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The long-term evolution of the Congo deep-sea fan: A basin-wide view of the interaction between a giant submarine fan and a mature passive margin (ZaiAngo project)

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Abstract:

We have integrated the relatively unknown distal domains of the Lower Congo basin, where the main depocenters of the Congo submarine fan are located, with the better-constrained successions on the shelf and upper slope, through the analysis of thousands of km of 2D seismic reflection profiles off-shore the Congo–Angola passive margin. The basin architecture is depicted by two ca. 800-km-long regional cross sections through the northern (Congo) and southern (Angola) margin. A large unit deposited basinward of the Aptian salt limit is likely to be the abyssal-plain equivalent of the upper-Cretaceous carbonate shelf that characterized the first post-rift deposits in West-equatorial African margins. A latest-Turonian shelf-deepening event is recorded in the abyssal plain as a long period (Coniacian–Eocene) of condensed sedimentation and basin starvation. The onset of the giant Tertiary Congo deep-sea fan in early Oligocene following this event reactivates the abyssal plain as the main depocenter of the basin. The time–space partitioning of sedimentation within the deep-sea fan results from the interplay among increasing sediment supply, margin uplift, rise of the Angola salt ridge, and canyon incision throughout the Neogene. Oligocene–early Miocene turbidite sedimentation occurs mainly in NW–SE grabens and ponded inter-diapir basins on the southern margin (Angola). Seaward tilting of the margin and downslope salt withdrawal activates the up-building of the Angola escarpment, which leads to a northward (Congo) shift of the transfer zones during late Miocene. Around the Miocene–Pliocene boundary, the incision of the Congo submarine canyon confines the turbidite flows and drives a general basinward progradation of the submarine fan into the abyssal plain The slope deposition is dominated by fine-grained hemipelagic deposits ever since.

Results from this work contribute to better understand the signature in the ultra-deep deposits of processes acting on the continental margin as well as the basin-wide sediment redistribution in areas of high river input.

Keywords: West Africa Margin; Angola escarpment; Salt tectonics; Submarine canyon; Lower Congo basin; Submarine fan

1.- Introduction

The Congo deep-sea fan is one of the largest submarine fan systems in the world and one of the most important depocenter in the eastern south Atlantic. The fan developed during the post rift evolution of the continental margin of West-equatorial Africa, which was formed following early Cretaceous rifting. It is currently sourced by the Congo River, whose continental drainage area is the second largest in the world (3.7 10^6 km²) (Droz *et al.*, 1996) (fig 1). Extending over 1000 km offshore the Congo-Angola continental margin, from the shelf up to the abyssal plain, this submarine fan covers a surface of about 300,000 km² (Savoye *et al.*, 2000; Droz *et al.*, 2003) and contains at least 0.7 Mkm³ of Tertiary sediments (Anka and Séranne, 2004). The existence of a direct connection between the Congo River mouth and the submarine fan through an impressive submarine canyon is one of the most important characteristics of this system. The Congo canyon cuts across the margin, it is 950 m deep at the shelf-break and more than 1300 m at 100 km offshore the coastline (Babonneau *et al.*, 2002). Thus terrigenous material coming from the continental drainage basin are transported through the canyon and directly transferred onto the abyssal plain, by-passing the shelf and upper slope (Droz et al., 2003; Turakiewicz, 2004).

Due to its economical relevance, the Lower Congo basin has been extensively studied since the sixties (*e.g.* (Brognon and Verrier, 1966) until recent basin-wide initiative as the ZaiAngo project, a research collaboration between the Ifremer and Total. The continental margin architecture, as well as the stratigraphy of the proximal areas, has been rather well constrained due to the presence of numerous oil wells on the shelf and upper slope (e.g.(Teisserenc and Villemin, 1989; Séranne *et al.*, 1992; Meyers *et al.*, 1996; Rasmussen, 1996; Nzé Abeigne, 1997; Uenzelmann-Neben *et al.*, 1997; Karner and Driscoll, 1999; Anderson *et al.*, 2000; Lavier *et al.*, 2000; Marton *et al.*, 2000; Mougamba *et al.*, 2000; Rosendahl and Groschel-Becker, 2000; Valle *et al.*, 2001; Ardill *et al.*, 2002; Lucazeau *et al.*, 2003; Robin *et al.*, 2005; Petzet, 2007). In addition, some regional works provided some hints on the regional significance of the distal provinces and an idea of the deep fan size (Emery *et al.*, 1975; Uchupi, 1989; Uchupi, 1992). More recently, other studies have provided a better understanding of the stratigraphy and evolution of the abyssal plain, where the main fan depocenters are located (Anka, 2004; Anka and Séranne, 2004). Nevertheless, a comprehensive integration of proximal and distal domains, assessing a global basin-wide view of the fan evolution is yet to be carried out.

This contribution complements previous work done in the abyssal plain of the Lower Congo basin and addresses questions regarding the sediment partitioning between the deep-sea fan and the continental margin, its timing and controlling factors. We focus on analysing how different processes known to affect the margin, such as submarine erosions, salt tectonics, basin tilting, and continental uplift, are recorded in the distal deposits of the lower slope and abyssal plain, and to what extent they control the submarine fan deposits. We present the results from analysis of 2D seismic reflection data on the slope north of the Congo Canyon that, once correlated to wells in the shelf domain and integrated to the distal seismic, allow to (1) re-interpret and better age-constrain the relatively unknown distal units deposited onto the oceanic crust, (2) analyse the possible interactions between the salt tectonics and the fan depocenter location/migration, and (3) reconstruct the basin-wide architecture proposing a long-term evolution for the Congo deep-sea fan.

2.- Geological setting

The Congo-Angola passive margin results from Neocomian rifting of Gondwana followed by oceanic accretion (Rabinowitz and Labreque, 1979). Although no magnetic anomaly is found in the Lower Congo basin, the age of the oldest oceanic crust is interpreted to be close to Chron M0 (118.7 Ma), that is Aptian (Nürnberg and Müller, 1991) or even older: Barremian (Marton et al., 2000). Moreover, a literature review reveals that the estimated ages in this area range from 127 to 117 Ma (Teisserenc and Villemin, 1989; Guiraud and Maurin, 1992;

Karner and Driscoll, 1999; Jackson *et al.*, 2000). The precise location of the Continent-Ocean boundary (COB) is rather unknown, but it would correspond to a narrow transition zone between extended continental crust and normal oceanic crust, located few kilometres landward of the Angola escarpment (Fig.1) (Moulin, 2003; Contrucci *et al.*, 2004; Séranne and Anka, 2005).

Following the continental break-up, a transgressive clastic succession, from fluvial sandstones to lagoon shales, accumulates in the basin (Fm. Chela, Fig 2). They are overlain by a thick evaporitic level deposited in restricted marine conditions during late Aptian (Fm. Loeme, Fig 2) (Emery *et al.*, 1975; Teisserenc and Villemin, 1989). This layer, composed mostly of massive halite topped by anhydrite, is the detachment level of the widespread salt tectonics that affects overlaying post-rift sequences (Duval *et al.*, 1992; Lundin, 1992; Vendeville and Jackson, 1992; Gaullier *et al.*, 1993; Spathopoulos, 1996; Cramez and Jackson, 2000; Fort *et al.*, 2004; Jackson and Hudec, 2005; Hudec and Jackson, 2007).

During the Albian, shallow carbonate accumulations (the Pinda Group) built up an aggrading ramp-profiled shelf. As sea-floor spreading goes on, open marine conditions establish and carbonate production is halted. In consequence, from the Cenomanian to the Eocene the sedimentation is characterized by the mudstones and marine siliciclastics of the Iabe/Landana Groups (Fig 2) and depositional rates remain very low throughout this time span (Anderson *et al.*, 2000; Valle *et al.*, 2001).

The early Oligocene is characterized by a major submarine erosion that removed as much as 500 m of sediments of the outer shelf (Nzé Abeigne, 1997; Lavier et al., 2000). This event is linked to the so-called “Oligocene unconformity” identified throughout the West African margin (Teisserenc and Villemin, 1989). Early Oligocene is also a time of a widespread stratigraphic reorganization along the margin, expressed by a generalized turn-over in the depositional pattern from aggradation to progadation deposits (Séranne *et al.*, 1992). An important increase in terrigenous supply is also registered at this time, which is evidenced by the development of the massive Congo deep-sea fan in the abyssal plain (Anka and Séranne, 2004). The origin of these widespread changes is still matter of discussion. They may result either from changes in climatic and oceanographic conditions (Séranne, 1999; Lavier et al., 2000) or from epeirogenic motions related to the uplift of the African continent (Bond, 1978; Walgenwitz *et al.*, 1990; Lunde *et al.*, 1992; Walgenwitz *et al.*, 1992; Burke, 1996), and most likely by the interplay among them.

Another erosive event is registered in the West African margin during early Neogene. AFT chronothermometry and fluid inclusion analysis place it around 22 Ma, that is early Miocene (Brice et al., 1982; Lunde et al., 1992; Walgenwitz et al., 1992; Valle et al., 2001). It is associated to a general seaward margin tilting (Brice et al., 1982; Lunde et al., 1992; Walgenwitz et al., 1992; Valle et al., 2001). Two-dimensional restoration performed across the northern Angolan margin suggests another minor uplift during late Miocene (Tortonian) (Lavier et al., 2000; 2001). Additionally, sediment supply increases steadily during the Neogene, which in junction to these proposed uplifts, renewed the gravity-driven extension on the shelf and upper slope.

As sedimentary loading enhanced upslope salt tectonics on the shelf and upper-slope, a variety of extensional structures developed: seaward-dipping rotational growth faults, salt diapirs, detached blocks and rafts, and salt rollers, which have been extensively studied over the past years (e.g. (Burrollet, 1975; Duval et al., 1992; Lundin, 1992; Vendeville and Jackson, 1992; Gaullier et al., 1993; Spathopoulos, 1996; Cramez and Jackson, 2000; Broucke *et al.*, 2004; Fort et al., 2004; Jackson and Hudec, 2005; Hudec and Jackson, 2007). This upslope thin-skinned extension is transferred downslope and balanced by the development of compressional structures as imbricate thrusting, large scale diapirs, salt walls, and canopies in the lower slope (Spathopoulos, 1996; Marton et al., 2000; Anka, 2004; Fort et al., 2004; Gottschalk *et al.*, 2004; Jackson *et al.*, 2004; Kilby *et al.*, 2004; Rowan *et al.*, 2004). The Angola escarpment, an impressive north-south bathymetric step at the present-day base of the Angolan slope (Fig.1), is the seaward limit of a thrust front (the “massive salt”) resulting from this compressional salt tectonics.

3.- Data and methodology

This study is based on a large seismic reflection dataset acquired during the ZaiAngo Project (Savoye et al., 2000). We interpreted more than 19.000 km of 2D multi-channel seismic reflection lines located between the lower slope and the abyssal plain of the Lower Congo basin (Fig 3). This dataset comprises three two-way travel time (TWT) seismic surveys: (1) 6-channeled high-resolution reflection, (2) 96-channeled high-resolution reflection, and (3) deep penetration reflection-refraction (DST). Additionally, several hundreds of kilometres of high-quality industrial seismic reflection lines located in the northern slope were supplied by Total. These profiles provided the link between the slope deposits and the submarine fan deposits in the abyssal plain, the base of the present-day slope being represented by the salt limit (Fig 3). Altogether the final seismic grid covered a total area of about 200.000 km² between 2000 m and 5000 m of bathymetry.

Penetration to more than 9 s TWT, permitted to analyse the entire seismostratigraphic record of the abyssal plain down to oceanic crust. The seismic profiles were analysed with the seismic interpretation & visualization software *Sismage Research* ™, following a conventional 2D interpretation methodology of delimitation of high amplitude reflectors, generation of surface-depth and isopach maps, long-distance well-seismic correlation, and seismic attribute extraction. The “seismic unit” and “seismic facies” concepts correspond to those proposed initially by Sangree and Widmier (1979). The geological interpretation of the seismic units was based upon the variations of seismic parameters, such as amplitude, frequency, continuity, and external and internal geometries, as well as on the classical concepts of sequence stratigraphy (Vail *et al.*, 1977). However, the interpretation of depositional environments from seismic data requires a link between the character of the seismic data and sedimentary facies. The absence of boreholes in the abyssal plain does not allow a direct tie of the seismic facies to lithology data. Hence, we also used the seismic signature of the sedimentary facies in the present-day submarine fan, in order to identify and interpret the distal seismic facies of older deposits (Fig. 4).

The age control relies on: (1) long-distance correlation of the distal seismic reflectors identified in the abyssal plain with more proximal, better age-constrained, reflectors in the slope, (2) north-eastern extended correlation towards the south Gabon basin where seismic markers are already dated from previous works, and (3) seismic-well ties in the platform. This methodology allowed us to establish a long-term chrono-stratigraphic framework that correlates deposits in the upper slope/shelf with the distal units in the abyssal plain.

4.- Seismic stratigraphy and chronology

A detailed description of the units basinward of the salt limit has been presented in earlier contributions (Anka, 2004; Anka and Séranne, 2004). Fig 5 shows the general distribution of the main seismic units and reflectors identified at the transition between the lower slope and the abyssal plain. As said, the base of the present-day slope corresponds in subsurface to the limit of the Aptian evaporite level, which is interpreted as toe-thrust of the salt layer over the oldest unit deposited over the oceanic crust.

A1: *Basal unit overlaying the Aptian salt (Albian-Turonian).*

The first highest-amplitude reflector identified above the salt level, “TC”, represents the boundary between a basal seismic unit A1 composed of high-amplitude, continuous, parallel to sub-parallel internal reflectors and an overlying unit (A2) of low-amplitude, discontinuous internal reflectors. On the lower slope, A1 is highly deformed by diapirs and thrusting associated to downslope compressive salt tectonics.

The nature of seismic marker TC varies as we trace it from the basin towards the slope. In the abyssal plain, it correlates with a prominent, high-amplitude reflector identified throughout the basin, which represents the upper boundary of the earliest sedimentary unit deposited onto the oceanic crust (Fig. 5). This basal unit reaches a thickness of more than 1 s TWT at about 100 km west of the salt limit. Eastward of this limit, on the upper-slope, we observe truncations of the internal reflections, which indicate that reflector TC is indeed the lower slope/abyssal plain correlative surface of this angular unconformity identified in the upper-slope (Fig. 6).

The estimated age of TC is rather variable whether we correlate it to the northern or southern shelf domain. A northeast correlation with seismic profiles in the Gabon basin suggests that TC may represent the seismic reflector 14 described by Nzé Abeigne (1997), and interpreted as the top of Fm. Cap Lopez, dated as earliest Turonian. On the other hand, to the southeast, Valle et al. (2001) identified in the Angolan margin a conspicuous seismic reflector “nt-Cret” at around the same stratigraphic level of TC, which presents similar seismic characteristics. According to these authors, this reflector is aged as late Maastrichtian. Nevertheless, correlations to the Congo shelf indicate that TC may be indeed equivalent to a sequence boundary (MS2) represented by a prominent seismic reflector. This boundary has been placed at the top of the CoXIVa palynological zone, that is, latest Turonian (Massala *et al.*, 1992). We favoured this datation, supported by data from internal reports (courtesy of Total), indicating that sequence boundary “MS2” defines the switch from shelf limestone deposits to marine shale sediments. Thus, we infer that the high amplitude of TC, as well as the variation in seismic character of upper (A2) and lower (A1) units, results from the large impedance contrast between the different lithologies of overlying and underlying deposits. Hence, TC would be the lower-slope equivalent to the described sequence boundary on the shelf.

These findings modify significantly our previous interpretation where, in the absence of correlation with nearby wells and based only in comparisons with regional seismic profiles (Musgrove and Austin, 1984) and DSDP Leg 75 Site 530 near the Walvis Ridge, TC was interpreted as the Eocene-Oligocene boundary.

In summary, the basal unit A1 deposited on the oceanic crust, top-bounded by reflector TC, represents the Albian-Turonian sedimentation in the abyssal plain. Thus, it is the ultra-deep lateral equivalent of the carbonate ramp-profiled shelf (Pinda Group and Loango Fm.) that characterized the first stages of post-rift sedimentation on the shelf of the Congo margin.

A2: *Basinward-thinning unit (post -Turonian – Eocene).*

Overlying the basal unit A1, and bounded by reflector BO, there is a unit less than 0.4 s TWT thick (A2). It is composed by low amplitude, parallel, discontinuous reflectors (Fig. 6). The unit thins progressively basinward and, at around 200 km west of the salt limit, it is either below seismic resolution or absent (Fig. 5). As mentioned above, the variation in the seismic signature of this unit may result from the lithology variation between the most-likely carbonates of underlying unit A1 and the probably shaly sediments that make up this unit.

North-east correlation and well datation of top reflector BO point to an age base of the Oligocene - south Gabon prominent reflector 5 of Nzé Abeigne (1997). The small thickness, as well as the eventual basinward pinch-out of the unit, correlates well with the low sedimentation rates reported in the shelf (Anderson et al., 2000; Valle et al., 2001). Based on these results, this relatively thin unit would represent a long time interval of about 65 My, from the Coniacian to the Eocene, characterised by very low or condensed sedimentation in the deep basin.

A3: ***Basinward-thickening wedge (Oligocene-Miocene).***

In contrast to the basinward thinning of the post-Turonian – Eocene succession, the overlying unit A3 is a basinward diverging wedge whose thickness increases dramatically, from about 0.5 s TWT in the lower slope to more than 1.5 s TWT beyond its base (Fig 5). The basal boundary BO, correlates landwards with a major regional unconformity, the "Oligocene unconformity", identified throughout the west African margin (*e.g.* (Massala et al., 1992; Séranne et al., 1992; McGinnis *et al.*, 1993; Meyers et al., 1996; Rasmussen, 1996; Mauduit *et al.*, 1997; Nzé Abeigne, 1997; Karner and Driscoll, 1999; Mougamba, 1999; Séranne and Nzé Abeigne, 1999; Cramez and Jackson, 2000; Lavier et al., 2000). Although its origin is still controversial, on the Congo margin it represents a large-amplitude submarine erosion in intermediate water depths of 500-1500 m that removed about 500 m of sediments (Séranne et al., 1992; McGinnis *et al.*, 1993; Nzé Abeigne, 1997; Lavier et al., 2000; 2001). In southern Gabon, this unconformity is related to a hiatus of at least 15 My on the shelf and upper slope (Teisserenc and Villemin, 1989).

The upper boundary of the unit is depicted by the highest-amplitude reflector identified in the northern slope: reflector R (Figs. 5, 6). This marker is also found on the south Gabon and the Congo-Angola margins. Some authors have interpreted it as the transition between middle Eocene and late Oligocene based upon correlation with ODP leg 175 (Uenzelmann-Neben *et al.*, 1997; Uenzelmann-Neben, 1998). However, none of the sites 1075, 1076, 1077 reached indeed the reflector's depth (Shipboard-Scientific-Party, 1998). North-eastern correlation with the southern Gabon slope, suggests an age probably latest Miocene / base of Pliocene. This result coincides with several academic publications based on internal reports from oil companies (e.g. (Gay, 2002; Turakiewicz, 2004). Consequently, the unit A3 comprises the early Oligocene-Miocene sedimentation span. Its seismic characteristics greatly differ from underlying units, as it is mainly composed of packets of highly discontinuous, wavy, and high amplitude internal reflectors (Fig. 6). This seismic configuration is similar to the seismic signature of the turbidite channel facies described in most deep-sea fans and in the Quaternary Congo fan (Lopez, 2001) (Fig. 4). Hence, we interpret the unit as a succession of turbidite channels from the Tertiary Congo submarine fan.

Interesting enough is the fact that, in the upper slope, these deposits are onlapping the base-of-the-Oligocene surface (Fig. 7). This architecture depicts a drastic modification in the stratigraphic pattern from the continuous aggradation of underlying successions A1-A2. These observations support an early-Oligocene onset of the submarine fan as we previously proposed from work carried out basinward of the salt limit.

A4: ***Upward & basinward facies change (Pliocene-Recent).***

This unit consists of a package, about 0.8 s TWT thick, of highly continuous, parallel, low-to-moderate amplitude reflectors that cover most of the present-day northern slope (Fig. 7). By comparison with the seismic facies of the Quaternary fan, it can be interpreted as facies of slope hemipelagics (Fig. 4). Moreover, the unit can be traced landwards where ODP Leg 175, site 1077, recovered hemipelagic deposits composed of diatom and nannofossil-rich clays (Shipboard-Scientific-Party, 1998), which validates the seismic interpretation. This indicates that around reflector R time, that is the Miocene-Pliocene boundary, the Oligo-Miocene turbidite deposits of underlying unit A3 are vertically replaced by these hemipelagics. In addition, A4 is affected by densely distributed, multiple, low-displacement vertical faults linked in polygonal networks, which are probably related to upward expulsion of fluids in the slope (Gay *et al.*, 2004; Gay *et al.*, 2006).

At about 200 km offshore the coast the internal reflection pattern shows a pronounced variation suggesting a lateral modification of the unit’s depositional environment. Not only the thickness of the unit increases basinwards to more than 1.5 s TWT, but also the continuous-parallel reflectors of the hemipelagics facies change to a stacked-onlapping channel-like geometry (Fig. 8). Around the same location, the basal boundary -reflector R- deepens for more than 1 s TWT and is disrupted by these interpreted channels, so it can not be identified further basinwards. These observations indicate that, since the latest Miocene-earliest Pliocene, there is a basinward shift of the submarine channel facies and thus a general progradation of the entire submarine fan. This process is concomitant to the above-described vertical substitution of channel facies by hemipelagic deosits on the northern slope**.** We will address the possible mechanisms behind these events later on.

5. Discussion

Basin architecture and fan evolution

We generated two regional sections, more than 600 km long, across the northern (Congo) and southern (Angola) lower slope and abyssal plain. We have also integrated published sections on the shelf and upper slope domains (Lavier et al., 2001) so the basin architecture is depicted along about 800 km covering the entire continental margin and oceanic domains (Fig. 9). As mentioned before, the nature of the crust beneath the salt limit is unknown, but it would be either proto-oceanic (Meyers et al., 1996) or transitional (Marton et al., 2000; Moulin, 2003). In contrast to the northern slope, where salt-related gravitational gliding of the sedimentary cover is mostly Oligocene, salt rising along the southern slope has been active until the present, building up the so-called Angola escarpment (Figs. 3 & 9).

The thickness of the Albo-Turonian unit remains almost constant along the upper and lower slope across the Congo margin, whilst it decreases towards the base of the slope in the Angolan margin. This is consistent with the ramp morphology described by other authors in the Angolan upper slope (Massala et al., 1992; Anderson et al., 2000; Lavier et al., 2001). On the other hand, the significant thickness (about 2 km) accumulated at, and beyond the base of the slope is especially surprising and seems to challenge former ideas of very-thin or nearlyabsent upper-Cretaceous accumulations in the abyssal plain of the basin (Leturmy *et al.*, 2003; Lucazeau et al., 2003; Evans, 2004).

The thinning of the post-Turonian-Eocene section allows inferring a pinch-out at about 250 km from the salt limit (Fig. 9). Well logs on the Congo shelf register a deepening during Palaeocene-Eocene, contemporaneous with a very low sedimentation rate in the upper slope (Anderson et al., 2000; Valle et al., 2001). Although, this section may be eroded in the Angolan shelf, north-south correlations with strike seismic lines indicate that it is present over the Angolan slope with a thickness up to 500 m. The presence of the massive salt walls associated to the Angola escarpment makes seismic correlation towards the abyssal plain across the Angola margin rather difficult. Nevertheless, in the outer abyssal plain, where the unit is no longer identifiable, the Coniacian-Eocene sedimentation interval would be condensed in reflector TC. Thus, TC is a diachronic seismic marker in the abyssal plain, where it represents a condensed sedimentation span of about 65 My. Therefore, the paleo-bathymetry increase identified in the Congo shelf and slope translates into a long period of basin starvation in the abyssal plain.

As a consequence of the Congo fan onset in early Oligocene, the distal abyssal plain was reactivated as a major depocenter. The Oligo-Miocene wedge is much larger than previously thought, and considerably thicker than the underlying and overlaying deposits (Fig. 9). Although, some authors place the boundary of the Tertiary fan around the present-day salt limit (Kolla *et al.*, 2001), it is shown here that this unit reaches maximum thickness basinward of this limit.

Another result worth discussing is that although the fan deposits are thicker in the southern shelf/upper slope (Angola) than in the northern slope (Congo), both sections show a similar thickness on the abyssal plain. Previous works, restricted to the proximal domains, suggested that the apparent thickness variation resulted from a different capacity of each margin to record climatic *vs.* geodynamic signals. For instance, on the Angola margin where the sediments were transported by the Congo river, whose watershed is influenced by on-land climate variations, the climatic signal would be more dominant. In contrast, on the Congo margin, where sediments were thought to be sourced from the shelf erosion by coastal rivers, geodynamics signals as continental uplift would be better recorded in the deposits (Lavier et al., 2001). However, since the fan deposits are homogenously distributed throughout the abyssal plain, depicting a clear radial fan-shaped depocenter around the present-day Congo River outlet (Fig. 10) we propose that, despite some possible contribution from coastal rivers, the main sediment supplier for both margins is the Congo river, and the variation in thickness between the Congo and Angola slopes is mainly due to their respective paleo-geographic positions with respect to the fan deposits.

The fact that the Tertiary submarine fan overlies the correlative surface of the prominent “Oligocene unconformity” leads us to consider the fan’s onset as one of the important stratigraphic changes that took place following this unconformity in several west African margins: *e.g.* (1) the development of contourites, deep canyon cutting, and submarine erosions in southern Gabon (Séranne and Nzé Abeigne, 1999), (2) the presence of incised valleys and increased sediment supply in northern Gabon (Mougamba, 1999), and (3) the switch from a general aggradation to a progradational stratigraphic pattern along West-equatorial Africa margins (Séranne, 1999; Séranne and Anka, 2005).

Neogene depocenter migration: salt tectonics and Congo canyon incision.

It has been shown that on the northern slope there is an upward substitution of turbidite facies by slope hemipelagics since the Miocene-Pliocene boundary, which is simultaneous to a basinward shift of the turbidite channels and a general progradation of the fan system (Fig 8). A possible driving mechanism for these fairly abrupt shifts is the onset of a submarine canyon during latest Miocene-earliest Pliocene. This paleo-canyon, probably located near to the present-day one, acted as a confining transit axis for the turbidite flows and the continent-derived clastics are delivered seawards of the previous Oligo-Miocene turbidite deposits. As a consequence, the Oligo-Miocene depocenter becomes a sediment-bypass area where slope hemipelagics is the prevailing sedimentation since the time of canyon incision. The existence and timing of this paleo-canyon is also supported by 3D seismic data, which show a conspicuous lower-Pliocene erosional surface below the Present-day canyon (Ferry *et al.*, 2004). This initial canyon incision has been followed by at least four erosion-filling phases until the Present (Gay, 2002). Its driving causes are still matter of debate, some authors propose an allocyclic -climatic or eustatic- origin (i.e. Babonneau *et al*. 2004, Turakiewicz, 2004, Ferry *et al.* 2004), while others suggest a local tectonic origin: graben collapse induced by the movement of a deep basement structure (Cramez & Jackson, 2000). Another possible cause may be related to an acceleration phase estimated by Lavier *et al*. (2001) on the margin uplift-rate at about 5 Ma. Since this uplift rejuvenation is likely to have caused a relative sea-level low, the initial canyon incision could be a by-product of sub-aerial erosion on the proximal areas.

We have individualized the fan deposits into two, pre- and post- reflector R, intervals: Oligocene-Miocene and Pliocene-Present (Fig. 11). The first period is characterized by two main depocentres: (1) one in the south-eastern upper slope (Angola) roughly oriented NW-SE and parallel to the upslope growth faults, and (2) one to the northwest (Congo), centred on the present-day canyon axis (Fig. 11a). The much thinner Pliocene-Recent deposits show only one depocentre, which is located basinwards of the salt limit (Fig. 11b) and is related to the previously-described general progradation of the submarine fan (Fig. 8) .

The integration of published information from several different sources allows deciphering the relative timing of the turbidite deposits within the two depocenters developed during the Oligocene-Miocene (Fig. 12). In Block 4, located near the south-eastern depocenter on the Angolan margin, lower-Miocene turbidite deposits are replaced by slope hemipelagics during middle Miocene (Anderson et al., 2000). In the western neighbouring

Block 17, the turbidites are found until mid-Miocene and slope hemipelagics replace them since late Miocene (Kolla *et al.*, 2001). In addition, to the west of both blocks, in the massive salt domain we find deformed inter-diapir channel-like deposits that are replaced by slope hemipelagics during late Miocene. This indicates that in the south-eastern depocenter (Angola) the successive replacement of turbidite deposits by slope hemipelagics occurs from east to west. That is, the western part of this depocenter receives turbidite flows for a longer time – until mid-late Miocene- than the eastern part, where the substitution by slope hemipelagics started earlier –by middle Miocene-. Then, from late Miocene to the Present, the dominant deposits throughout this south-eastern depocenter are slope hemipelagics. In contrast, the north-western depocenter (Congo) contains turbidite deposits spanning throughout the Oligocene and Miocene. In fact, a level of upper Miocene channels has been identified (Ferry *et al.*, 2004), which proves that turbidite flows continued to fill this depocenter even after turbidite deposition has already ceased on the south-eastern depocenter (Angola).

All these observations suggest that: (1) Although the north-western depocenter received episodic turbidite flows, the lower-middle Miocene turbidite sedimentation takes place mainly in the south-eastern depocenter (Fig. 11a). (2) Within this depocenter there is a westward migration of turbidite deposits during middle-late Miocene (Fig 12 -1). This event was probably linked to an enhanced downslope salt flow across the Angola margin driven by the combined action of continuous sediment input and the mid-Miocene westward tilting of the margin (Brice *et al.*, 1982; Walgenwitz *et al.*, 1990; Lavier *et al.*, 2000). (3) The relief of the Angola escarpment, which is still building up in the Present (Figs. 3, 9), must have developed during late Miocene at the time of the substitution by hemipelagic facies (Fig 12-2). (4) As accommodation space decreases across the Angola margin due to the accelerated rise of the salt walls turbidite flows are deflected to the northwest (fig 12-3), where gravitational gliding of the sedimentary cover ceased during the Oligocene (Fig. 9) and accommodation space is still available, filling this depocenter until the end of Miocene (Fig. 11a). (5) Then it follows the general basinward migration of the fan's turbidite channels that filled the post-Miocene depocenter while hemipelagic deposition dominates the slope (Figs. 8, 11b). Since the Pliocene to the Present, no turbidite deposition is recorded in the northern slope, but in the abyssal plain.

Based on the findings and the above discussion, we propose that the general time-space partitioning of sedimentation within the deep-sea fan, results from the interplay among margin uplift/tilting, growth of diapirs in the salt ridge, and canyon incision that can be explained as follows:

i) During Oligocene-early Miocene, unconfined turbidite flows were mainly controlled, and directed by the margin-parallel listric faults, associated to extensional salt tectonics, and by inter-diapirs "valleys". Hence, the deposition occurs mainly in NW-SE grabens and in ponded inter-diapir basins in the slope, feeding primarily the south-eastern depocenter (Fig 13a).

ii) Continuous increase in sediment supply and the seaward tilting of the margin during middle Miocene (Brice *et al.*, 1982; Walgenwitz *et al.*, 1990; Lavier *et al.*, 2000) enhances differential loading on the southern margin. Up-dip extensional salt and raft tectonics trigger the gravitational gliding of the sedimentary wedge, which creates additional accommodation space and terrigenous deposits migrate westwards.

iii) The seaward withdrawal of salt that accommodates the upslope extension increases downslope-compressional salt tectonics and activates the up-building of massive salt walls – which is still active today- and triggers the development of the Angola escarpment during late Miocene (Fig 13b). Since the sediments are no longer able to cross this massive salt domain the channels connected to the river outlet deflect the turbidite flows to the northwest, driving the northward shift of the transfer zones.

iv) At the Miocene/ Pliocene boundary, the interaction between the erosion linked to an acceleration on the margin uplift-rate and the instability created by the structural growth of rising diapirs on the salt ridge favours the onset of a paleo Congo canyon, which confined the turbidite flows. Continent-derived sediments bypass the shelf and slope and are delivered directly into the abyssal plain. As a consequence, the whole system progrades basinwards and the slope deposition is dominated by fine-grained hemipelagic deposits ever since (Fig 13c).

6.- Conclusions

The analysis of 2D seismic reflection data from the abyssal plain and the northern slope of the Lower Congo basin allowed us to integrate these relatively unknown distal domains, where the main depocenters of the Congo submarine fan are located, with the better-constrained successions in the shelf and upper slope. The results yield a contribution to better understanding the signature in the ultra-deep accumulations of geological processes acting on the continental margin and the resulting partitioning of sediment transport in areas of high river input.

We show that reported low sediment rates during Coniacian-Eocene, associated to a deepening registered in the shelf, are recorded in the abyssal plain as a single very-high seismic amplitude reflector representing a long-period of post-Turonian to Eocene condensed sedimentation and distal basin starvation. Prior to this event, a large Albian-Turonian unit exists, which is likely to be the abyssal-plain equivalent of the upper-Cretaceous carbonate shelf described in the literature.

The onset of the giant Tertiary Congo-deep-sea fan, in early Oligocene, follows the basin starvation event and reactivates the abyssal plain as the main depocenter in the basin. Two regional cross sections running through the Congo and Angola slope and into the deep basin provide the basin-wide architecture and show that the Tertiary fan deposits, although more important in the Angola margin, are indeed homogeneously distributed in the lower slope and abyssal plain.

Our model proposes that the interplay between sediment supply, margin Neogene uplift, and salt tectonics is reflected in the migration of the fan depocenters during the Neogene. Continuous and increasing sediment influx associated to the development of the Tertiary fan, in addition to the westward-tilting of the margin, drives the growth of the massive salt domain and the development of the Angola escarpment, which in turn leads the northwestern migration of the sediment transfer zones during late Miocene. There is a general basinward progradation of the fan depocenter during Pliocene until the Present driven by the incision of the Congo submarine canyon in latest Miocene- early Pliocene. This last might have resulted from erosion associated to the relative sea-level fall triggered by acceleration on the rate of the margin uplift.

Future work will address the nature of the distal upper-Cretaceous unit, its potential as hydrocarbon source rock and possible relation with gas-leakage features reported in the slope of the basin.

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Figure captions

Fig.1.

Location of the Congo deep-sea fan complex in the context of the South Atlantic and the West African margin. The fan is currently sourced by the Congo River whose drainage basin (white line) is about $3.7x10^6$ km². There is a direct connection between the river mouth and the fan through the Congo submarine canyon, so terrigenous sediments bypass the shelf and slope, and are directly delivered to the abyssal plain, basinward of the Angola escarpment. (Sea-floor bathymetry and land topography DEM from Gtopo30).

Fig 2.

Generalized litho-stratigraphy and main post-rift tectonic events registered on the shelf and upper-slope of Lower Congo basin (compiled and modified from Jansen 1985, Mougamba 1999, Anka and Séranne, 2004, and internal reports from Total).

Fig 3.

EM12 bathymetry (within the dash-lined rectangle) and 2D seismic reflection dataset from the ZaiAngo project analysed in this work. The grid consists of about 19000 km seismic profiles and covers an approximate area of 200,000 km² between 2000 and 5000 m of bathymetry. The base of the present-day slope is defined by the limit of the Aptian salt basin. White dots in the northern slope are sites from ODP leg 175. Black rectangles are seismic profiles shown in figs. 5-9. The Angola escarpment is an impressive margin-paralleled salt ridge located southwards of the Congo canyon.

Fig 4.

Block diagram showing the schematic spatial distribution of the facies in the Quaternary fan and their seismic signatures (Droz et al., 2003; Turakiewicz, 2004). These last were used as identification criteria for the seismic facies in the older fan deposits.

Fig 5.

Uninterpreted (upper panel) and interpreted (lower panel) seismic profile showing the distribution of the seismic units identified around the transition between the slope to the abyssal plain of the Lower Congo basin (see location in figure 3). The base of the present-day slope is defined by a toe-thrust of the Aptian salt level over the most basal oceanic unit A1. The age control of seismic markers was achieved by correlation to wells in the upper-slope and shelf. TC: top Turonian, BO: base of Oligocene, R: boundary Miocene-Pliocene. (The details of each unit are given in the text).

Fig 6.

Detail of the truncation of high-amplitude, semi-continuous internal reflectors of seismic unit A1 against the unconformity TC in the slope. Note the contrast with the seismic characteristics of overlying unit A2, mainly composed of low-amplitude and discontinuous reflectors, which thins significantly to the West, in the abyssal plain (see location in figure 3).

Fig 7.

Uninterpreted and interpreted seismic profile across the upper slope showing stacking, discontinuous and high-amplitude reflectors of unit A3 onlapping the base of the Oligocene (see location in figure 3). This pattern differs from the aggradation of underlying units A1-A2, which suggests a drastic change in the nature of sedimentary deposits during early Oligocene. Upper-most unit A4 consists mostly of slope hemipelagic deposits and is densely affected by vertical faulting that has been related to upward fluid expulsion (Gay, 2004).

Fig 8.
Upward substitution of the Oligo-Miocene turbidite deposits of unit A3 by slope hemipelagics of unit A4 on the northern slope during reflector "R" time (Miocene-Pliocene boundary). In turn, the hemipelagic deposits shift to onlapping stacking channels basinwards. This seaward facies change takes place as unit A4 deepens and thickens considerably to the west (see location in figure 3).

Fig 9.
Regional transects across the Lower Congo basin, covering more than 800 km from the shelf domain into the abyssal plain. The geometry of the fan deposits is clearly depicted north (Congo) and South (Angola) of present-day Congo canyon. Salt-realted gravity gliding of the sedimentary cover is mostly Oligocene on nothern slope, while it is still active on the south. Note the relative thickness between the Oligo-Miocene deep-sea fan and the Plio-Quaternary. Shelf sections are modified from Lavier *et al.* (2001). (Read text for details).

Fig 10.
Isopach map of the Congo deep-sea fan deposits from Oligocene to Present. The main depocenter is homogenously distributed throughout the abyssal plain, and is centred on the present-day axis between the Congo canyon and the active channel. This clearly indicates the Congo River has been the main fan's feeder.

fig 11.
Isopach maps of the **a)** Oligocene-Miocene (unit A3) and **b)** Pliocene-Present (unit A4) deposits. The Oligo-Miocene succession presents two main depocenters located to the southeast, landward of the massive salt, and to the northwest, basinward from the salt limit. In contrast, the Pliocene-Present deposits are rather thin and present only one depocenter to the northwest. (The thin dashed line depicts the limit of the facies change in unit A4 shown in fig.8).

Fig 12.

Synthetic map depicting the relative timing and location of turbidite deposits within the 2 Oligocene – Miocene depocenters, based on published information. (1) During mid-Miocene there is a seaward migration of turbidite deposits on the southern slope (Angola) (2) No turbidite deposition is recorded on this slope since late Miocene, only hemipelagics (3) During late Miocene turbidite flows are redirected to the northwest (Congo) where four levels of turbidites are identified during the Oligocene- Miocene.

Fig 13.
Block diagram showing the proposed Congo submarine fan evolution since the Oligocene, and the interaction among the development of the Angola escarpment, the fan depocenter migration, and the submarine canyon incision. (See text for details).

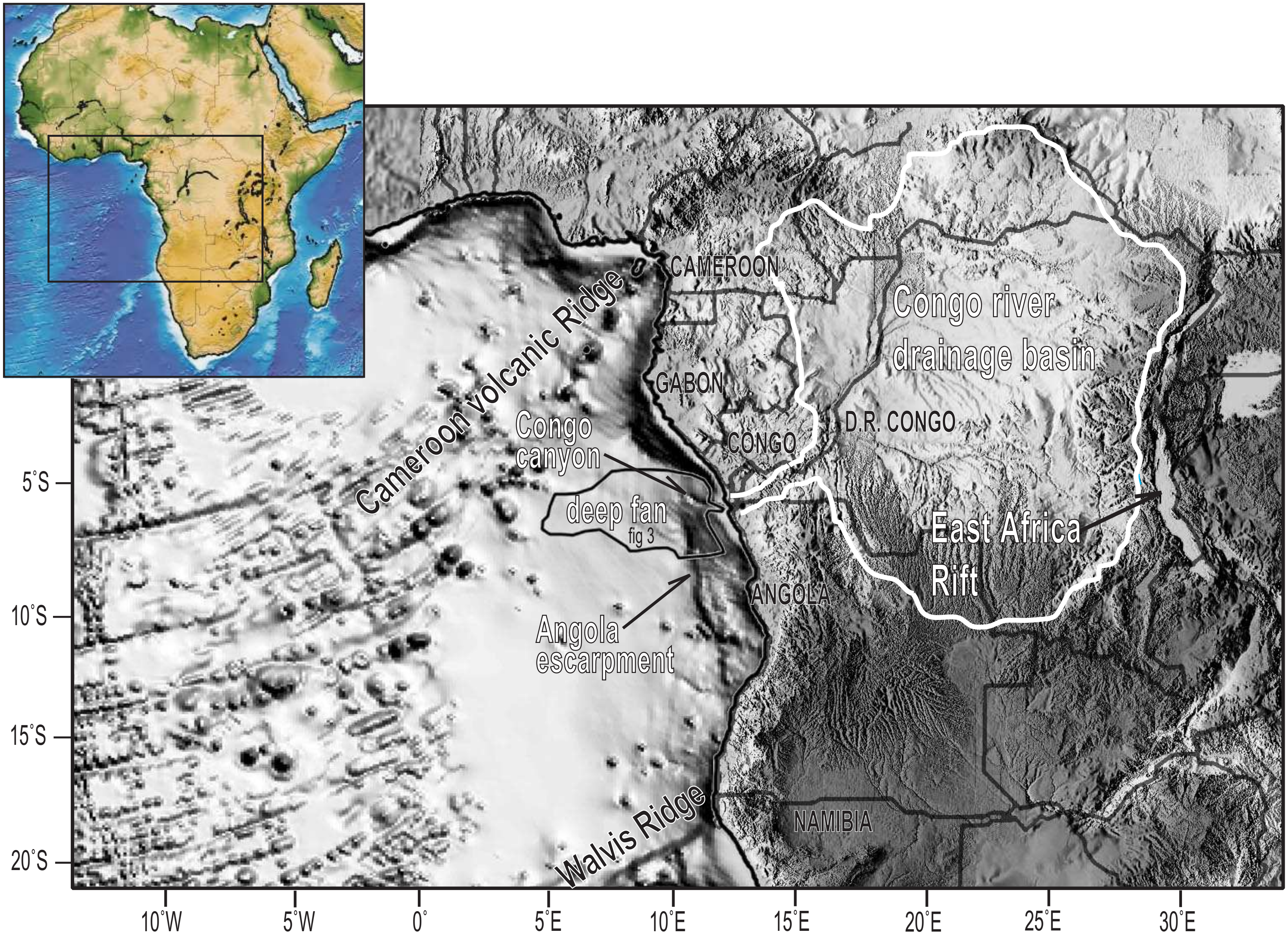

CAMEROON
Cameroon volcanic Ridge
GABON
CONGO
D.R. CONGO
Congo river drainage basin
Congo canyon
deep fan
fig 3
East Africa Rift
ANGOLA
Angola escarpment
Walvis Ridge
NAMIBIA
5˚S
10˚S
15˚S
20˚S
10˚W
5˚W
0˚
5˚E
10˚E
15˚E
20˚E
25˚E
30˚E

Figure 1

Figure 2

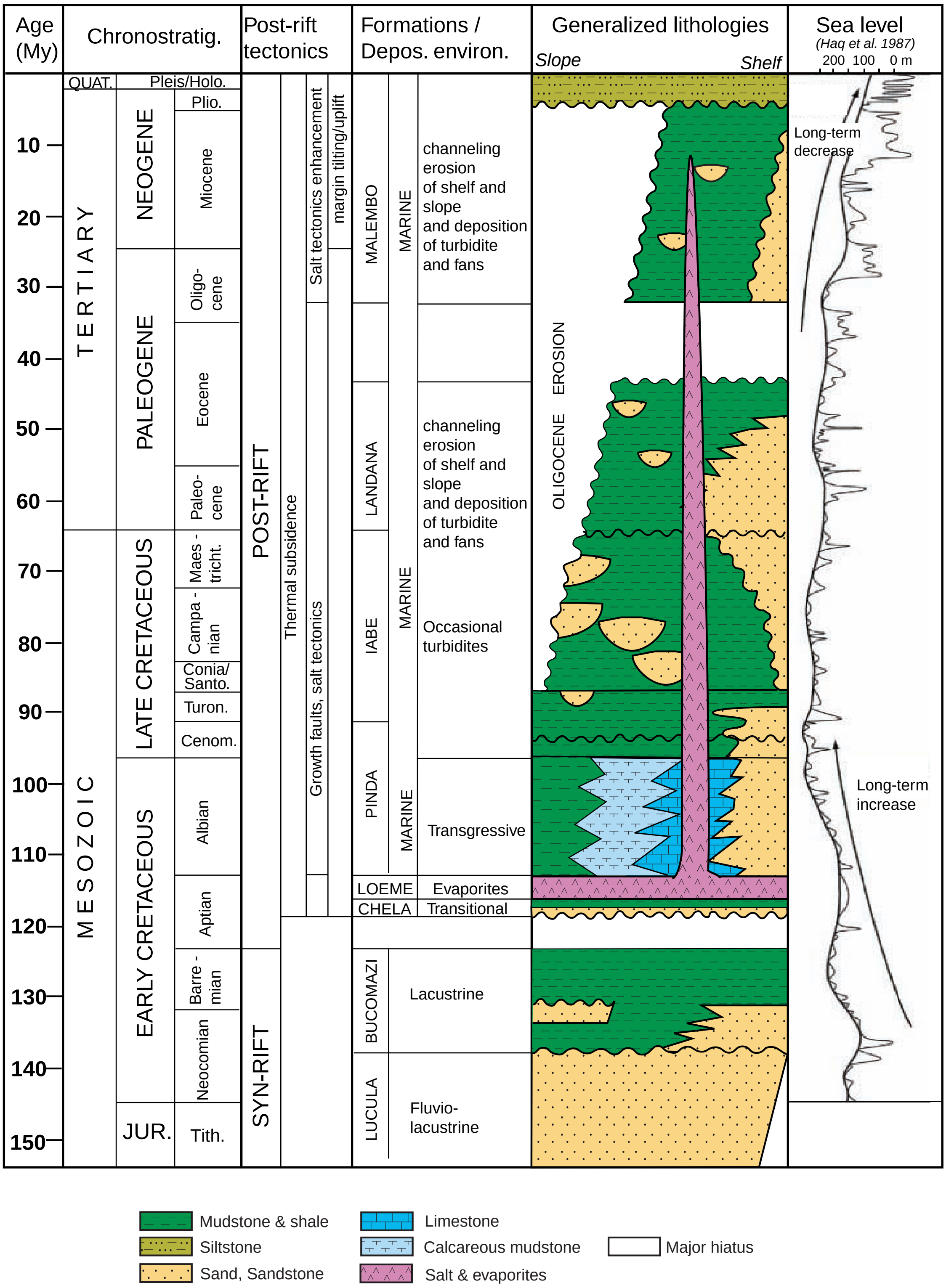


Figure 2.

Figure 3

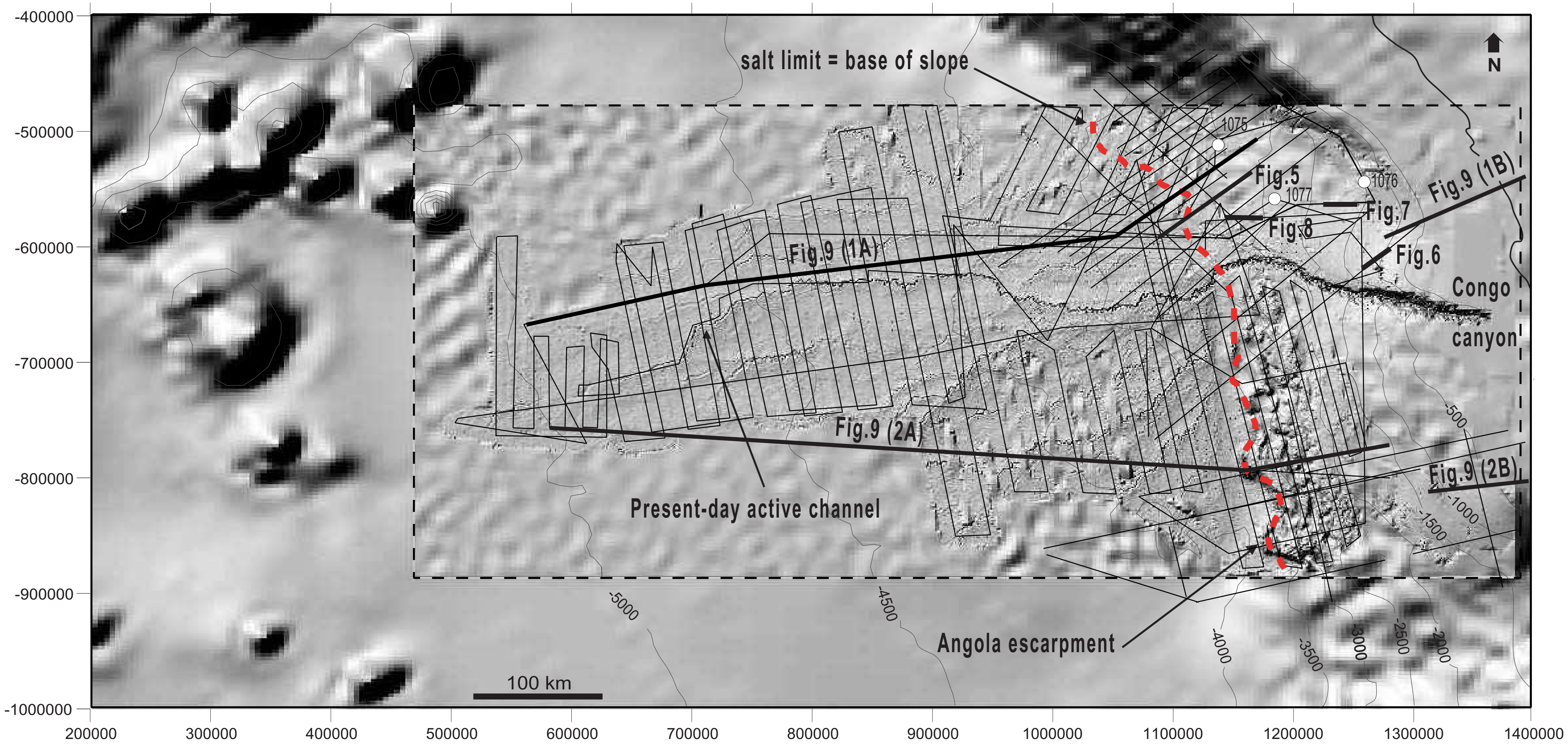


Figure 3

Figure 4

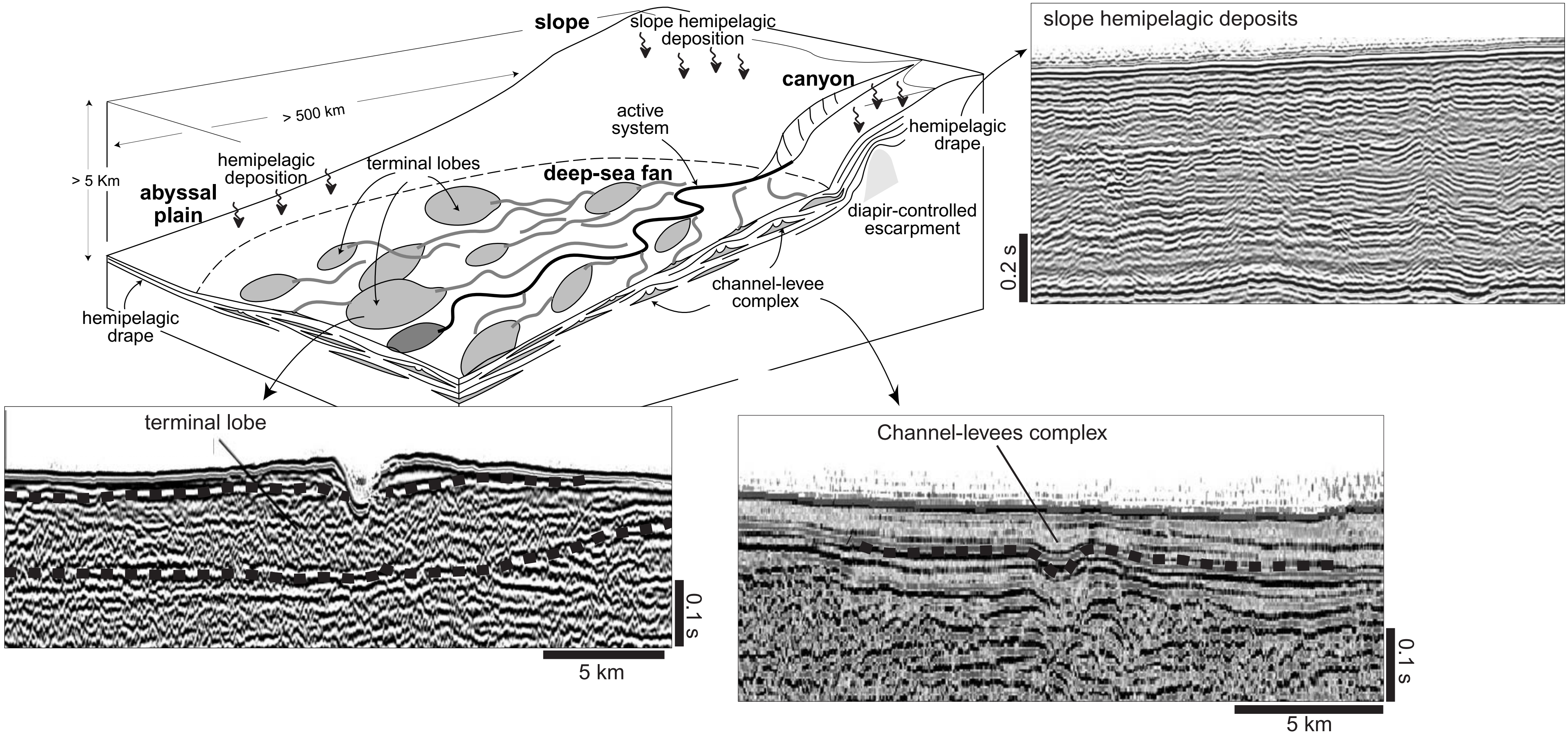


Figure 4

Figure 5

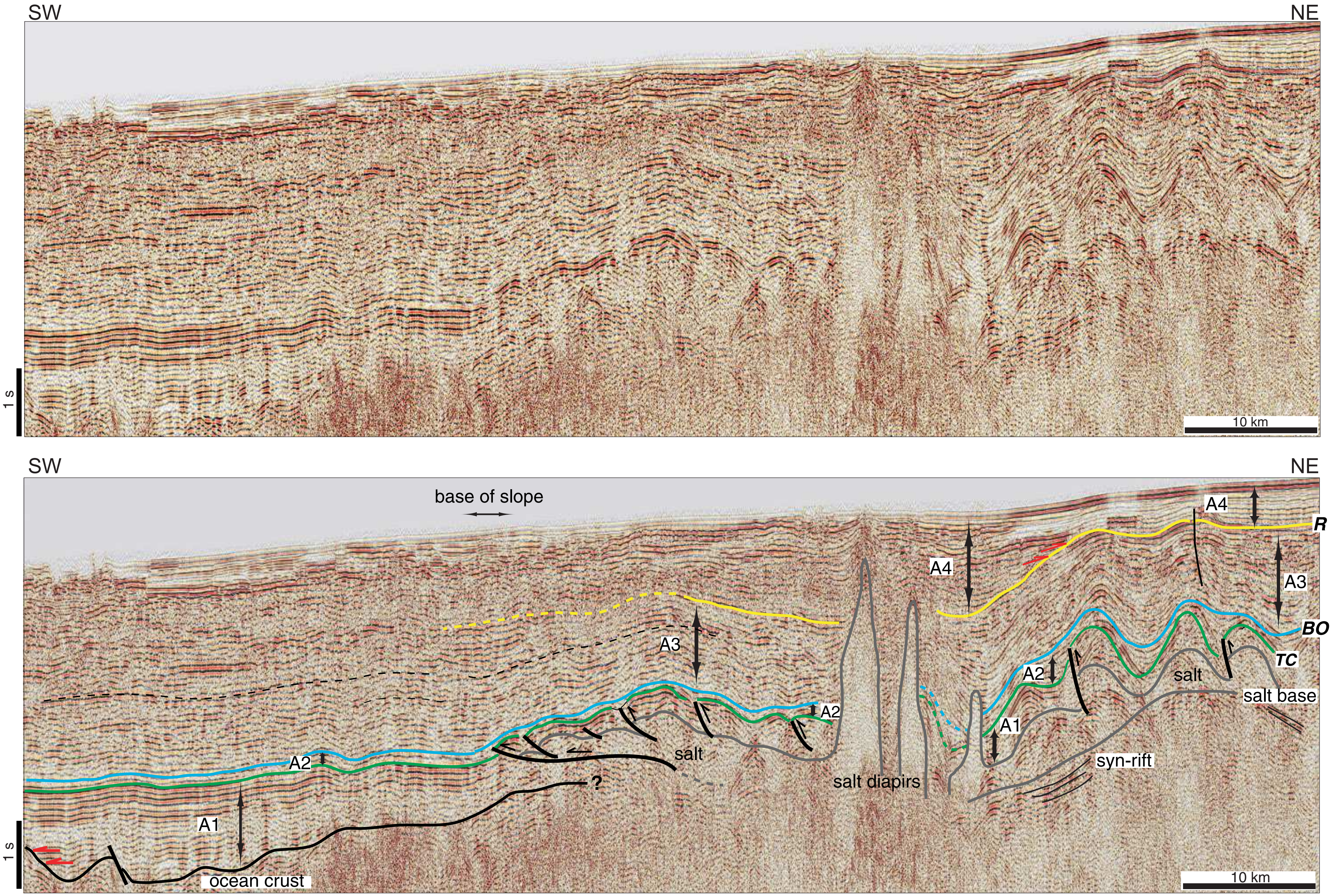


Figure 5

Figure 6

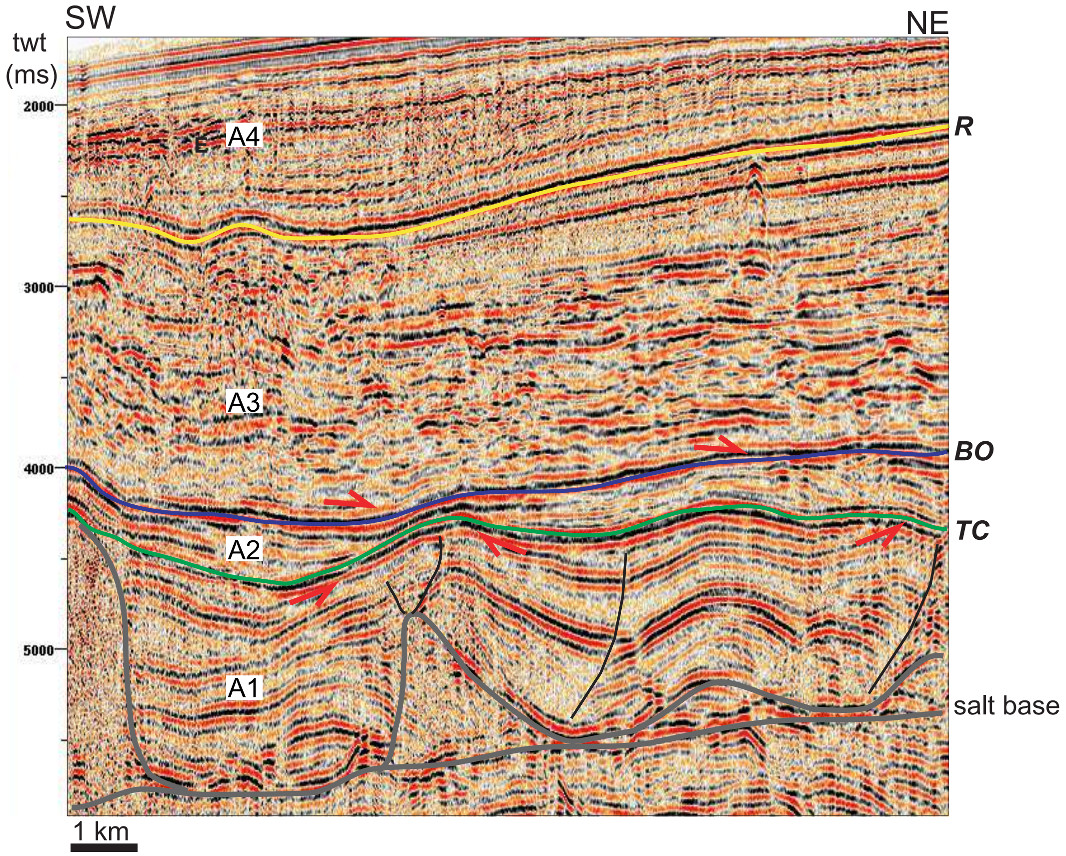


Figure 6

Figure 7

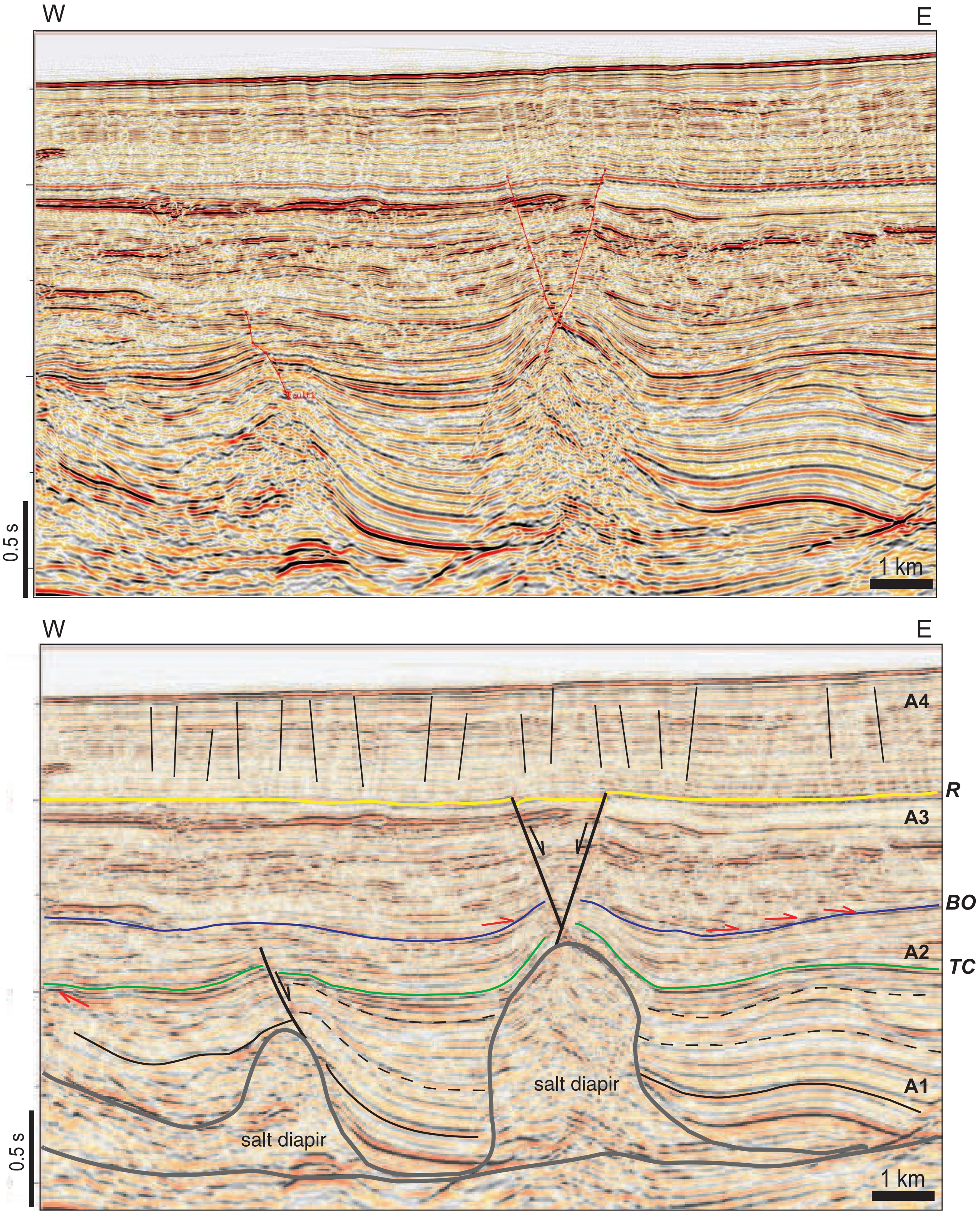


Figure 7

Figure 8

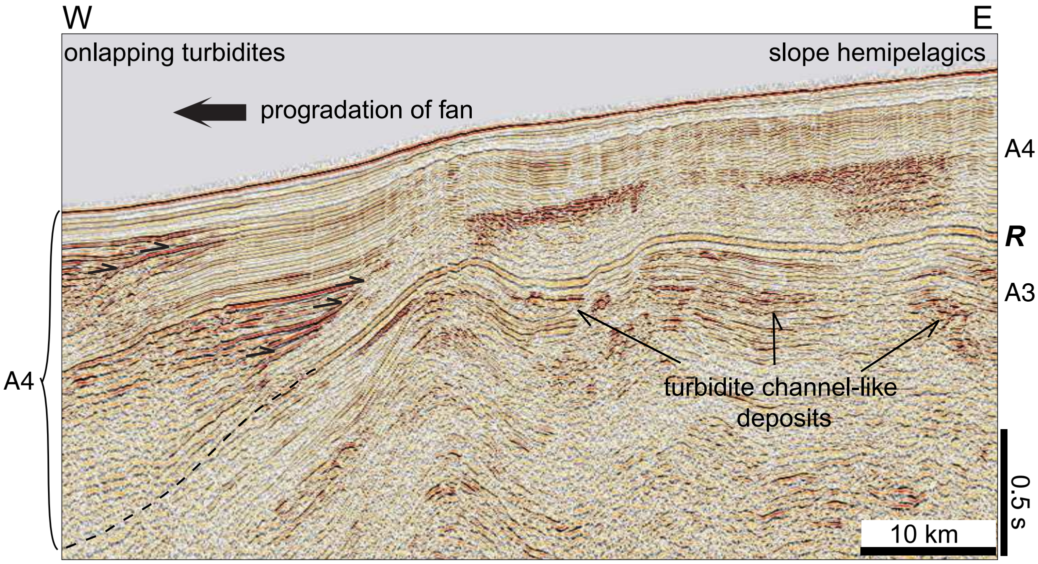


Figure 8

Figure 9

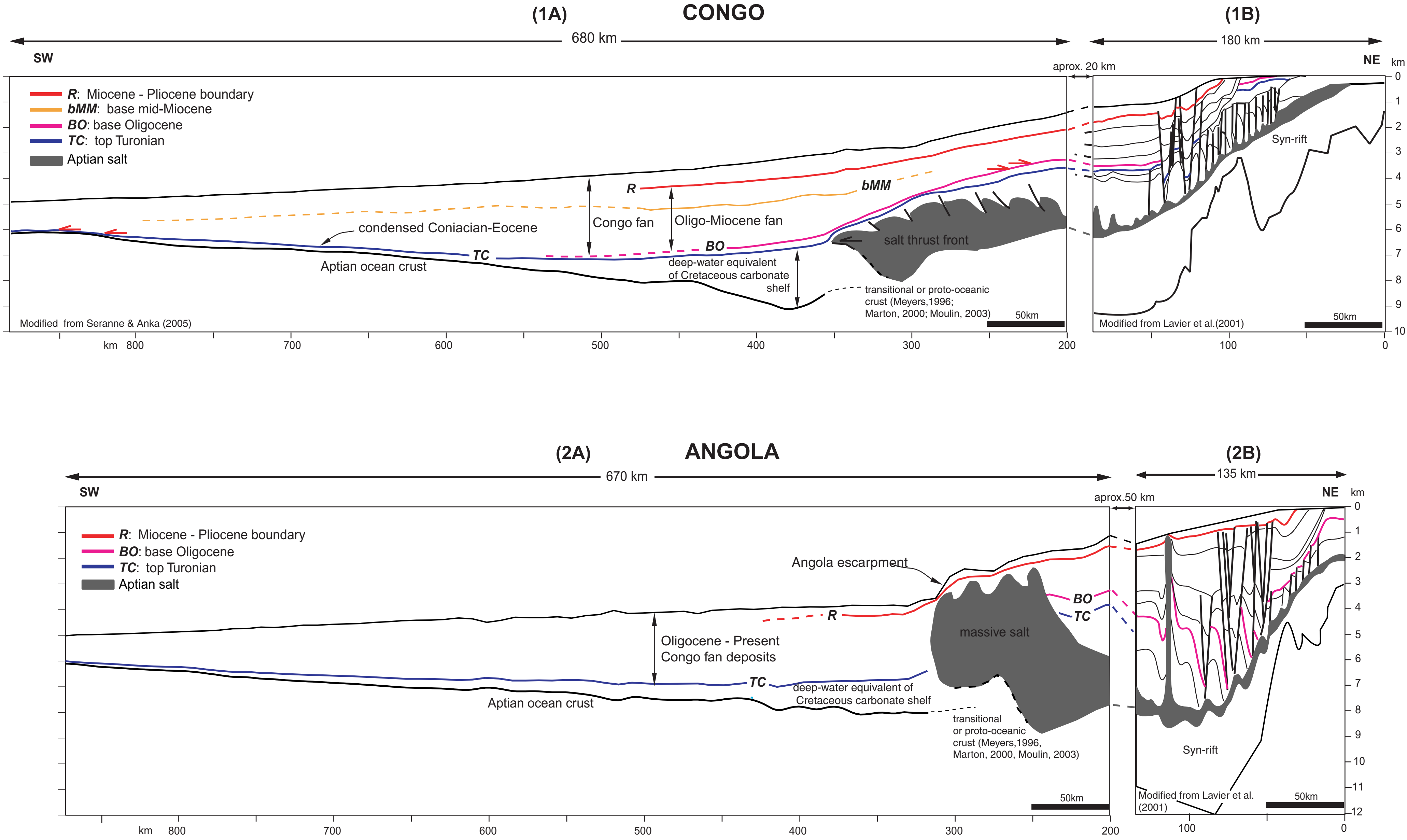


Figure 9

Figure 10

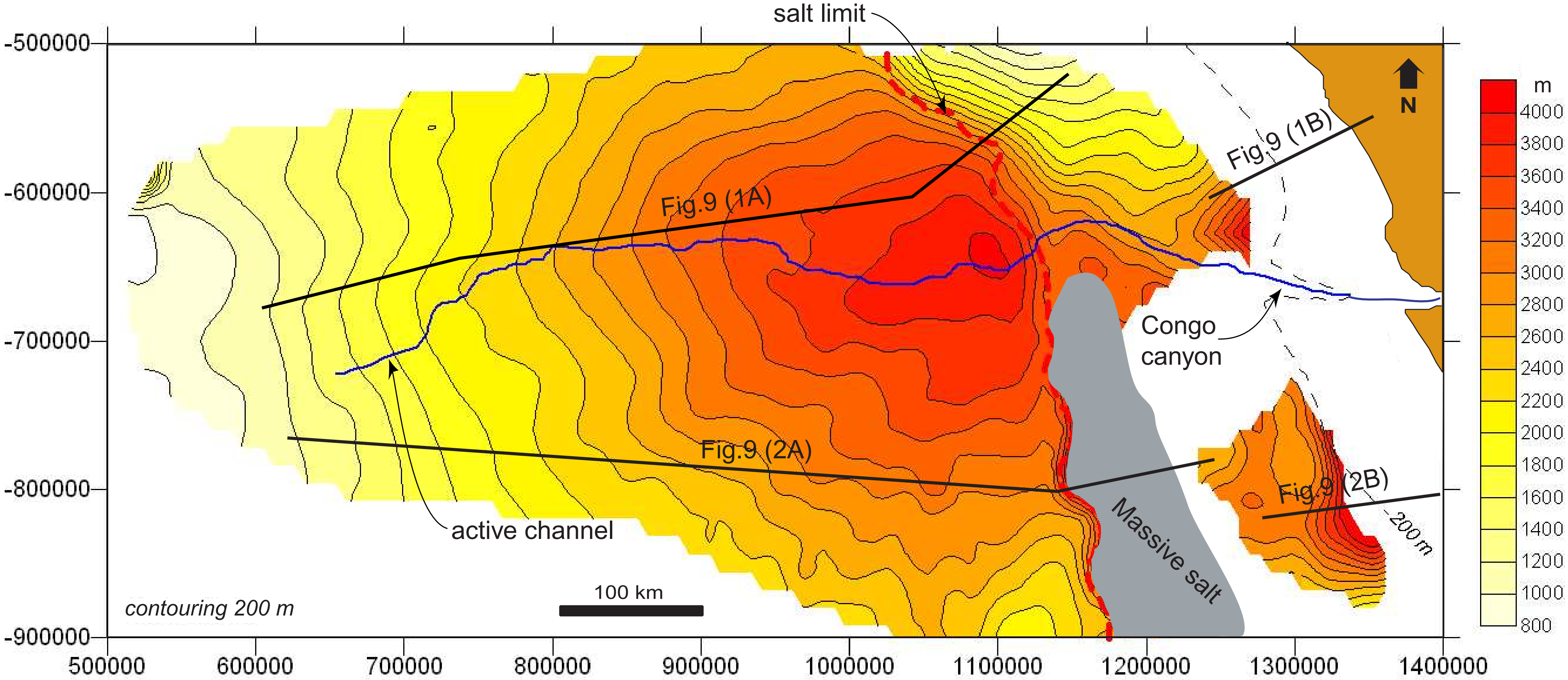


Figure 10

Figure 11

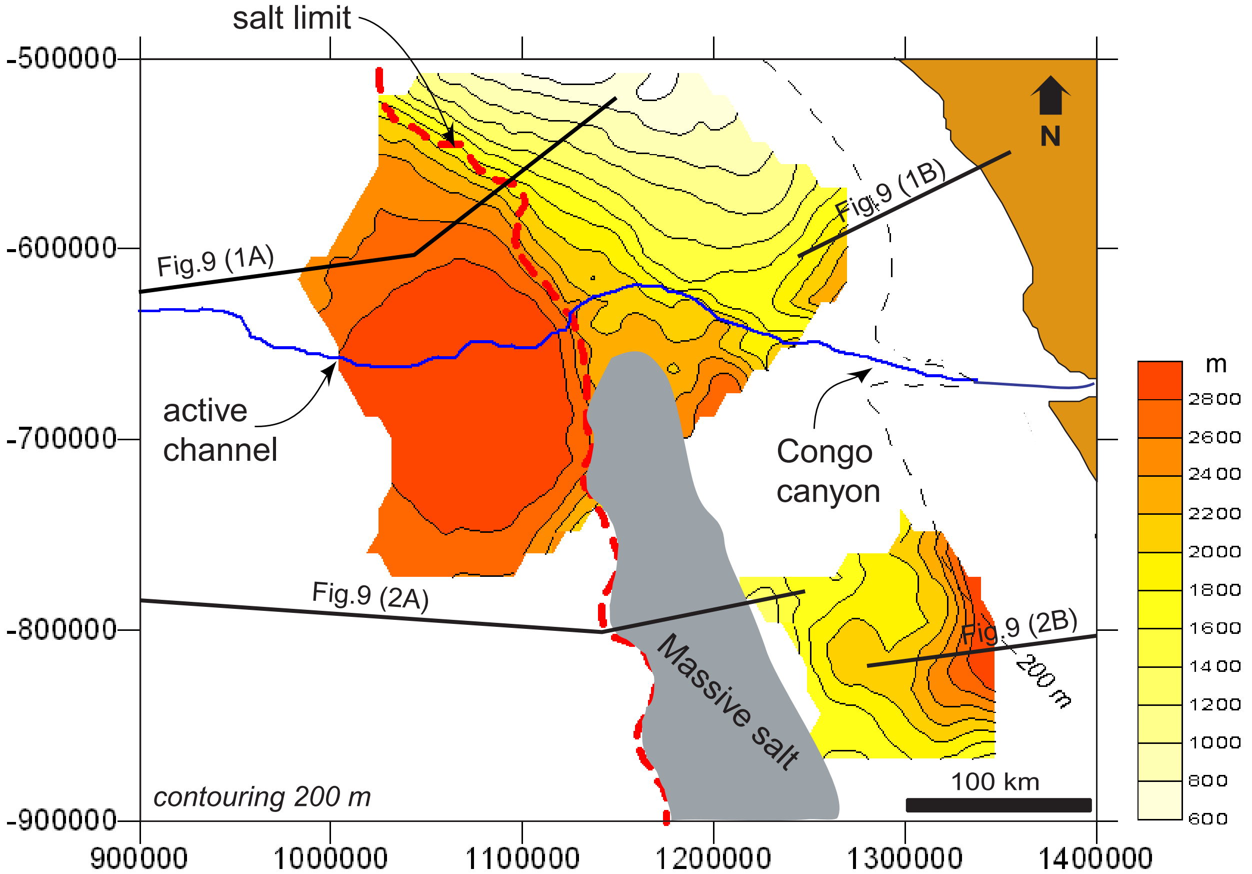


Figure 11a

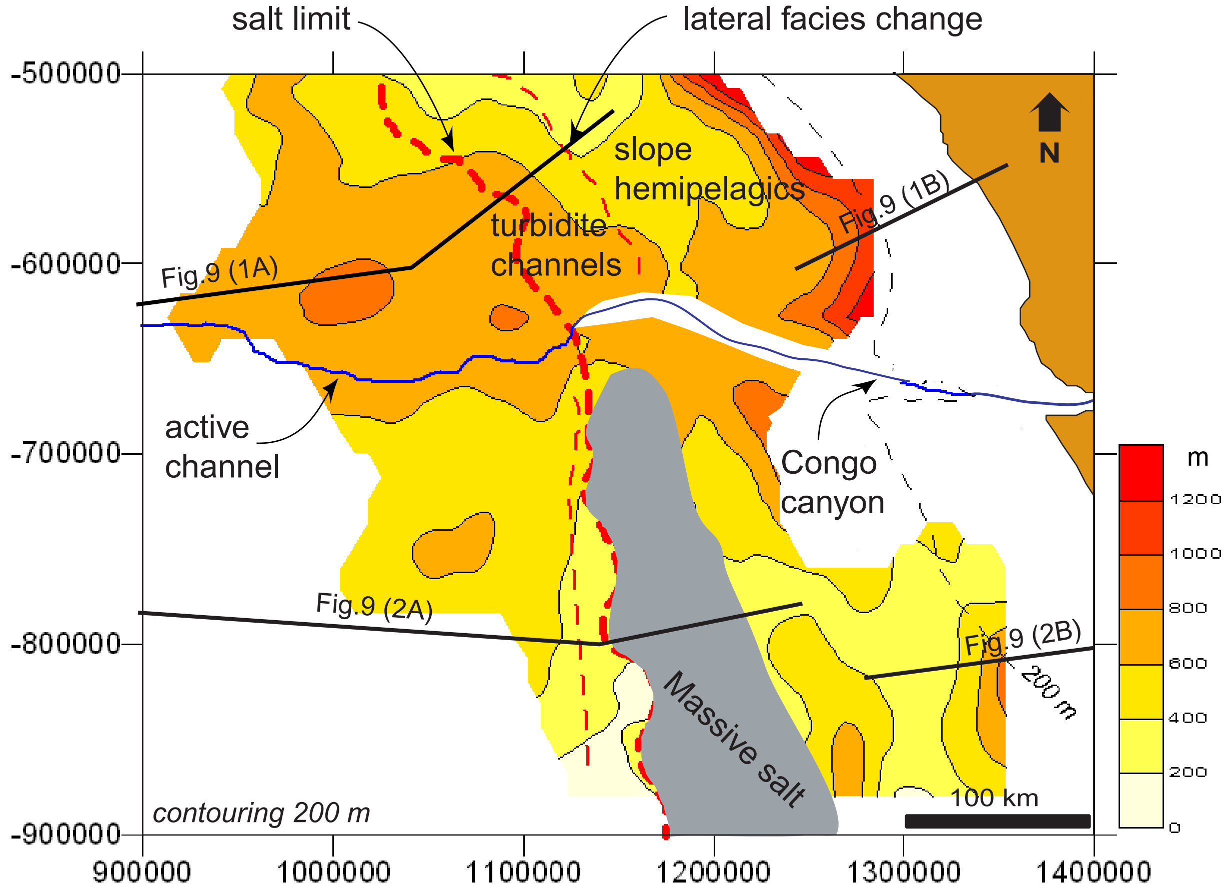


Figure 11b

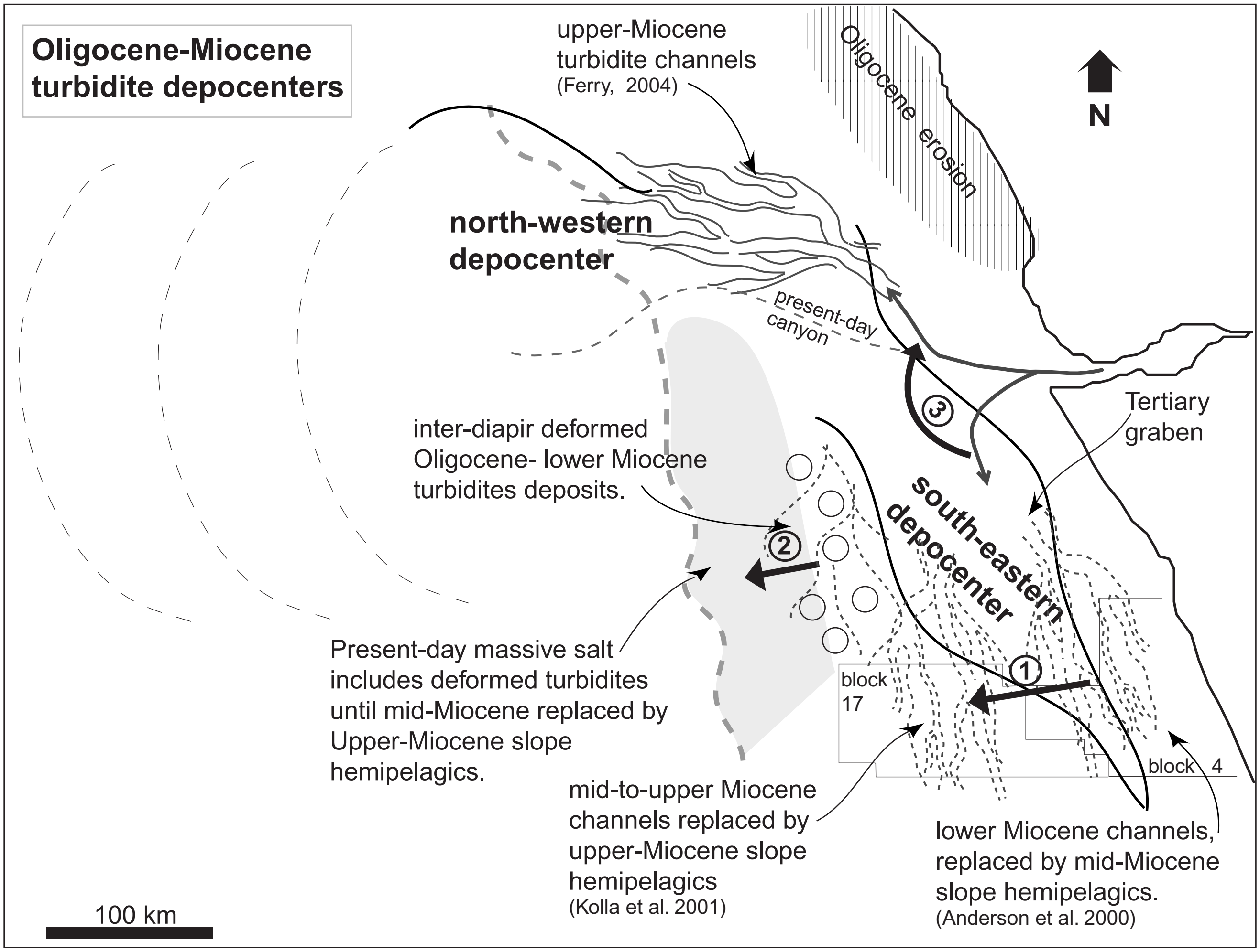
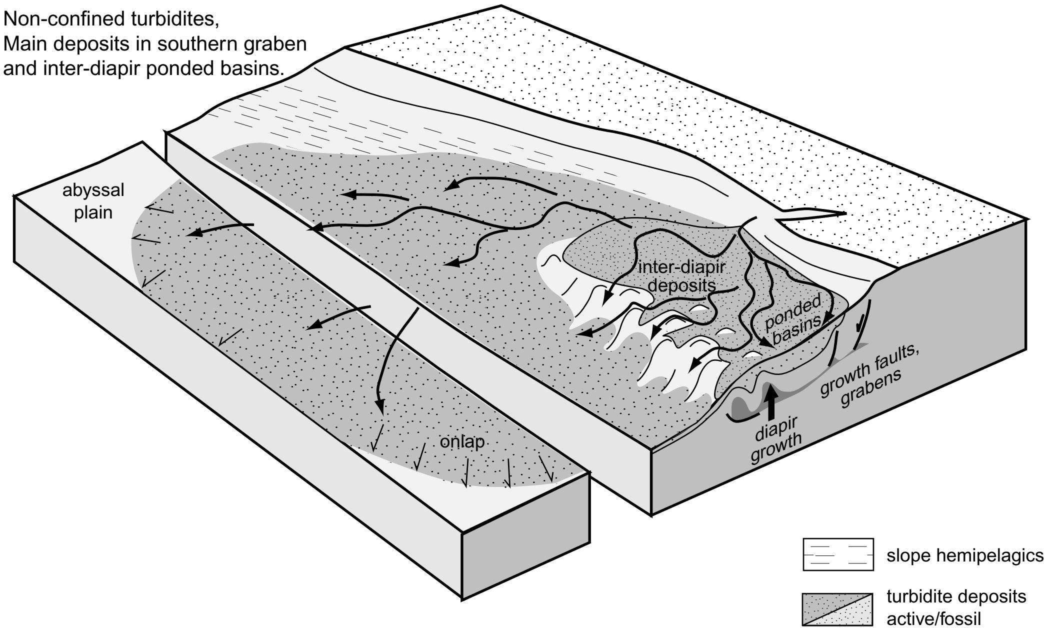

Oligocene-Miocene turbidite depocenters
upper-Miocene turbidite channels
(Ferry, 2004)
Oligocene erosion
N
north-western depocenter
present-day canyon
③
Tertiary graben
inter-diapir deformed Oligocene- lower Miocene turbidites deposits.
②
south-eastern depocenter
Present-day massive salt includes deformed turbidites until mid-Miocene replaced by Upper-Miocene slope hemipelagics.
block 17
①
block 4
mid-to-upper Miocene channels replaced by upper-Miocene slope hemipelagics
(Kolla et al. 2001)
lower Miocene channels, replaced by mid-Miocene slope hemipelagics.
(Anderson et al. 2000)
100 km

Figure 12

Figure 13

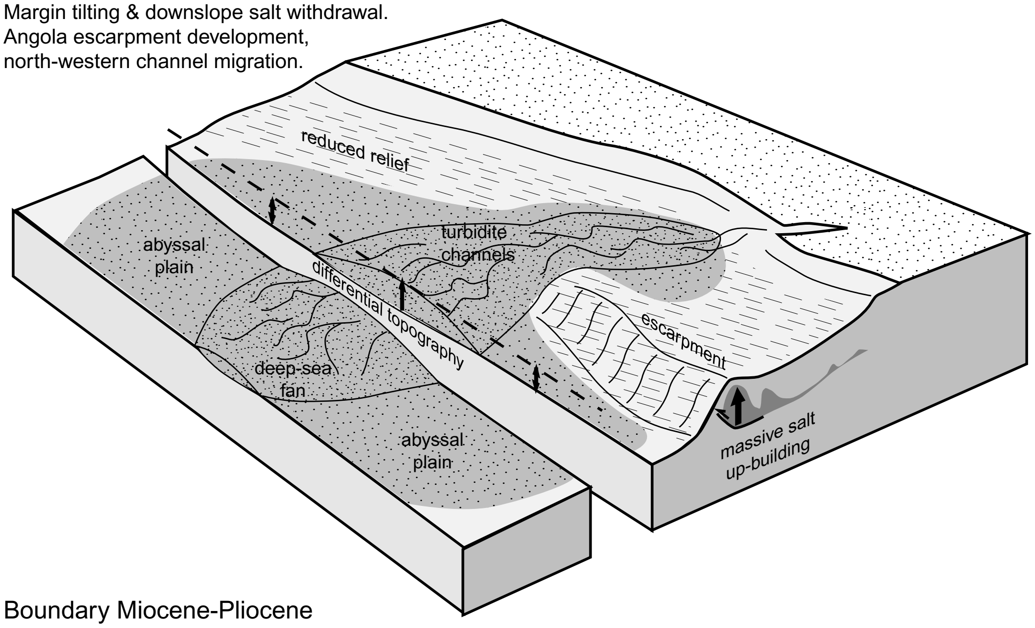
a) Oligocene - early Miocene

Non-confined turbidites,
Main deposits in southern graben
and inter-diapir ponded basins.



b) Late Miocene

Margin tilting & downslope salt withdrawal.
Angola escarpment development,
north-western channel migration.



c) Boundary Miocene-Pliocene
(Reflector "R" time)

Acceleration margin uplift-rate, canyon incision, confined flow,
basinward progradation of deep-sea fan.

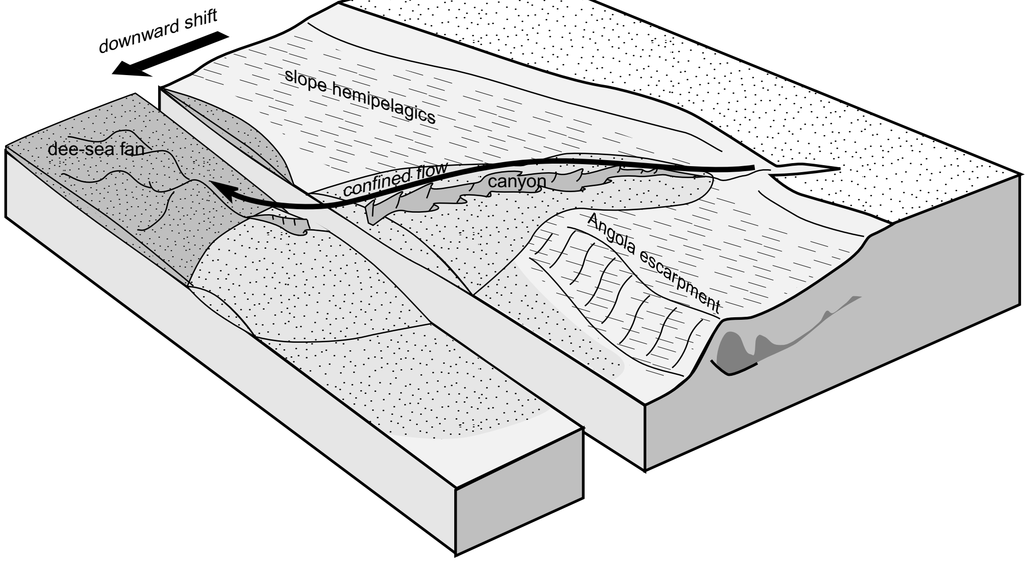


figure 13.