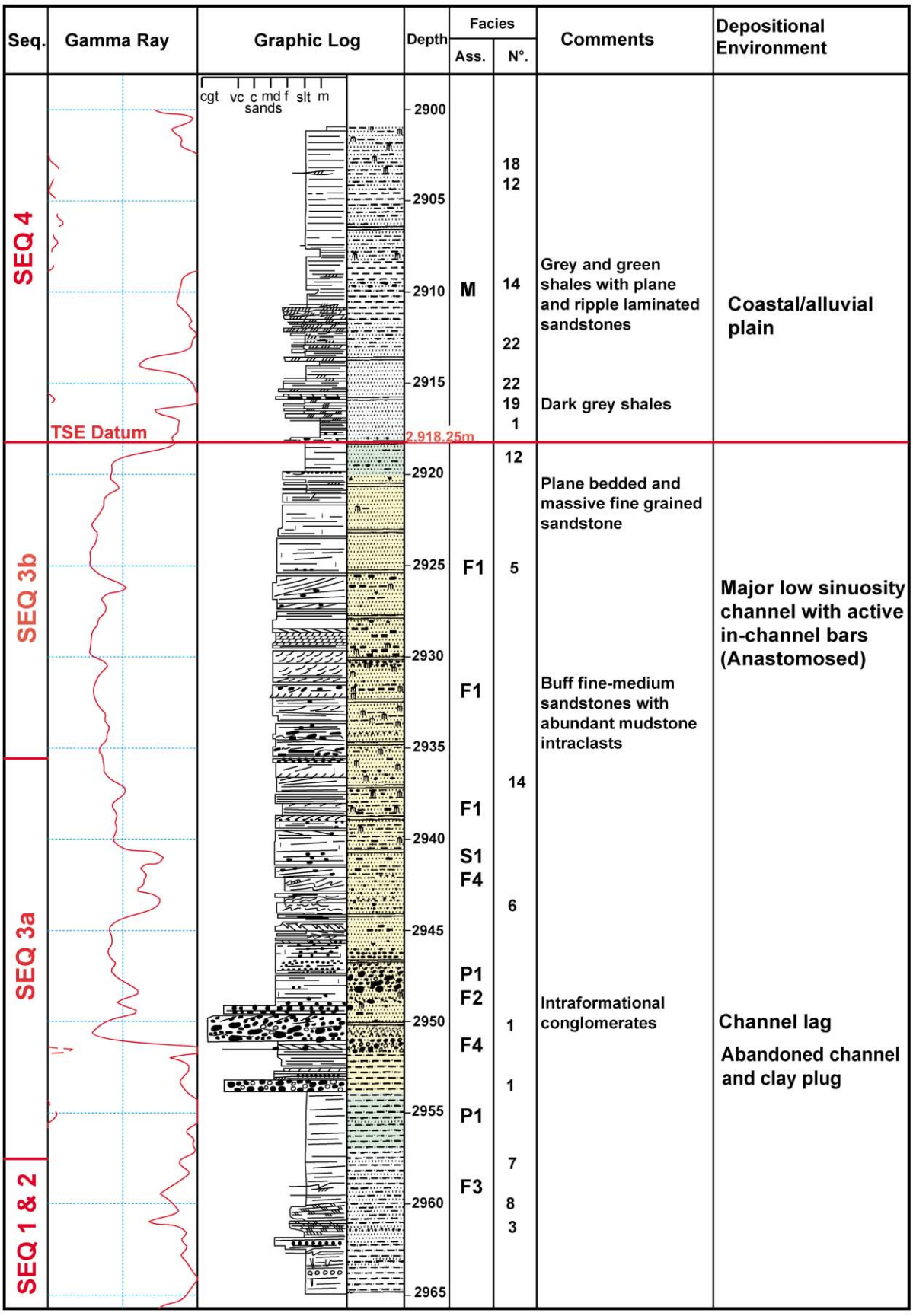


Fig. 4. Sedimentological profile of Well SFNE-1. The details of lithofacies codes and associations are shown in Tables 1 and 2.

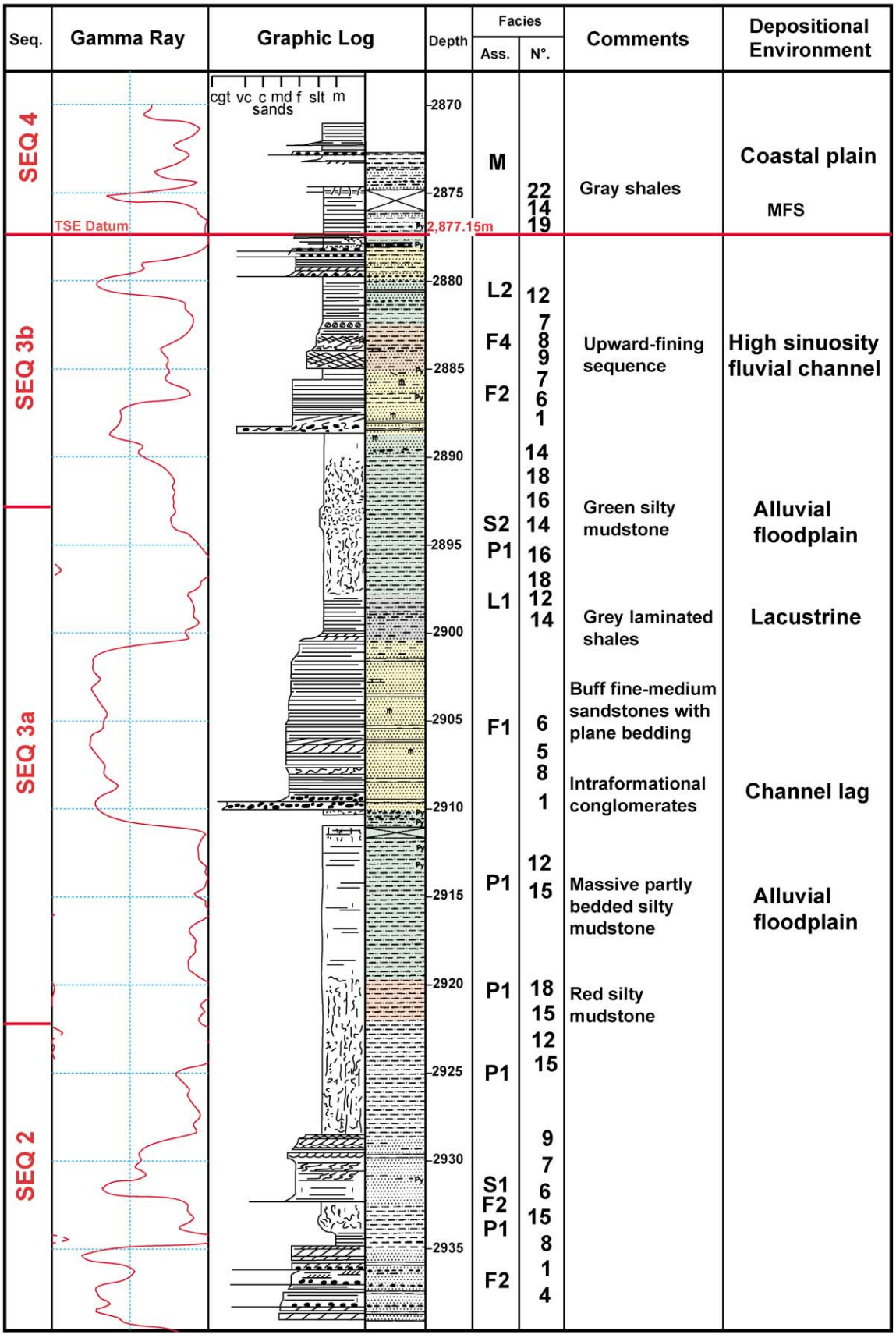


Fig. 5. Sedimentological profile of Well ROD-1. The details of lithofacies codes and associations are shown in Tables 1 and 2.

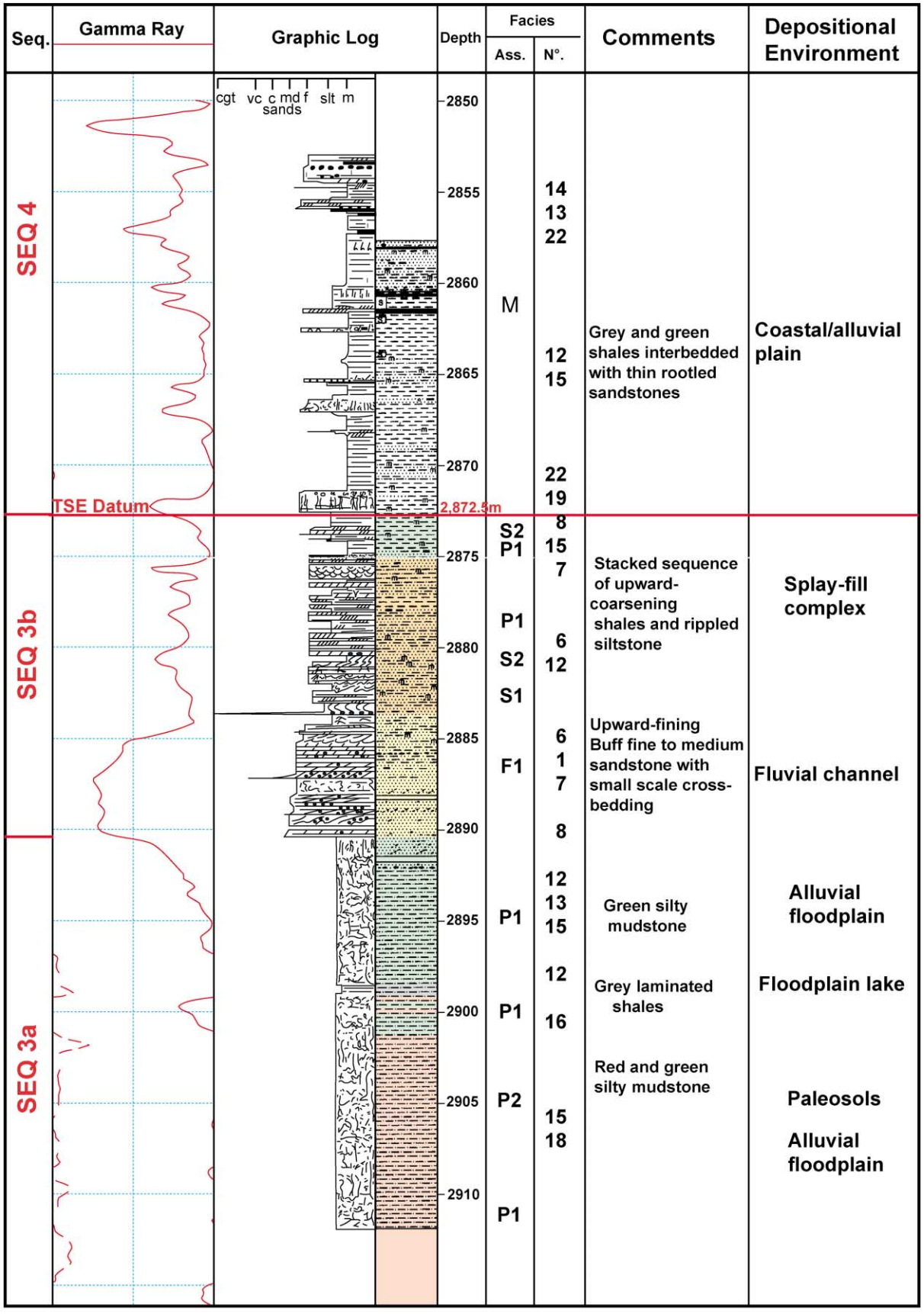
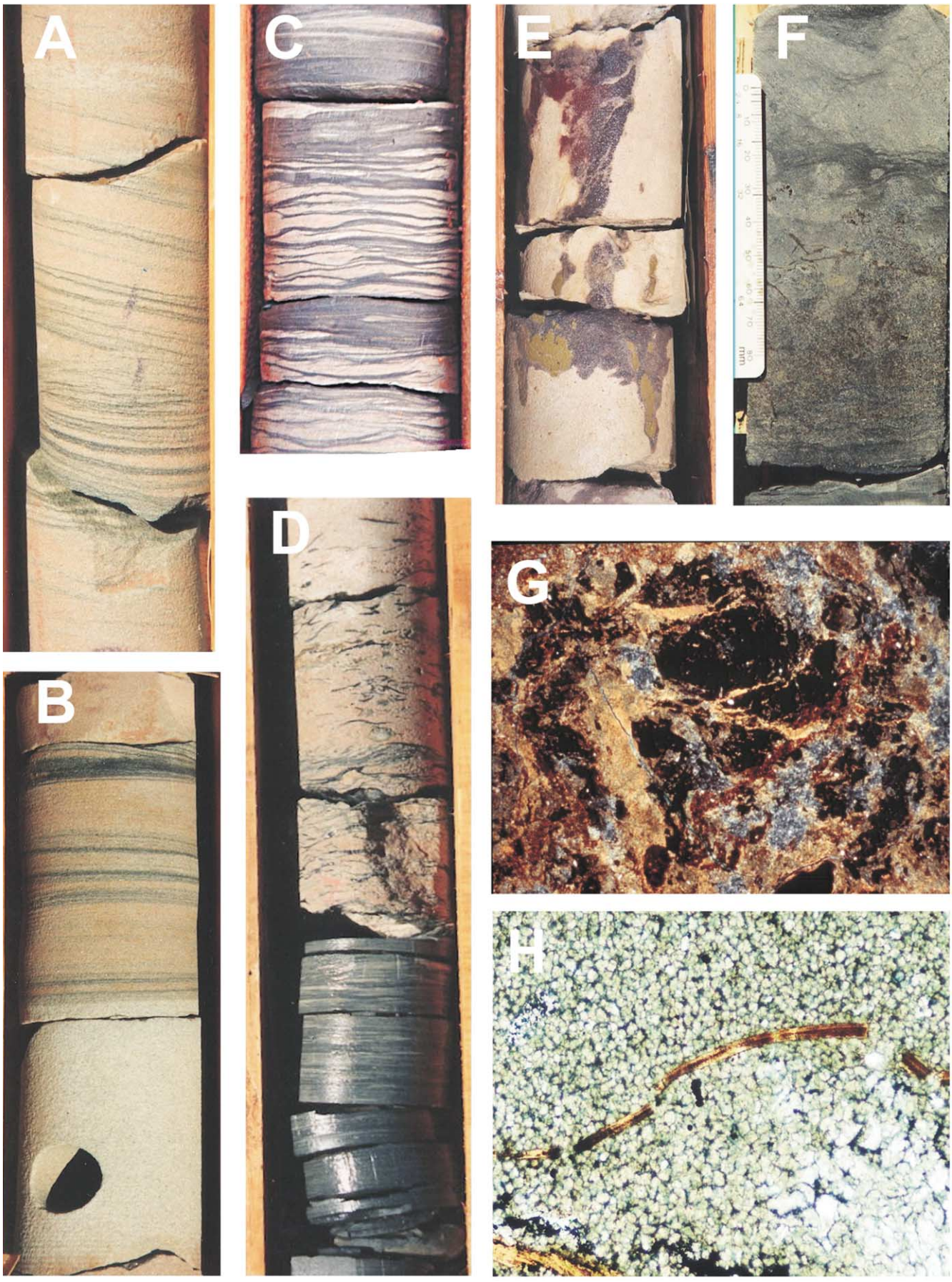


Fig. 6. Sedimentological profile of Well BSFN-2. The details of lithofacies codes and associations are shown in Tables 1 and 2.


A
B
C
D
E
F
G
H

(2b) *Very dusky red–purple palaeosols* only in mid-Sequence 3 of well BSF-2. No roots or peds are observed; (2c) *Purple palaeosols* are the most important mature palaeosols, they are very extensive and can be used for inter-well correlation. In rare cases the thickness can reach 7 m, but the average thickness ranges between 1 and 2 m. In some case, the thickness of the palaeosol has been reduced by subsequent erosion. These palaeosols are characterised by coarse, angular blocky peds (3 cm max) with listric surfaces, which are coincident with blocky fractures. The blocky peds are surrounded by a reticulate pattern of reddish/brown veins (cutans) and are interpreted as ferrans or ferri-argillans. Rhizoconcretions, sphaerosiderites and very small green mottles are common.

Mature palaeosols of this type are best developed in areas some distance from major fluvial channels (e.g. ROD-3); here the whole of Sequence 3 is made up of a 25 m + thick sections of pedogenically-modified floodplain sediments. The distribution of mature and immature palaeosols in the TAG-I provides a clear indication of the proximity of channel sand bodies as observed in similar sequences (Kraus, 1987, 1999; Kraus & Bown, 1988).

3.2. Interpretation

The fluvial deposits in the TAG-I vary in style, both temporally and spatially. A number of factors including climate, relative sea level and autocyclic changes are considered to have influenced the depositional architecture (Aslan & Blum, 1999; Blum, 1990, 1993; Blum & Price, 1998; Blum & Valastro, 1994; Blum, Toomey, & Valastro, 1994; Schumm, 1985). Initial deposits include braided rivers, particularly in Sequence 1. These formed under more arid-climate conditions and the fluvial channel deposits are relatively thinner and more ephemeral in character than older units within the formation. The thick channel sands in Sequences 2 and 3 are considered to be the deposits of anastomosing river channels (Nanson & Knighton, 1996; Smith, 1976, 1986. These anastomosed channels are recognised by the presence of stacked, erosively-based sands with plane bedding and small scale cross stratification.

Channel sinuosity of primary channels cannot be easily determined but was probably of low sinuosity. Lateral accretion units of the type associated with meandering river point bars appear to be rare. Well-to-well correlation indicates that these channel sandbodies are relatively continuous parallel to the dispersal direction (SW–NE) (Fig. 9) although in some areas e.g. SF, SFNE, RER there are thicker sandbody developments (up to 20 m+). These may represent the anabranches of major anastomosed complexes. Some of the more continuous sandbodies can be traced for distances of over 40 or 50 km along the sediment dispersal direction. In a cross-section of the basin, normal to the main sediment dispersal direction (NW–SE) the sandbody distribution is quite different (see Fig. 10). The main sand development lies along the SE flank of the basin in the RRM-SDL-RMD areas. Here Sequence 3 sand complexes 50 m+ in thickness are interpreted as the deposits of a braided channel system which lies to the east of an intrabasinal drainage divide parallel to the basin margins (see Fig. 11).

The base of Sequence 3 marks a major incision surface on which anastomosed channels were developed (SF1-SFNE-1, Fig. 10). In the upper part of Sequence 3, there is a marked increase in more isolated sandbodies consistent with the development of higher sinuosity channel systems.

In *floodplain-dominant* environments there are a variety of depositional facies including pedogenically-modified floodplains, lacustrine, lacustrine delta-fill and crevasse splay deposits. Floodplain facies are red or green (secondarily reduced) silty mudstones with evidence of rootletting and desiccation cracks. A characteristic feature of this facies are abundant listric surfaces indicating the widespread development of palaeosols. The co-existence of calcretes and sphaerosideritic palaeosols may testify to a seasonally humid climate during Sequence 2 and 3 times.

Lacustrine deposits comprise finely laminated dark-green to black, waxy shales with well preserved plant fossils and non-marine bivalves. The depth of these floodplain lakes is difficult to determine but their close juxtaposition with upwards-coarsening sandbodies with wave and current ripples indicates that there were areas with substantial lacustrine developments (e.g. around BSFN in the 401a/402a area, Fig. 6). Some of the thinner sandbodies are demonstrably more laterally extensive. These may correspond to secondary or tertiary channels of the anastomosed systems or could equally be major floodplain splay deposits similar to those described by Jorgensen and Fielding (1996).

The marine transgressive systems tract is marked by a surface of erosion overlain by comminuted phosphatic bone debris in a granular microdolomitic matrix (Fig. 7F and H). Above this are dark grey–green laminated waxy shales which correspond to hot shale markers on gamma

Fig. 7. Core photographs illustrating typical sedimentary features of the TAG-I. (A) Cross-stratified sandstones showing green micaceous siltstone drapes on foresets, ELB-20, 2429 m. (B) Cored section showing the transition from clean, massive into plane laminated micaceous/carbonaceous sandstone, ZESW-1, 2625 m. (C) Heterolithic wavy and ripple laminated silty mudstone of lacustrine origin from the lower part of an upwards-coarsening splay-fill sequence, ELB-17, 2447 m. (D) shows a typical erosive channel base in contact with black lacustrine shales. The basal lag conglomerate is rich in woody intraclasts, ELB-18, 2445 m. (F) Slabbed surfaces of the marine transgressive unit. This condensed horizon is a micro-dolomite with abundant phosphatic debris (see 7H). (E) Characteristic appearance of Sequence 1 sandstones. The dark purple and ochre mottling are rhizoconcretions in a mature palaeosol. These sandstones have a kaolinitic matrix, HTB-1, 2524 m. (G) Thin section of a mature palaeosol (P2). Note the well-formed peds and birefringent clay cutans. Width of view = 3.4 mm, BSF-1, 2966.1 m. (H) Thin section photomicrograph of the marine transgressive surface. There is a marked absence of terrigenous sediment and the unit is composed of microdolomite with abundant large vertebrate fragments (light brown colour, centre field. Width of field of view = 3.4 mm, BMA-1, 2490 m.

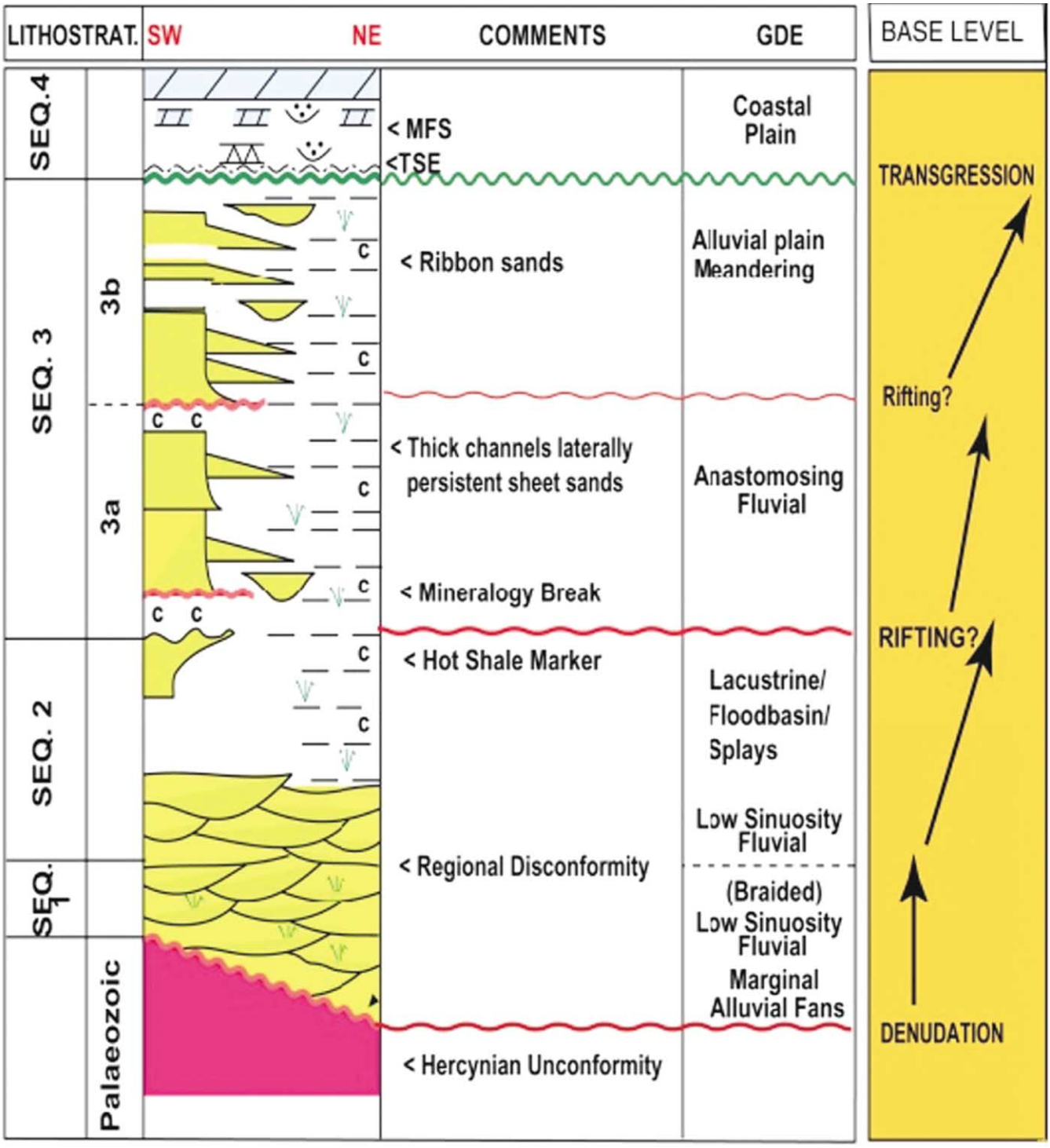


Fig. 8. Sequence stratigraphy of the TAG-I based on Blocks 401a and 402a.

ray logs. Overlying sediments include a variety of upwards coarsening ripple laminated siltstones and fine sandstones, sparse nodular and enterolithic anhydrites and thin bioturbated sandstones. This sequence is interpreted as the deposits of coastal embayments with supratidal sabkha development. This facies is capped by thin crystalline dolostones which can be correlated on a basin-wide scale.

4. Sequence stratigraphy and basin-filling

The TAG-I sequence is a response to changes in base level, climate and tectonic events during the late Triassic. Relative base level and climatic changes (Leeder, Harris, & Kirby, 1998) appear to be the main controls on fluvial form (Dalrymple, Boyd, & Zaitlin, 1994; Fielding, 1999)

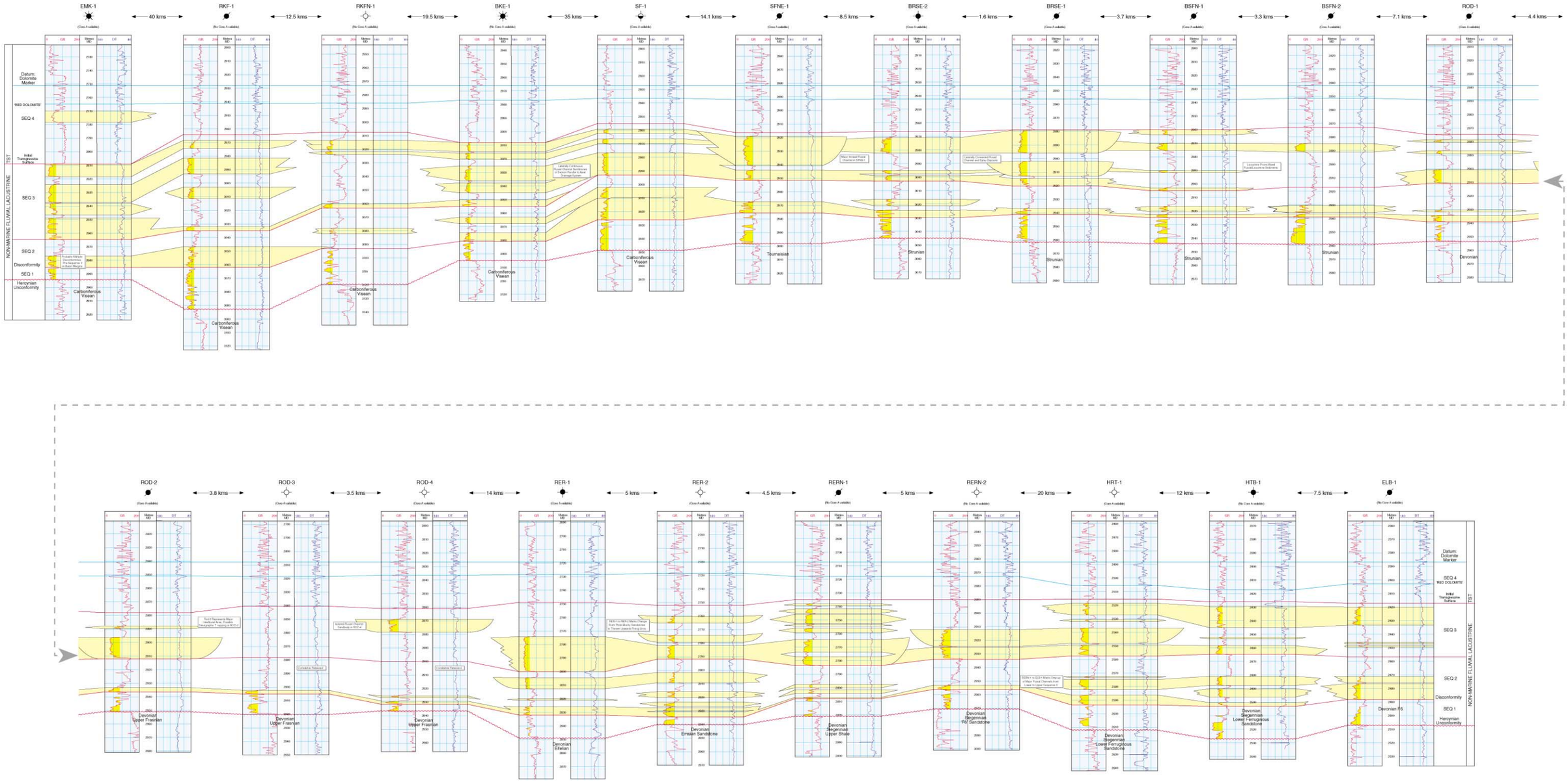


Fig. 9. Detailed correlation of the TAG-I parallel to the regional palaeoslope of the Berkine Basin (SW–NE) (see Fig. 2- Section 1 for well locations). This section from El-Maerk in the SW (EMK-1) to El Borma in the NE (ELB-1) (260 km) shows the relatively constant thickness of Sequences 2 and 3. The scarcity of fluvial sand bodies in the ROD-3, 4 and BSFN-2 area is due to the major development of lacustrine and floodplain conditions in this area.

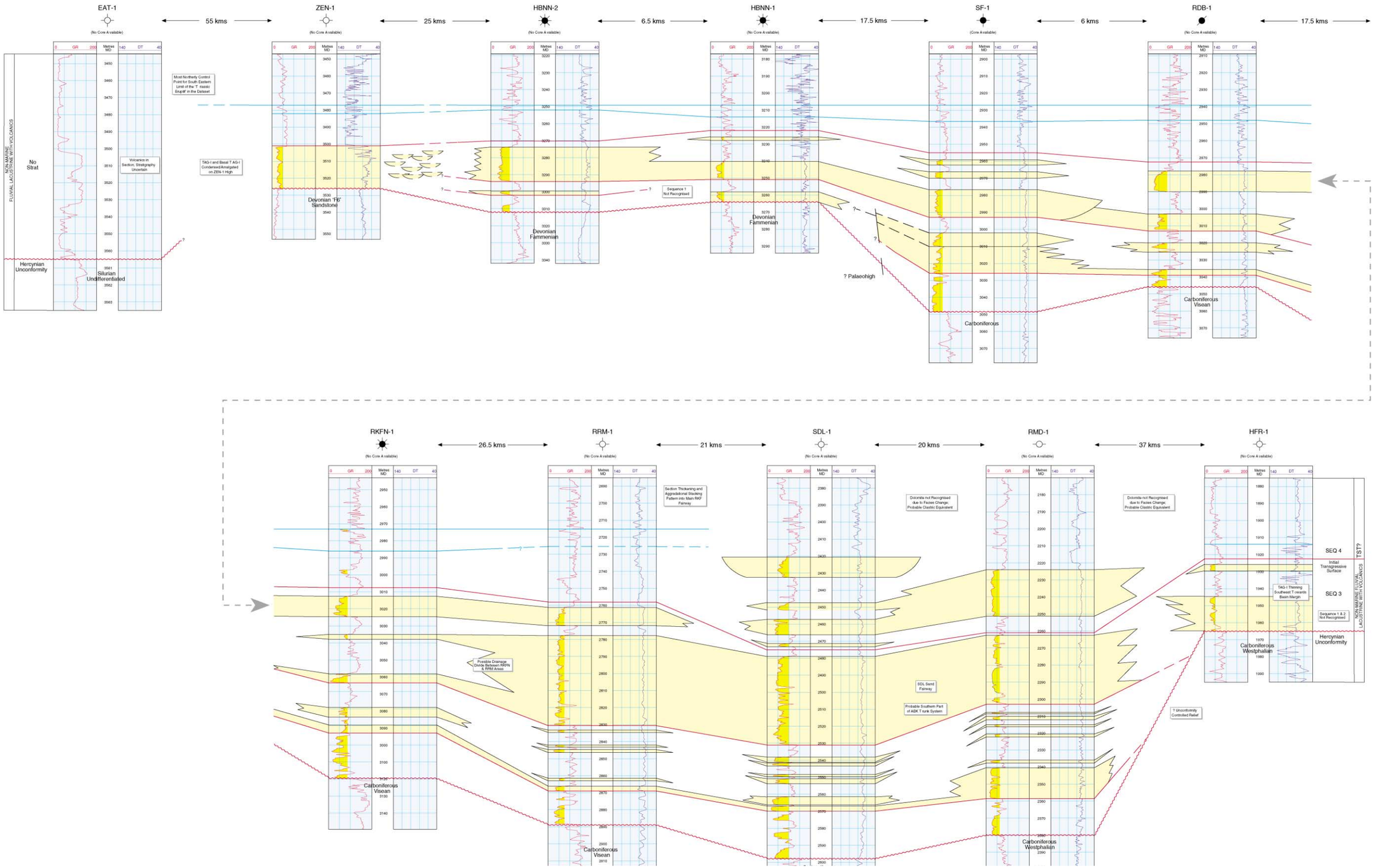
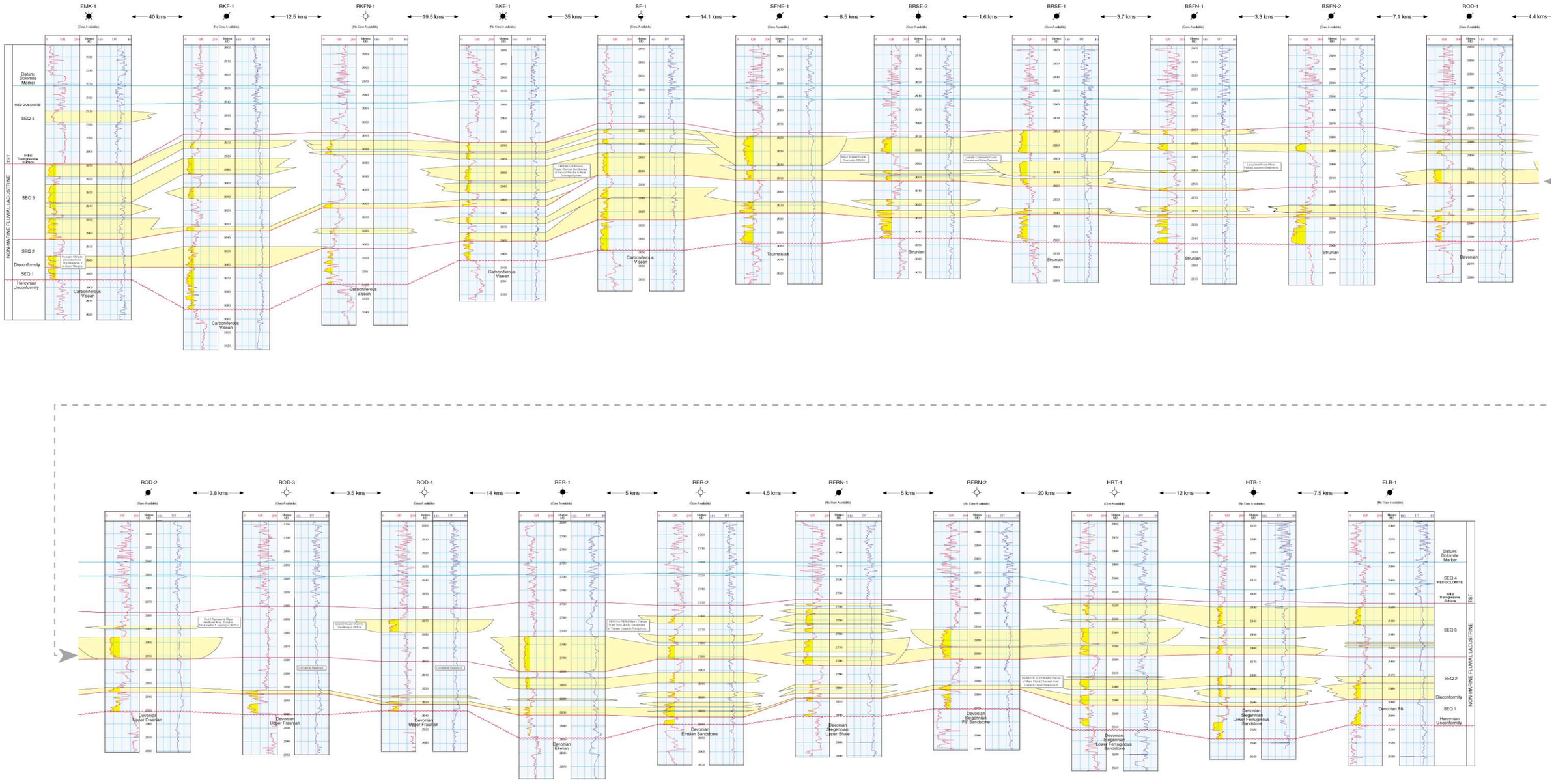


Fig. 10. Detailed correlation of the TAG-I normal to the regional palaeoslope of the Berkine Basin (NW–SE) (see Fig. 2 — Section 2 for well locations). The sand body correlations on this section are more speculative than those of Section 1 (Fig. 9) because of the much greater distance between wells. This section from EAT-1 to HFR-1 (325 km) shows the increase in thickness and sand net:gross of the TAG-I towards the SE (see also Fig. 11). The progressive overstep and onlap of Sequence 3 is also clearly seen.



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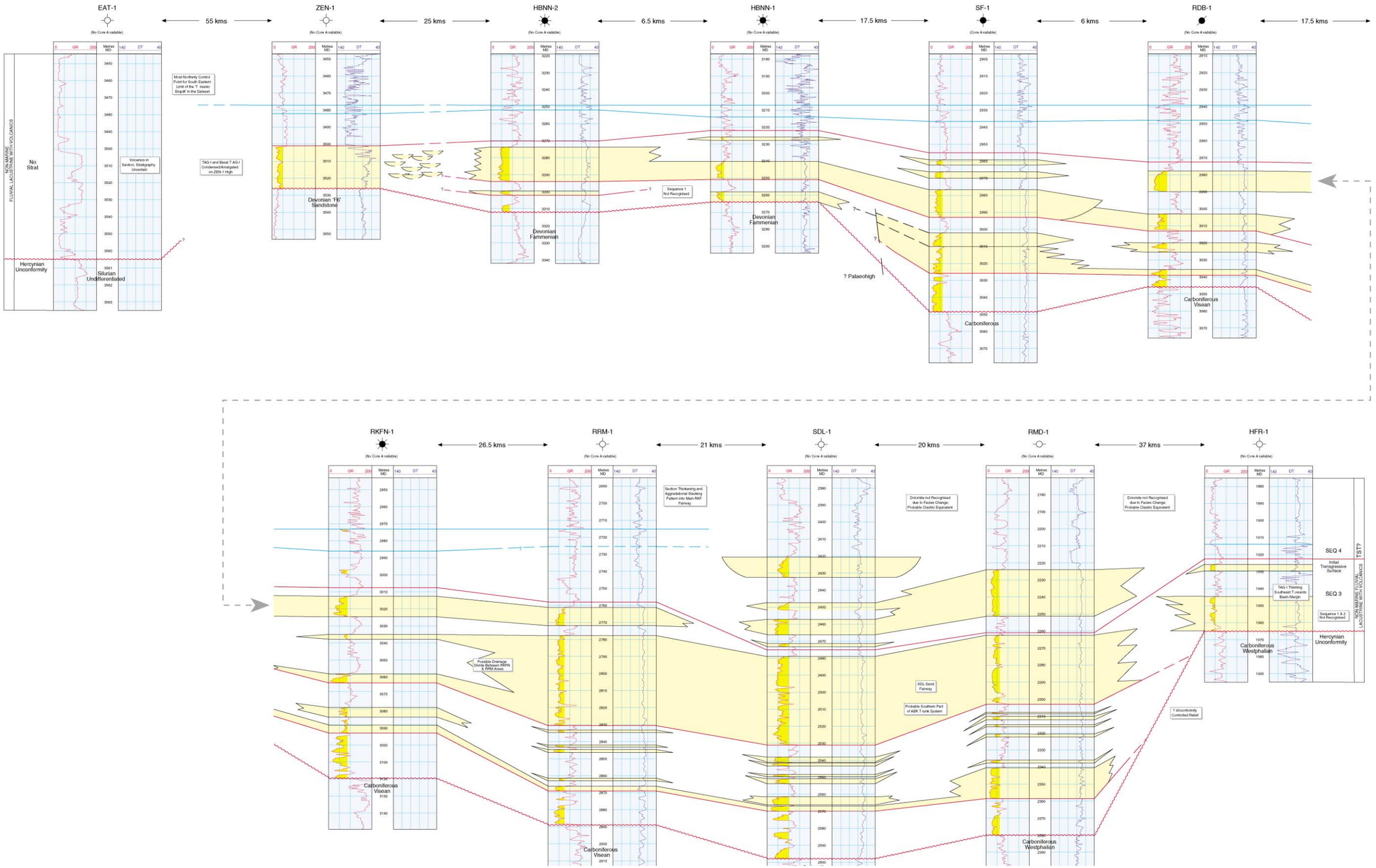

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although there is some evidence that tectonics played a key role in the pattern of basin filling. Throughout TAG-I times, relative sea level was rising and punctuated by tectonic events (rifting), which resulted in incision and seaward base level shifts.

Four depositional sequences (Sequence 1–4 in ascending stratigraphic order, Fig. 8) have been identified based on extensive core data and regional interpretation of wireline logs. A variety of criteria have been used to constrain the sequences including hiatal surfaces and incision events, sand content and grain size trends, and the occurrence of lacustrine mudstones and palaeosols. Cored sections of the depositional sequences can be tied precisely to wireline logs and subsequently extrapolated to non-cored wells on a basin-wide scale. Sections of the basin-fill parallel and normal to the main dispersal direction are shown in Figs. 9 and 10 respectively. The basin wide cross-section (Fig. 10) shows how Sequences 2 and 3 progressively onlap the basin margins and that Sequence 4 transgresses all previous deposits including the basin margins Sequence 1 (Fig. 8) comprises an unconformity/disconformity bounded section of older, more intensely weathered, fluvial Triassic strata. Thickness variations reflect infilling of inherited relief on the unconformity surface. Petrographic studies indicate that the sandstones in this unit are entirely quartzose in contrast to the feldspathic sandstones higher in the TAG-I. This feature is consistent with the presence of a significant disconformity at the top of this interval (e.g. ROD-3, EMK-l, HTB-l).

Sequence 2 is a disconformity-based, upward-shaling section of fluvio-lacustrine origin. The top of Sequence 2 is a candidate continental sequence boundary indicated by the dramatic incoming of erosively-based incised channel sandstones or the development of correlative palaeosols in sections where reservoir is absent.

Sequence 3 represents the optimum hydrocarbon-bearing reservoir in the Berkine Basin. Basally constrained by a candidate sequence boundary, this fluvial unit comprises thick channelised sandstones, moderate quality crevasse or avulsed sandstones and, occasionally, thick packages of non-reservoir, floodbasin fines. The upper part of the sequence generally demonstrates rapid fining and cessation in sediment supply, and is terminated by a marine transgressive system. Thickness variations from the margins to the axis of the basin are related to increased generation of accommodation space under conditions of overall transgression. The authors consider the transgressive surface to represent the true stratigraphical top of the TAG-I Formation with Sequence 4 effectively the basal marine unit of the Triassic Lower Carbonate. Recent studies have proposed a further sub-division of Sequence 3 into a lower 3a and an upper 3b. This subdivision reflects the local development of thick lacustrine shale within the main reservoir interval and is supported by the sections observed in RERN-3 and SFNE-2.

The base of Sequence 4 is marked by a transgressive surface of erosion with an associated marine flooding surface represented by a hot shale marker bed. The sequence becomes increasingly dolomitic both upwards and distally and is interpreted as a mud-dominated coastal plain. In conventional marine sequence stratigraphy, this unit could be considered the transgressive systems tract (TST) genetically related to the Sequence 3 deposits during lower relative sea level (Posamentier & Vail, 1988; Weimer & Posamentier, 1993). However, because the Sequence 3 deposits are entirely non-marine we think the picking of a sequence boundary at this level is important in recognising the difference in depositional styles between Sequences 3 and 4.

Reservoir development is limited to thin, highly sinuous channel and coastal plain sandstones. However, more proximal sections may demonstrate thicker reservoir development, particularly in the south of the basin where the marine dolomites are time equivalent to locally thick sand-bodies. The top of the Sequence 4 is picked regionally at a thick dolomitic development with a characteristic double or twin peak on resistivity and sonic logs. Also recognised is an intermediate dolomite informally named the 'Red Dolomite'. The regional correlation of the TAG-I and Lower Triassic Carbonate based on wireline logs is shown in Figs. 9 and 10 and a corresponding isochore diagram outlining the general basin geometry in Fig. 11. The isopach distribution of the TAG-I shows a broad western terrace area and a depocentre lying along the eastern flank of the basin. A longitudinal ridge termed the 'central ridge' forms an important drainage divide especially mid-TAG-I times.

5. TAG-I Palaeogeography

The development of the Berkine Basin throughout the TAG-I and basal Lower Triassic Carbonate is presented in this section as a series of annotated palaeogeographical (GDE) maps that are constrained at or near to the key stratal surfaces documented previously (Figs. 12–16). Presented in ascending stratigraphical order, the accompanying text documents significant events that may have influenced sediment distribution in a regional context. At the largest scale, the TAG-I formation of the Berkine Basin is predominantly of fluvio-lacustrine origin with the main sand fairways draining northeast towards the Proto-Tethyan Sea and with the main sediment supply in the south-west. Gross facies and thickness changes suggest the initial presence and persistence of intra-basinal palaeohighs (the orientation of which parallels the basin margins), which influenced drainage patterns and fluvial style. In general terms, the TAG-I of the 401a/402a area is significantly more shale prone in proximity to the northwest margin than lithostratigraphically equivalent section to the south and east. Ultimately the entire basin was inundated by the Proto-Tethyan Sea from the northeast resulting in the development of a

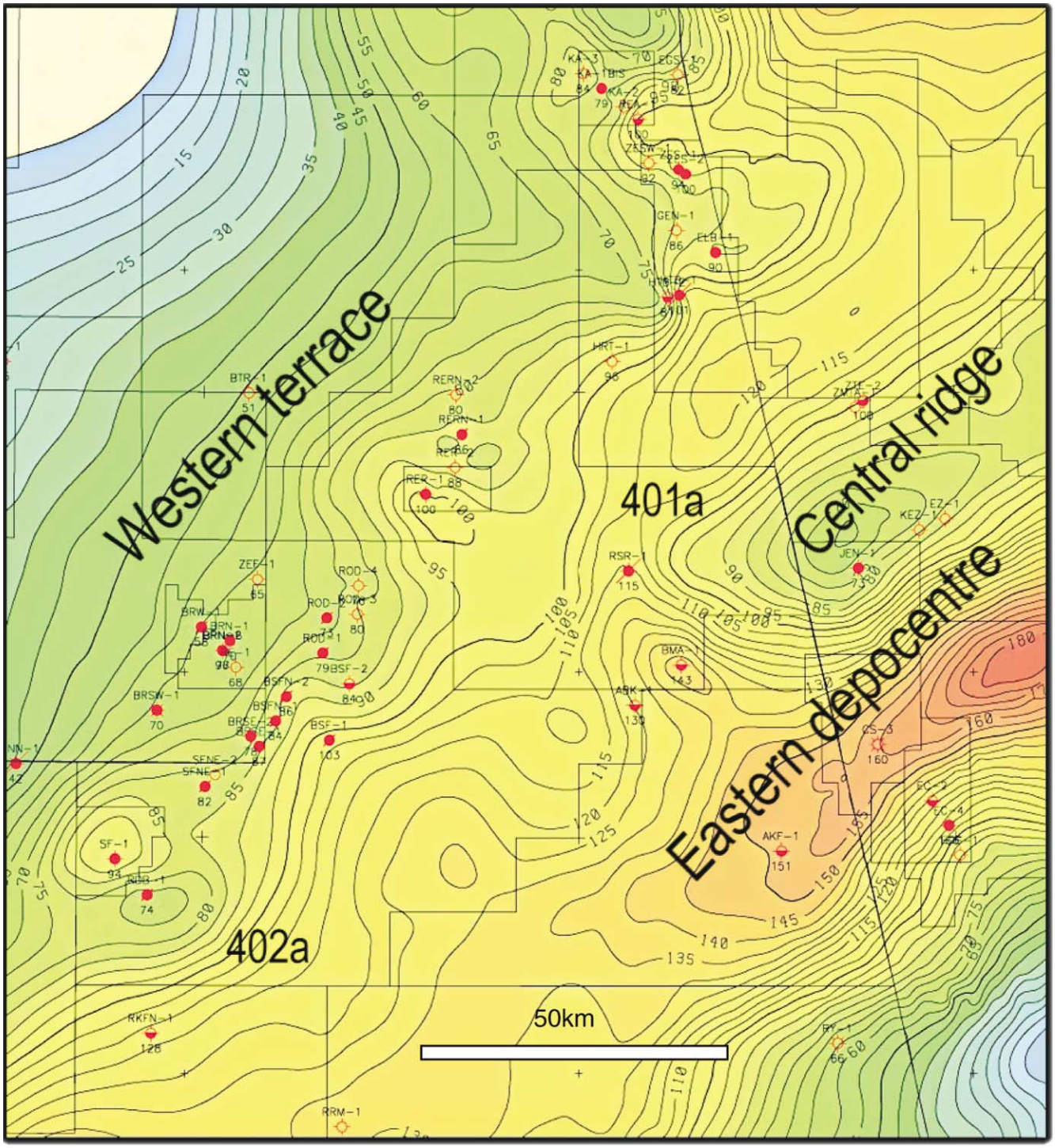

Fig. 11. Thickness distribution of the TAG-I in the Berkine Basin. Three main Intrabasinal features are apparent: the western terrace, central high which forms a drainage divide in Sequence 3 times and the eastern depocentre.

brackish to marine coastal plain traversed by thin, possibly tidal channel sandstones and dominated by a combination of argillaceous sediments and marine dolomites. This sequence stratigraphic analysis allows the changing basin development of the TAG-I to be reconstructed. In Section 6 an outline of each of the four sequences is presented.

Sequence 1 (Fig. 12) times are characterised by an unconformity-bounded interval of fluvial sandstones and shales with an overall upward-fining aspect. Log profiles confirm an increase in argillaceous sediments to the north-east, i.e. distally. Sedimentation style suggests a more arid fluvial system than that recorded in overlying sequences as

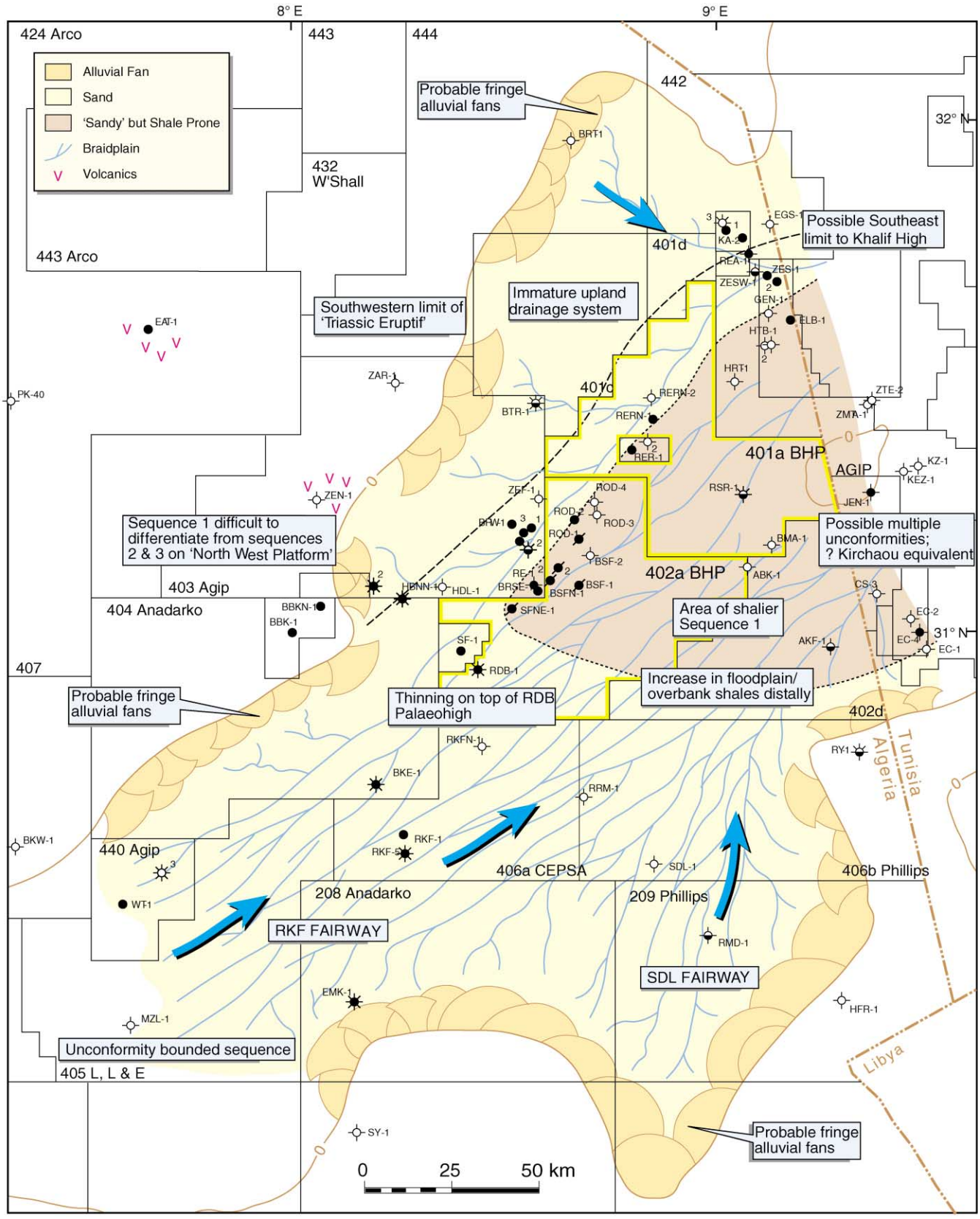

Fig. 12. Palaeogeography of mid Sequence 1.

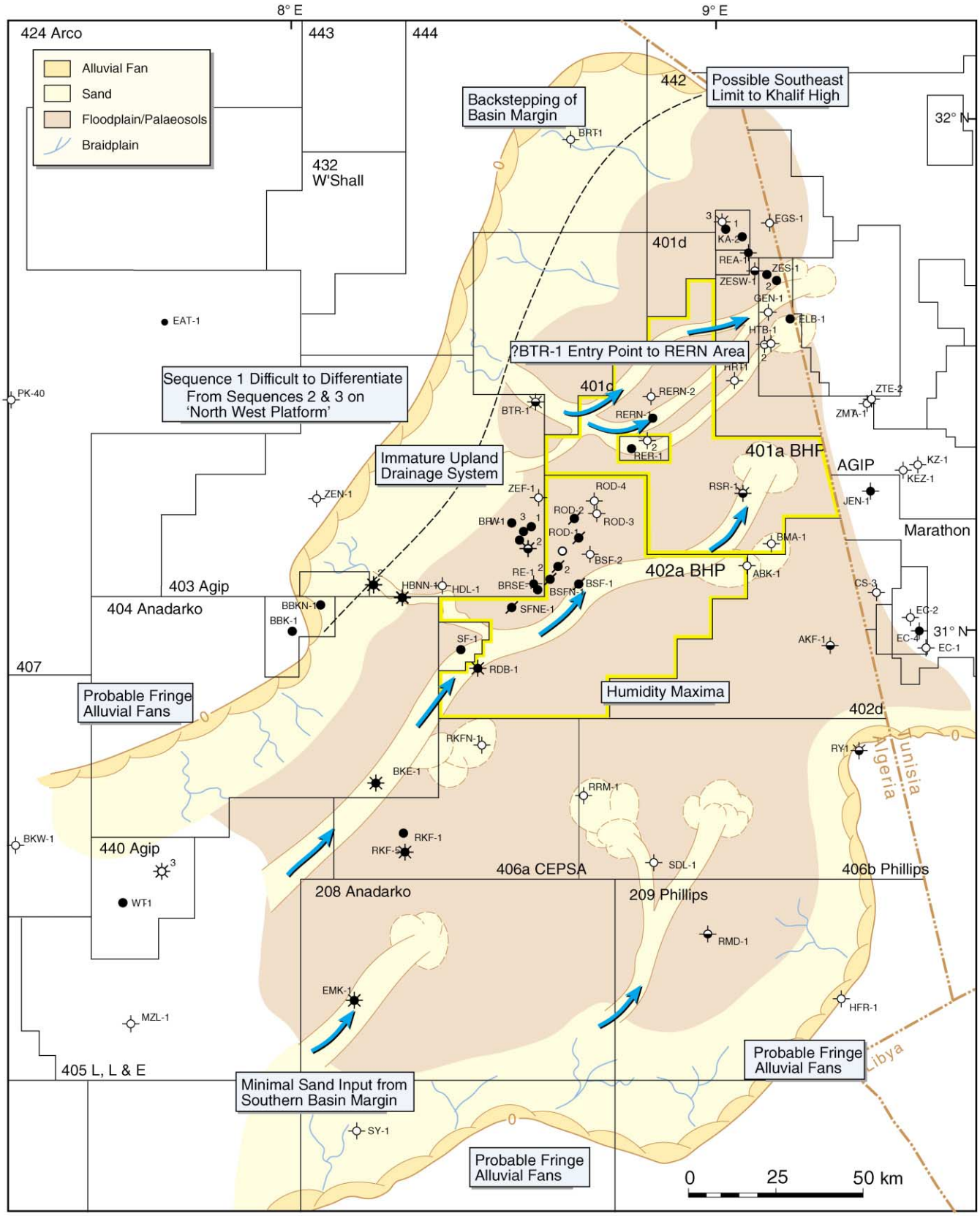

Fig. 13. Palaeogeography of mid Sequence 2.

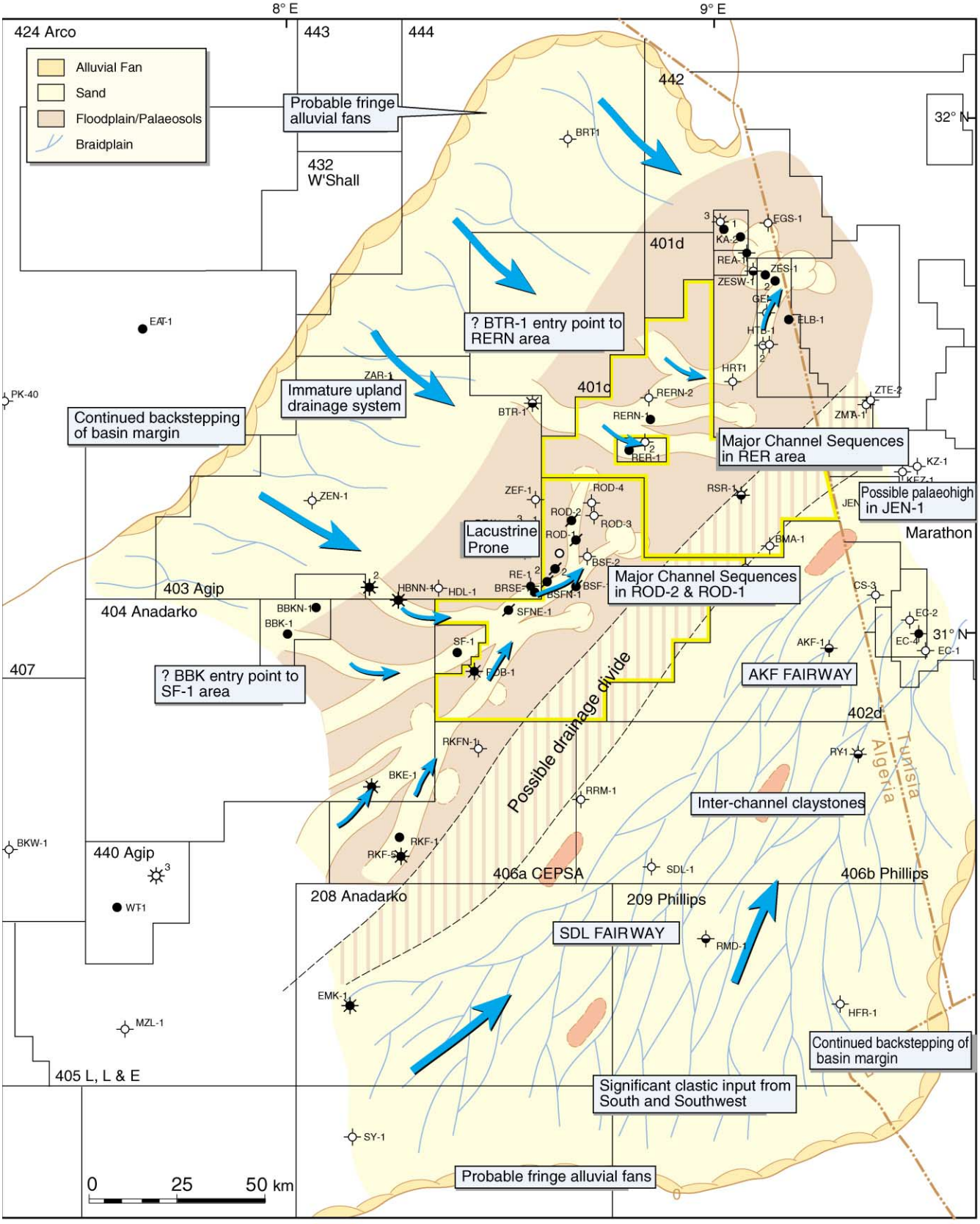

Fig. 14. Palaeogeography of mid Sequence 3.

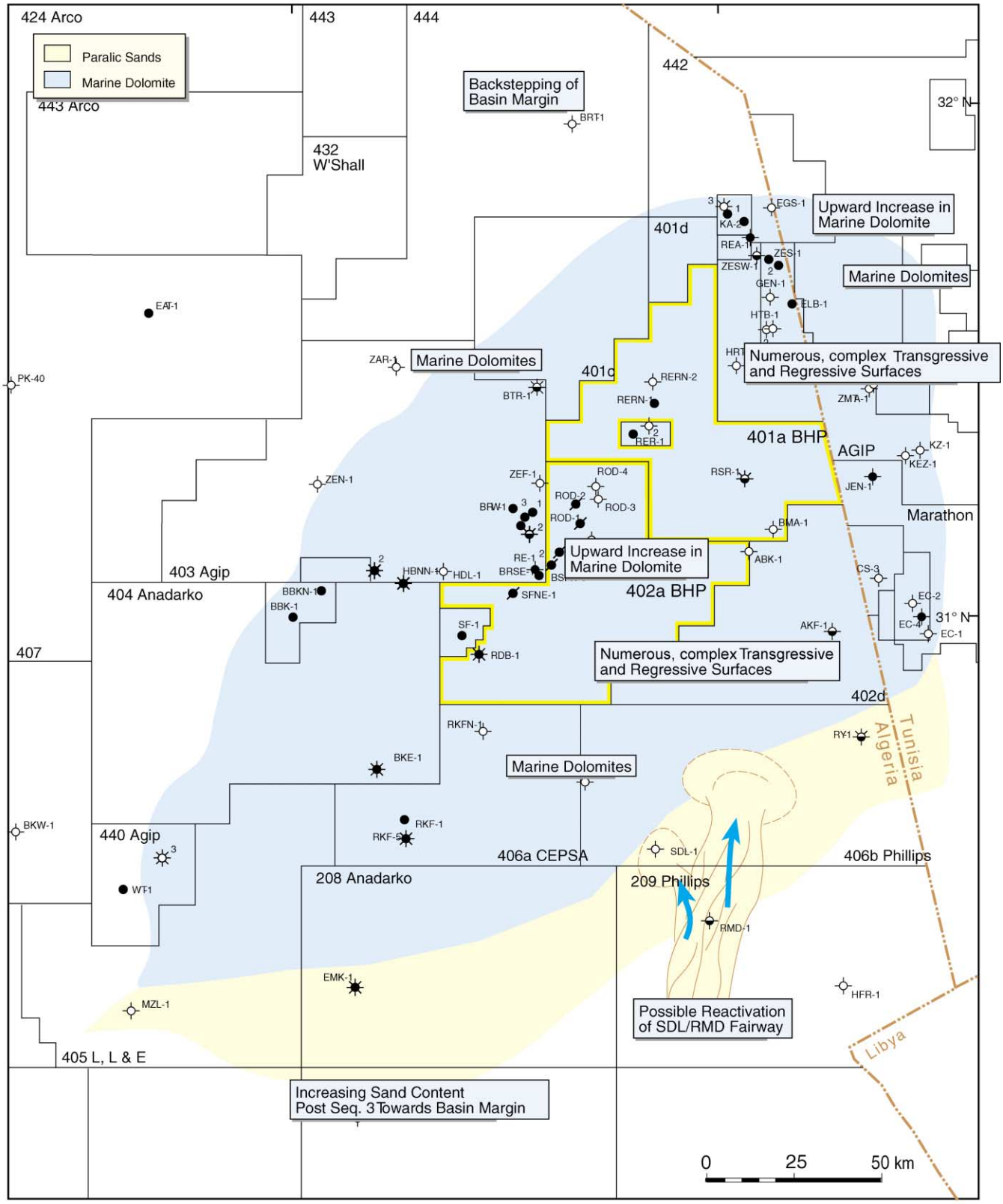

Fig. 15. Palaeogeography near/mid-top Sequence 4.

indicated by the relative abundance of ephemeral fluvial deposits. Isochores and sediment-stacking patterns suggest a prominent and persistent palaeohigh in the northwest, trending southwest to northeast. Sequence 1 represents an older Triassic section that in-filled inherited palaeo-relief on top of the post-Hercynian unconformity surface. Evidence for prolonged exposure and enhanced weathering relative to the overlying sequences is recorded in the form of goethite, kaolinite and siderite cements.

Petrological studies prove the presence of numerous disconformities in Sequence 1 (e.g. ROD-3, EMK-1, HTB-1), particularly in marginal or distal areas. Resolution of Sequence 1 is therefore limited, particularly on the northwest high where potentially coeval volcanics are recorded in available composite logs.

Sequence 2 (Fig. 13) is constrained basally by a regional disconformity defined by petrological criteria in cored section and, in the ROD-SFNE area, a distinctive, bell-shaped fluvial sandstone (e.g. ROD-2 and BRSE-l). The basal segment comprises an overall upward-fining interval from low sinuosity fluvial sandstones into floodplain and rare lacustrine siltstones. The section reflects rejuvenation of fluvial systems above the regional disconformity under conditions of increasing climatic humidity that culminates in a lacustrine hot shale marker. This boundary also correlates with a change in the bulk mineralogy as indicated by an upward increase in potassium on spectral gamma logs, interpreted as a regional change in provenance and access to more feldspathic-rich subcrop lithologies. The disconformity at the base of Sequence 2 is not always followed by fluvial channel deposition. In sections where the boundary occurs in mudstones, the contact corresponds to mature palaeosols. Intrabasinal tectonic activity, which clearly played an important role in this transition, resulted in a base level shift, which resulted in fluvial incision and the contemporaneous formation of mature interfluvial palaeosols (see Fig. 8).

Sandbody types comprise low sinuosity, relatively isolated channels within extensive floodplain siltstones (e.g. BRSE-1 and ROD-1). Crevasse splay development is common and potentially extensive suggesting low depositional gradients. Regional isochores suggest a southwest to northeast palaeoslope, with lateral input from the northwest high(s). The non-recognition of Sequence 2 on the northwest platform reflects an absence of core control and may either be a function of non-deposition or sequence condensation. The siltstones deposited in response to the initial humidity maxima did not onlap the basin margins at this time.

By mid-Sequence 2 times major floodplain shales were deposited in a seasonally humid climate as evidenced by varying degrees of pedogenic modification. Clastic deposition was limited to the northwest platform areas, probably as ephemeral or flashy drainage systems. Similar features probably developed on the southeast and southwest margins. Subtle changes in mineralogy measured on spectral gamma logs indicate the development of new source terranes coinciding with the advent of the Sequence 3 clastic (fluvial) event comprising limited development of laterally restricted channels that supplied sediment by avulsion into adjacent floodbasin areas (e.g. BSF-1 and BSF-2).

Sequence 3 (Fig. 14) deposition coincides with a major increase in clastic sediment input into the basin due to a second episode of intrabasinal rifting (Fig. 8). Channel sandstones in the ROD-SFNE area have an almost catastrophic expression with thick intraformational conglomerates and strongly aggradational profiles (e.g. BRSE-1 and BRSE-2). Significant expansion in basin size/area occurred, as margins became on lapped. Regional isochores suggest strong axial drainage to the northeast with a possible lateral contribution from the northwest highs.

Log profiles and core data suggest two dominant fluvial styles along the SF-BRSE-SFNE-BSFN-ROD-RERN trend. A basin margin parallel, southwest to northeast draining, anastomosing system developed, with common crevasse splays (e.g. BSFN-1), well developed lakes and better drained, pedogenically modified floodplains. Further to the south and east, section thickening and higher net sandstone content suggest a low sinuosity basin axial drainage system developed along the RKFN-ABK-BMA-RSR trend. The possibility of a drainage divide between the two areas cannot be discounted, in effect a geomorphological feature that controlled sedimentation styles. Towards the top of Sequence 3 there is a marked increase in stream sinuosity as the drainage system loses accommodation space due to base level rise (impending marine transgression). This suggests a significant reduction in sediment supplied from the northwest highs and significant onlap onto all the basin margins and backstepping of the more bedload dominated river systems.

The base of *Sequence 4* is marked by an initial flooding surface of basin-wide extent including onlap of basin margins. This flooding surface immediately overlies and is intimately linked to a transgressive surface of erosion (TSE) or ravinement surface, which is characterised by a transgressive lag deposit of intraclasts, bone/fish fragments and reworked dolomites in a microdolomitic matrix. The overlying, flooding-related claystone is generally gamma-ray 'hot', waxy and relatively carbonaceous. Clastic sedimentation is rare and limited to thin, probably highly sinuous channel sediments developed on a low gradient coastal plain and upwards-coarsening lagoonal-fill or bay fill ripple laminated sandstones (Fig. 15). Later in Sequence 4, regional marine incursions across the entire basin are manifested as a suite of distinctive dolomites with a characteristic log signature (Fig. 10).

The transgressive surface of erosion at the base of Sequence 4 is a basin-wide event and is considered to be effectively isochronous across the Berkine Basin. The subsequent development of a low-relief coastal plain proves that limited relief existed in the preceding TAG-I sections, thereby promoting rapid inundation of the basin during

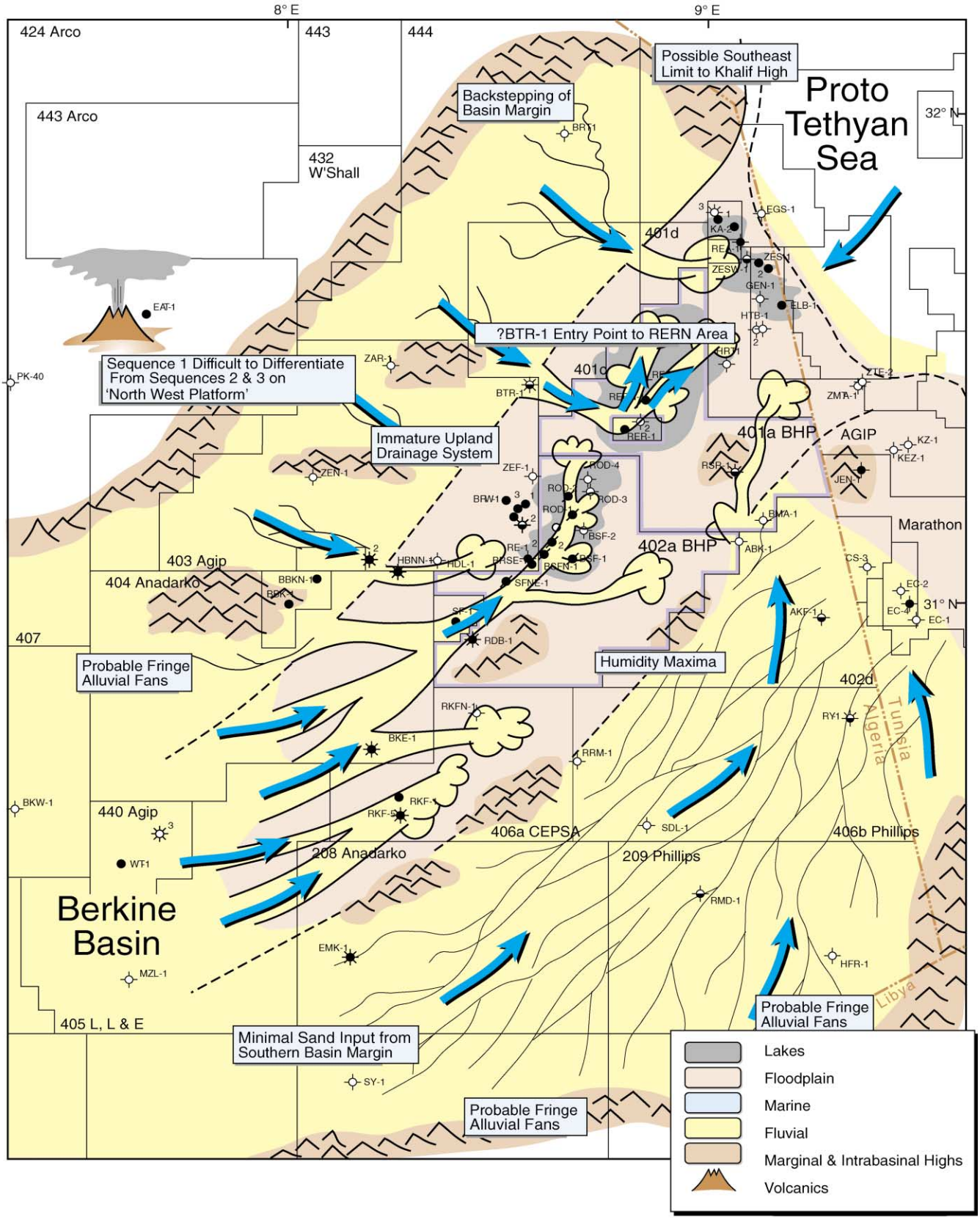

Fig. 16. Generalised palaeogeography of the TAG-I.

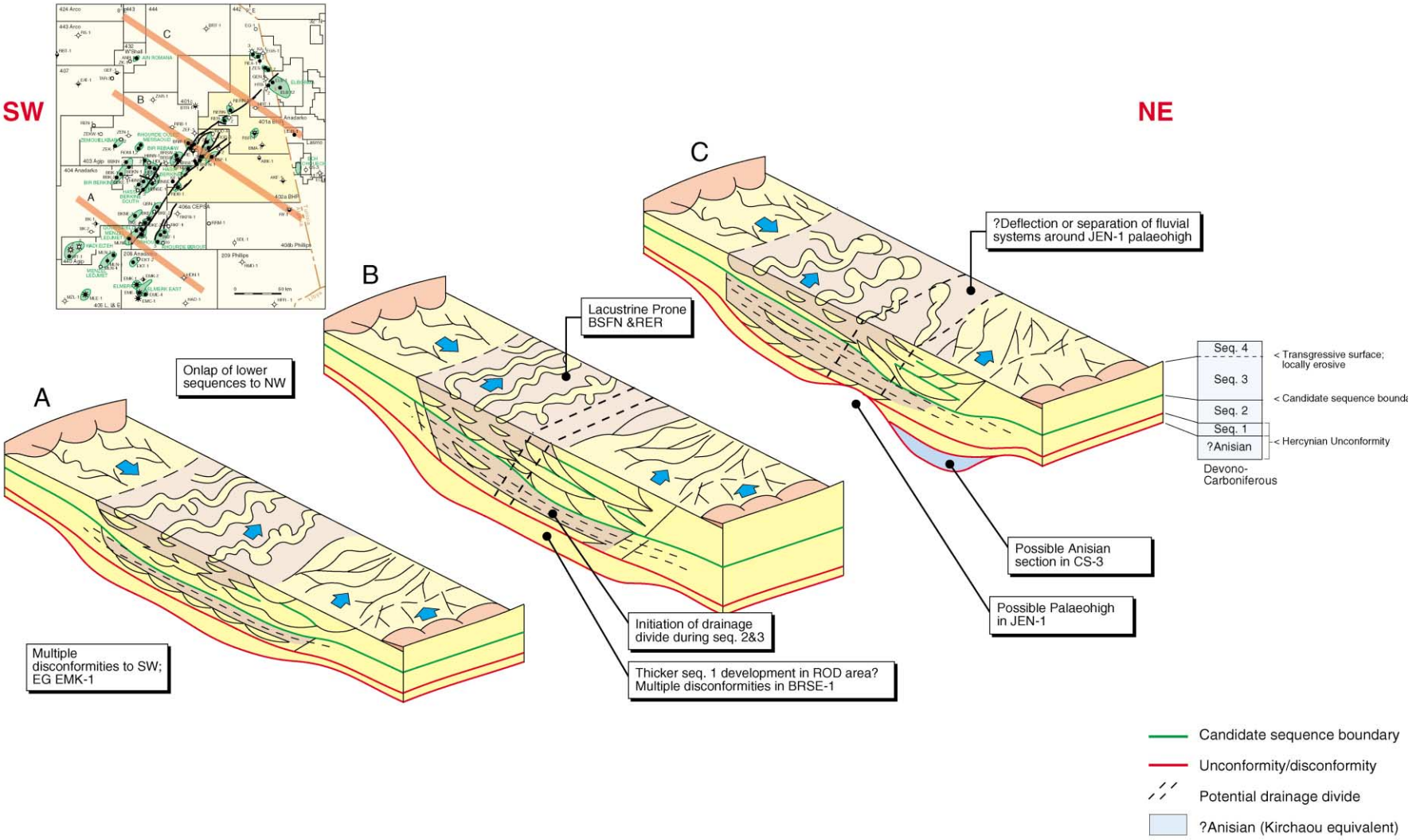

Fig. 17. Block schematic of TAG-I with gross depositional environments.

transgression. A different scenario occurs in the southwest part of the basin where logs suggest continued clastic deposition of possible marginal marine origin. These sandstones are considered to be time-equivalent to the marine dolomites developed to the northeast and demonstrate the diachroneity of facies during transgression.

Conceptualised diagrams showing the major facies distribution and stratigraphy of the Berkine basin are shown in Figs. 16 and 17.

6. Conclusions

The Triassic TAG-I and basal Trias Argilo-Carbonaté of the Berkine Basin are Carnian to Norian in age. However, the age of the oldest depositional sequence (Sequence 1) remains uncertain and may be as old as Ladinian or Anisian and therefore equivalent to the Triassic of the Zarzaitine area or the Kirchaou Formation of Tunisia. For the first time the top of the TAG-I has been precisely defined at a marine transgressive surface of erosion associated with a phosphatic bone bed. This key surface (base Sequence 4) is everywhere associated with a hot shale marker, which signifies a maximum flooding surface.

Core description and petrographic studies have also facilitated subdivision of the TAG-I and basal Trias Argilo-Carbonaté interval into four depositional sequences:

Sequence 1 is characterised by a semi-arid, formative basin-fill of fluvial sediments, the distribution of which is controlled by the relief of the Hercynian unconformity. This defines a broad, southwest to northeast trending, effectively symmetrical trough that thickens progressively to the northeast. The irregular contours in the centre of the basin suggest the presence of intrabasinal highs that may be linked to inherited palaeo-relief on the post-Hercynian unconformity surface or faults generated by Intrabasinal rifting.

Sequence 2 represents an upward-fining interval of fluvial and floodbasin sediments indicating rejuvenation of source terranes following a depositional hiatus. Initially sand-prone, a basin-wide increase in climatic humidity results in the development of extensive floodplain areas and palaeosol development. This sequence demonstrates the initial phase of sediment onlap onto the basin margins and persistence of some of the palaeo-highs. A major trough developed to the south in the vicinity of SDL-1, again with a southwest to northeast orientation. The northwest margin is still clearly defined with sediment entry points postulated around BTR-1 and BBK-1. Other input directions include axial transport down the basin axis and a probable contribution from the south.

Sequence 3 is characterised by the widespread introduction of fluvial sandstones in northeast draining river systems which reflect the main episode of basin margin onlap and source denudation. During Sequence 3 times, a pronounced axial trough developed which drains towards the El Borma area. Although sediment is still being supplied from the northwest high, onlap of the basin margins is clearly evident, particularly to the south.

Sequence 4 represents the transgressive inundation of the Berkine Basin as indicated by the basal marine ravinement surface and associated MFS. The isochores demonstrate marine incursion from the northeast resulting in the development of a broad, low-relief coastal plain. Onlap of the basin margins is clearly demonstrated with minor thickening towards the northeast.

These four sequences represent a basin-filling episode associated with increase in late Triassic relative sea level punctuated by uplift and incision associated with Triassic rifting. Fluvial depositional style in the Berkine basin was controlled by a number of inter-related factors including climate, tectonics and relative sea level.

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