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Seismic characteristics of sediment drifts: An example from the Agulhas Plateau, southwest Indian Ocean

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Abstract

Sediment drifts provide information on the palaeoceanographic development of a region. Additionally, they may represent hydrocarbon reservoirs. Because of this, sediment drift investigation has increased over the last few years. Nevertheless, a number of problems remain regarding the processes controlling their shape, the characteristic lithological and seismic patterns and the diagnostic criteria. As an example, sediment drifts from the Agulhas Plateau, southwest Indian Ocean, are presented here. They show a variety of seismic features and facies including an asymmetric mounded geometry, changes in internal reflection pattern, truncation of internal reflectors at the seafloor and discontinuities. This collection of observations in combination with the local oceanography appears to comprise a diagnostic tool for sediment drifts.

Introduction

Deep-water bottom currents and deep-reaching wind-driven surface currents (in this paper the term bottom currents will be used as a synonym for both types since they result in the same kind of deposit) have been the focus of a number of investigations over the last 40 years (e.g., Heezen et al., 1966; Faugères and Stow, 1993; Shanmugam et al., 1993; Stow et al., 1998; Shanmugam, 2000; Stow and Mayall, 2000). Still, a number of items concerning contourites including e.g. the processes of bottom current deposition, the seismic patterns and the paleocirculation patterns recorded in contourite drifts remain to be discussed (Faugères and Stow, 1993).

One way to characterise sediment drifts and thus approach a solution to the mentioned problems is a seismic investigation of those features. Seismic data from the Agulhas Plateau clearly show structures which have been interpreted as sediment drifts (Uenzelmann-Neben, in press). Those structures will be presented and discussed with respect to the seismic characteristics, which qualify them as sediment drifts.

Geological and oceanographic setting of the Agulhas Plateau

The Agulhas Plateau forms a morphological structure about 500 km southeast of the Cape of Good Hope in the southwesternmost Indian Ocean where it rises up to 2,500 m above the surrounding seafloor (Figure 1). The plateau was formed during the early stages of the opening of the South Atlantic about 90 my ago. The exact tectonic evolution has been widely discussed. The latest hypothesis considers the main crustal growth to have been controlled by the proximity of several spreading centres and passage over the Bouvet Hotspot at 80–100 Ma, and thus adds the plateau to the world-wide suite of large igneous provinces (LIP) of predominantly oceanic origin (Labreque and Hayes, 1979; Allen and Tucholke, 1981; Martin and Hartnady, 1986; Kristoffersen and Labreque, 1991; Ben-Avraham et al., 1995; Uenzelmann-Neben et al., 1999; Gohl and Uenzelmann-Neben, 2001).

Reconstruction of the plateau's sedimentary development starting in the Maastrichtian appears to be difficult. As shown by sediment cores, the input of terrigenous material from Africa is small, with sedimentary sequences characterised by a number of hiati since Paleocene times due to low sedimentation rates as well as strong erosion (Barrett, 1977, Tucholke and

Carpenter, 1977, Dingle and Camden-Smith, 1979, Tucholke and Embley, 1984, Siesser et al., 1988). An erosional zone encircling the plateau has been traced back to the effect of the Antarctic Bottomwater (AABW, Camden-Smith et al., 1981, Tucholke and Embley, 1984), hence bearing witness to the activity of that current in this area.

Unfortunately, the paths, strengths, velocities and depths of water masses in the area of the Agulhas Plateau are known mainly in general terms and few details have been published. Since the strong increase of the glaciation of the West Antarctic in Middle Miocene times AABW has been active anticlockwise around the Agulhas Plateau (Tucholke and Embley, 1984). The western flank of the plateau shows a south-southwestward flow of AABW (Figure 1), and a strong northeasterly flow of AABW was reported across the southern margin of the plateau (Tucholke and Embley, 1984). From here the AABW turns east to flow into the Mozambique Basin (Read and Pollard, 1999). An erosional zone at the western rim and thinned sediments at the eastern flank are the result of this flow pattern (Tucholke and Embley, 1984).

A strong water mass transport across the Agulhas Plateau region was observed by Macdonald (1999), which involves the water column from the surface down to the Upper Circumpolar Deep WATER (UCDW). This indicates strong erosion due to intermediate and deep water. The surface Agulhas Current (AC) is a deeply reaching (2,000 m), fast current (Lutjeharms, 1996), which has a strong erosive nature. Shortly after reaching the South Atlantic the Agulhas Current retroflects and subsequently carries the bulk of its waters eastward, back into the Indian Ocean (de Ruijter et al., 1999). The Agulhas Current is very sensitive to bottom topography and its location at the retroflection is very unstable (Lutjeharms, 1996). The Antarctic Intermediate Water follows the same path near South Africa as the AC and also shows a retroflection. It then flows eastward across the Agulhas Plateau (Figure 1, Lutjeharms, 1996). Thus, the area south of Africa represents a critical gateway within the oceanic circulation system where Indian-Pacific Ocean and Atlantic Ocean watermasses meet.

Agulhas Plateau stratigraphic concept

All data presented here are multichannel seismic reflection data gathered on the southern Agulhas Plateau in 1997/1998 which were processed up to migration (for further details on data processing see Uenzelmann-Neben et al., 1999; Gohl and Uenzelmann-Neben, 2000). Amplitude transmission losses were removed using a spherical divergence correction. No automatic gain correction (AGC) has been applied for display. Thus, the seismic profiles show true amplitudes.

The stratigraphic concept used here is based on a stratigraphy presented by Tucholke and Carpenter (1977) and Tucholke and Embley (1984). They identified four distinct horizons in their seismic lines which they could date via ground truth data from piston and gravity cores and dredge samples. The horizons were related to regional hiati. A detailed correlation with the seismic data can be found in Uenzelmann-Neben (in press), which is shortly repeated in the following.

Sealevel highstand and low sedimentation rates led to a regional hiatus at the Paleocene/ Eocene boundary (Tucholke and Embley, 1984). This is documented via a reflection with strong amplitudes which runs mostly conformable to beds above or below (reflector LE in Figures 2–6). An Early/Middle Oligocene hiatus is interpreted to be the result of intensified abyssal currents, e.g. the production and spreading of the Antarctic Circumpolar Current (ACC, Tucholke and Embley, 1984; unfortunately, no flow paths for ACC across the Agulhas Plateau have been published). This led to an unconformity of medium to strong amplitudes (reflector LO, Figures 2–6).

Reflector Middle Miocene was inferred to have been formed by erosion and redeposition due to Antarctic Bottomwater (AABW, Tucholke and Embley, 1984). Weaker amplitudes and frequent wedge-outs at the seafloor characterise this reflector (Figures 2–6, reflector MM). The most important regional hiatus is of Upper Miocene/Lower Pliocene age and can be attributed to erosion and redeposition of sediments by circumpolar deep water within the ACC (Tucholke and Embley, 1984). This hiatus is represented by a strong reflection which is often found very close to and thus indistinguishable from the seafloor (reflector LP in Figure 2).

The veneer of Plio-Pleistocene sediments on top of reflector LP in places grows several 10s m thick. This is mostly the case where sediment drifts were identified on the Agulhas Plateau (Figure 2).

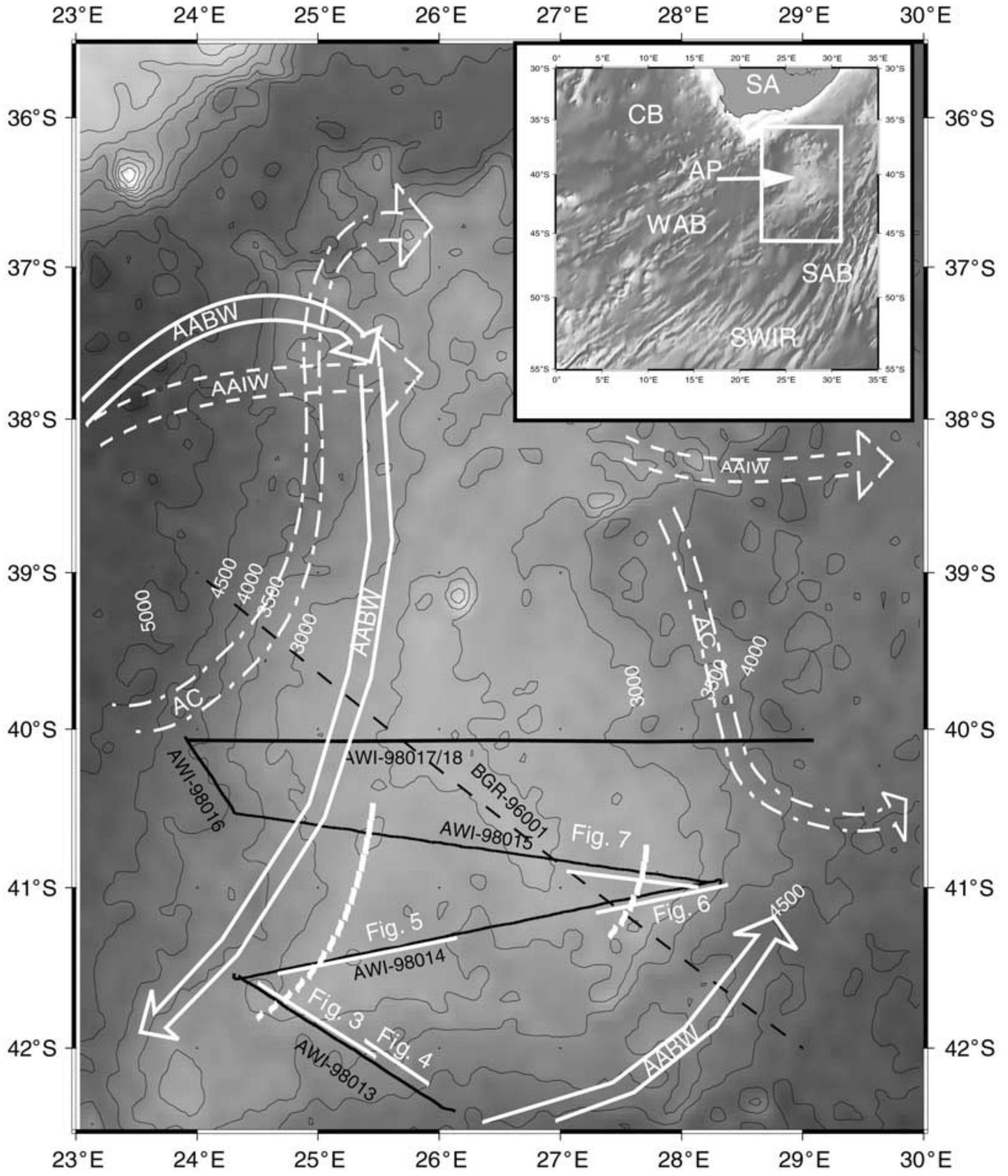

Figure 1. Bathymetric map of the Agulhas Plateau showing the location of seismic reflection lines. The numbers refer to the figures shown in the text. The insert map shows the location of the Agulhas Plateau relative to South Africa. Bathymetry is satellite derived from Smith and Sandwell (1997). The arrows show the present day flow path of the Antarctic Intermediate Water (AAIW), the Antarctic Bottomwater (AABW) and the Agulhas Retroflection (AR) (modified from Faugères et al., 1993, and Lutjeharms, 1996). The dotted lines show the crests of the identified drifts according to Uenzelmann-Neben (in press). AP = Agulhas Plateau, CB = Cape Basin, SA = South Africa, SAB = South Agulhas Basin, SWIR = Southwest Indian Ridge, WAB = West Agulhas Basin.

Agulhas Plateau sediment drifts

The Agulhas Plateau's main sedimentary features are structures which have already been reported as being shaped by bottom currents (e.g., Tucholke and Embley, 1984; Uenzelmann-Neben, in press). Those structures comprise dunes, drifts, channels, erosional unconformities and truncation of reflectors at the seafloor. But what are the seismic criteria which in detail qualify the structures as sediment drifts? This will be discussed for a number of examples (Figure 1). Unfortunately, neither side scan nor bore hole data exist to support the interpretation. Thus, the discussion is solely based on the seismic data and its correlation with the presented stratigraphy.

Starting in the southwest of the plateau a prominent feature with a mounded geometry can be observed (Figure 2). This feature is ~30 km wide at the seafloor (Figure 2, CDPs 5,000–6,300). The feature has its origin in the deeper sedimentary layers and was built-up since Lower Oligocene times (Figure 2, CDPs 3,300–5,400, 4.9–5.1 s TWT). Internal reflectors are truncated abruptly (Figure 2, CDPs 5,000–5,300 and 6,150–6,300). Several discontinuities and changes in the reflection pattern can be identified. Transparent units alternate with units characterised by continuous parallel reflectors (Figure 2b). Internal reflectors are truncated at the discontinuities (Figure 2b). We interpret this feature as a sediment drift, which is shaped by bottom currents on both flanks. The discontinuities as well as the changes in reflection pattern are probably the result of hydrographic modifications, which comprise modifications in flow velocity, current width and location and variations in surface water mass and productivity leading to changes in sediment composition (Faugères and Stow, 1993; Faugères et al., 1999).

Towards the southeast, the sediment drift thins and shows a more chaotic to hummocky reflection pattern (Figure 3). Here, the seafloor in part reflects the hummocky wavy pattern (Figure 3, CDPs 1,000–3,200). The different seismic facies observed represent different depositional processes. The transparent unit points towards a more uniform sedimentation, which can be the result of either a longer period of quiet sedimentation or increased sediment input within a shorter period. The sediment is probably deposited continuously at the side of the axis of the current (comparable to spill over?). The subparallel and chaotic units indicate an episodic deposition with more variability in either current velocity or sediment input or both (comparable to overbank deposition?).

Line AWI-98014 (Figure 4) crosses another drift about 20 km to the north where it shows a width of ~ 135 km and is distinctly mounded with an asymmetric geometry. On the western slope the internal reflectors are truncated at the seafloor indicating erosion (Figure 4). No indications can be found for major current erosion on the eastern side of this drift as detected for the drift farther south (Figure 2). We infer that such symmetry is due to Coriolis force enhanced sedimentation (McCave and Tucholke, 1986). In fact, the observed geometry is compatible with a leftward deflection (due to Coriolis force in the southern hemisphere) of a southward flowing current (like the AABW). The current responsible for erosion of the eastern flank, for which we found indications in the south, appears to flow northeastward across the plateau. Tucholke and Embley (1984) found indications for a similar current from bottom photographs. This current might result from a turning back of the western south setting current when encountering greater water depths at the southern tip of the plateau (a result of Coriolis force), flowing then northwards past the sediment drift observed on line AWI-98013.

The main body of the sediment drift on line AWI-98014 appears transparent or shows only weak amplitude reflections, which may be the result of a continuous deposition at the rim of the current (spill-over) onto the gentler side of the drift, thus building up the drift. It is difficult to determine the base of the drift, but onlaps and downlaps onto reflector LO indicate that it was formed at least in LO-MM times (Figure 4, CDP 2,700–6,600). The less-steep slope of the drift is covered by wavy structures (Figure 4, CDPs 3,700–6,100). Sediment waves commonly mantle sediment drifts (McCave and Tucholke, 1986; Reading, 1996; Faugères et al., 1999). They are generally oriented perpendicular to the depositing current, and hence can be found on the less steep flank of a drift, and have subparallel, sinuous wave crests. Sediment waves may show an upslope as well as downslope migration or appear as standing waves (Faugères et al., 1999). In analogy, the wavy structures on the gentler side of the drift shown in line AWI-98014 may be interpreted as slightly downslope migrating sediment waves (Figure 4). Unfortunately, the resolution of our seismic data is too low for a detailed analysis of the sediment waves.

The drift in line AWI-98014 shows a slightly different structure to the one in line AWI-98013. Because of this and the fact that we don't have any additional information on the drifts (e.g., connecting seismic lines, bathymetric data) we cannot say whether the lines AWI-98013 and -98014 show the same drift. Still, we infer that the western flank was shaped by the same south setting current. If we connect the drift crests we see a NNE-SSW trend. This follows the topography of the Agulhas Plateau. Furthermore, the drifts are aligned close to the western flank of the plateau. AABW crosses the western flank of the Agulhas Plateau from north to south before entering the South Agulhas Basin and taking a turn to the northeast (Figure 1, Dingle et al., 1987; Faugères et al., 1993; Read and Pollard, 1999). This current and its precursor (proto-AABW?) are interpreted to have initiated and formed this drift.

On the eastern part of the Agulhas Plateau (line AWI-98014) another mounded asymmetrical structure can be found (Figure 5). Several discontinuities define depositional units within the structure. The reflection pattern varies from subparallel moderate reflections to transparent and again to subparallel reflections (Figure 5). At the base of the depositional units above MM the internal reflections show onlap onto the discontinuities (Figure 5, CDPS 11,500–11,800). At the top of the youngest depositional units the internal reflectors are truncated at the seafloor (Figure 5, 11,200–11,500 and 11,700–12,500).

After deposition of the transparent unit LO-MM progressive onlap of subparallel medium-high amplitude laterally continuous reflectors describing an upslope prograding pattern occurs above reflector MM. This can be interpreted as a moat migrating upslope (CDP 11,600–11,550, 3.4 s TWT), which has been identified by McGinnis and Hayes (1995) as a diagnostic criterion for contourites. Hence, the crest is upslope migrating from about CDP 11,900 to CDP 11,400. This is followed by erosion, formation of an erosional surface (LP?) and consequent shifting of the crest to 11,600.

The drift is crossed also by line AWI-98015 (Figure 6) where it shows a mounded asymmetric geometry and, at the seafloor, is about 20 km wide. The internal reflection pattern varies from subparallel with moderate reflections to transparent and even chaotic appearance. Those distinct changes in reflection pattern indicate significant modification in deposition (transparent-homogeneous deposition, subparallel-changes in sediment texture or structure due to variations in sediment composition, chaotic-erosion and re-deposition in channel-levees systems, e.g., CDP 1,400 and 1,500) (Figure 6). The internal reflectors are truncated at the seafloor and at strong discontinuities (Figure 6, CDPs 900–1,800). Reflectors are laterally not as continuous as in the south and thus make an identification of a clear upslope-prograding onlap-pattern more difficult.

The orientation of the crest is NNE–SSW. It follows the topography of the Agulhas Plateau and is aligned along the eastern flank of the plateau. The Agulhas Retroflection flows southwards along the eastern flank of the Agulhas Plateau (Figure 1, Dingle et al., 1987; Lutjeharms, 1996). An extension of the retroflection farther to the south would lead to the observed sediment drifts and is within limits (Winter and Martin, 1990; O. Boebel, pers. communication). Another possibility would be the AABW, which here flows to the northeast. This current may easily be responsible for the upslope prograding geometry observed above MM. With water depths here ranging from 3,500 m to about 2,500 m this is a borderline case when trying to decide whether AC or AAIW are active in such great or AABW is such low water depths. Still, with the western flank of the drift being the steeper one, one would expect a south setting current to have shaped the drift.

Summary and discussion

Even after a number of years of investigation, the identification of sediment drifts still remains equivocal. As a further example, and thus in order to increase the 'database', the Agulhas Plateau sediment drifts have been analysed with respect to their seismic characteristics. They are all mounded bodies, most of them showing an asymmetric geometry. This is a result of both erosion and Coriolis force-enhanced deposition. We clearly see erosion on the steep flank and the far part of the gentler flank (Figures 2, CDPs 6,150–6,300 and 4,950–5,500, 4, CDPs1,200–2,400 and 4,200-6,000, 5, CDPs 11,250–11,500 and 11,750–12,500, and 6, CDPs 1,600–1,850 and 900–1300). Especially at the steeper flank, a current seems to eat into the mounded structure, take up the material and transport it away. Material, which already is in suspension in the flow, may be deposited at the rim of the current where flow velocity is low. If this was turbidity current deposition we would expect two mounds. Since we observe just one mound and since turbidity currents will probably not be able to travel up the Agulhas Plateau's flanks, we assume bottom current deposition in analogy to the observations of Faugères et al. (1999). This can best be seen in the western drift on line AWI-

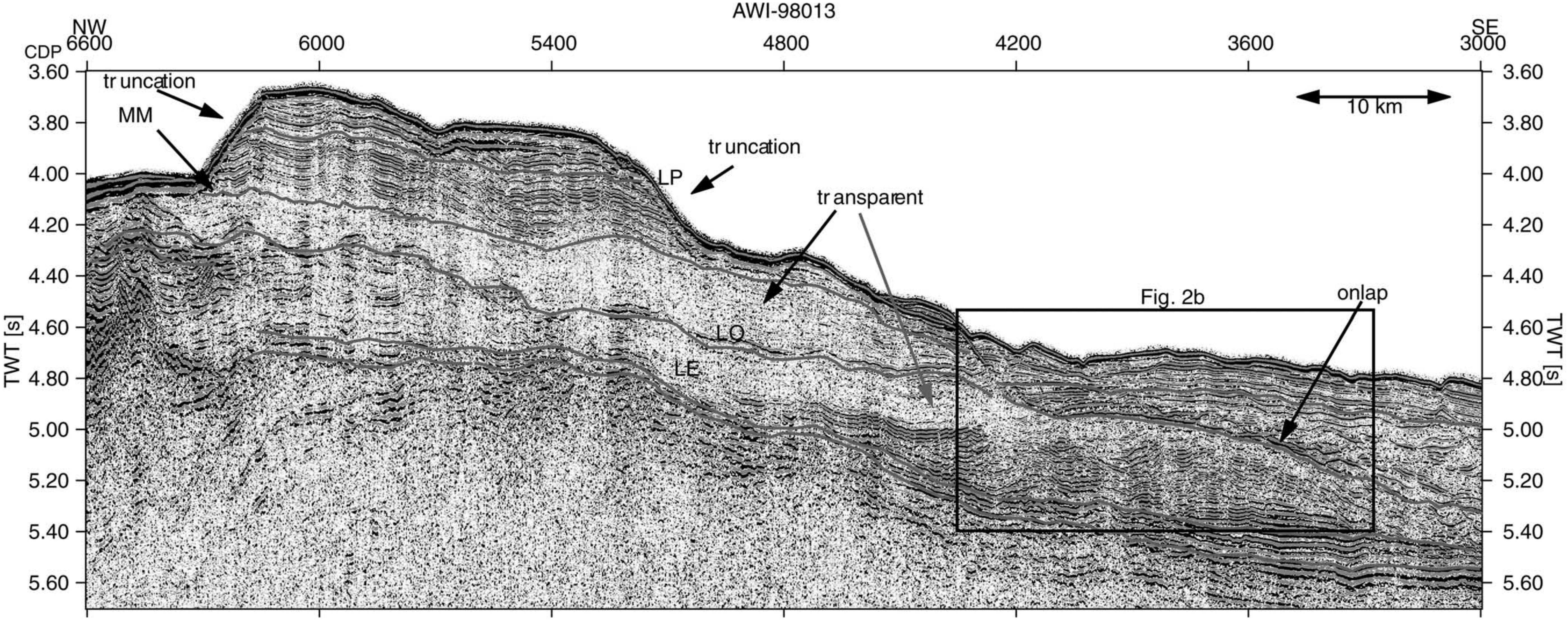

Figure 2. a) Western part of line AWI-98013 showing a sediment drift which for the last few million years was shaped on two sides. Note the strong discontinuities and the change in internal reflection pattern from subparallel reflectors to transparent and back to subparellel. The internal reflectors show onlap and truncation at the discontinuities and truncation at the seafloor. b) blow-up of the eastern part showing onlap, truncation and the change in internal reflection pattern in more detail. LE = Lower Eocene, LO = Lowert Oligocene, LP = Lower Pliocene, MM = Middle Miocene

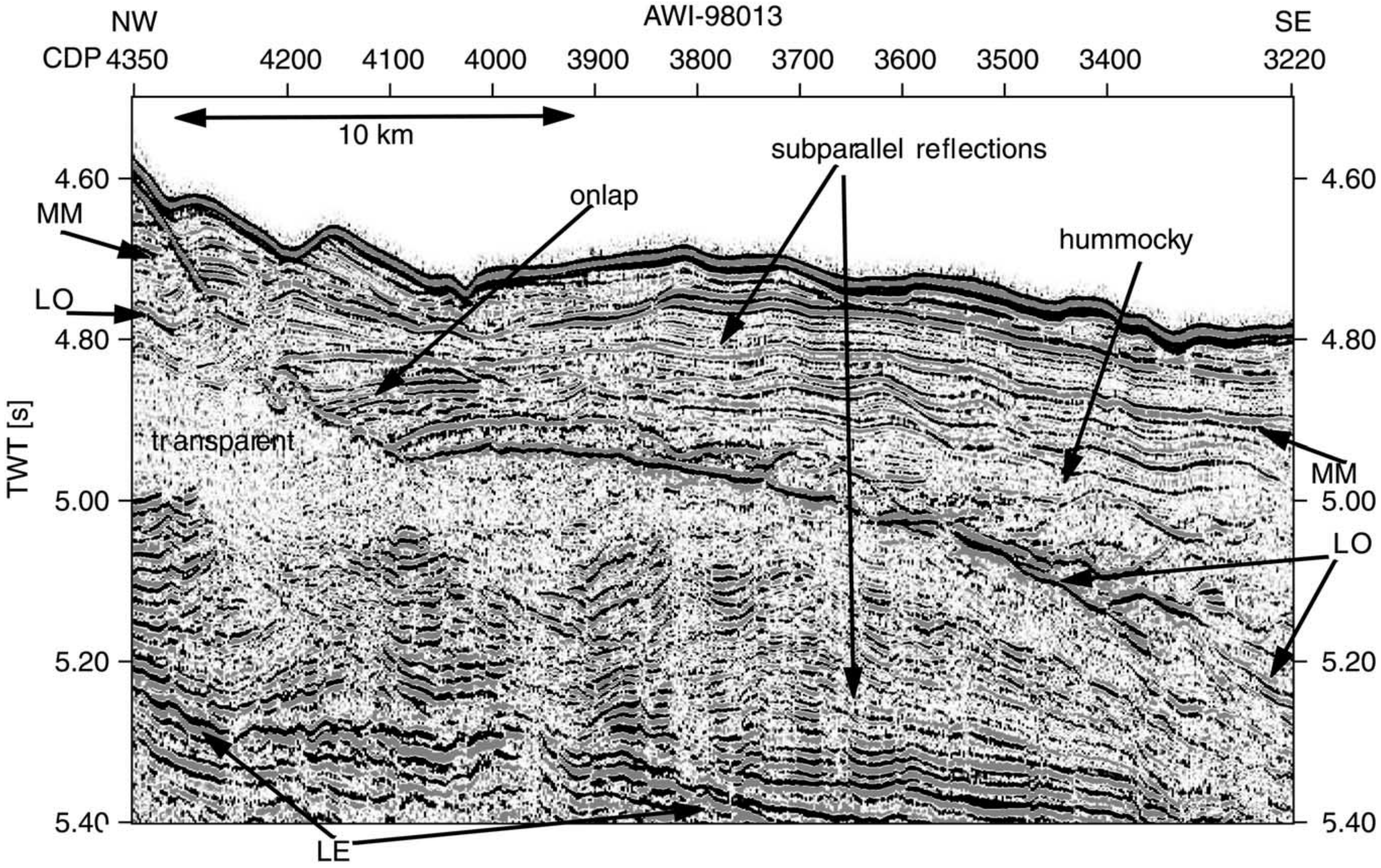

Figure 2. Continued

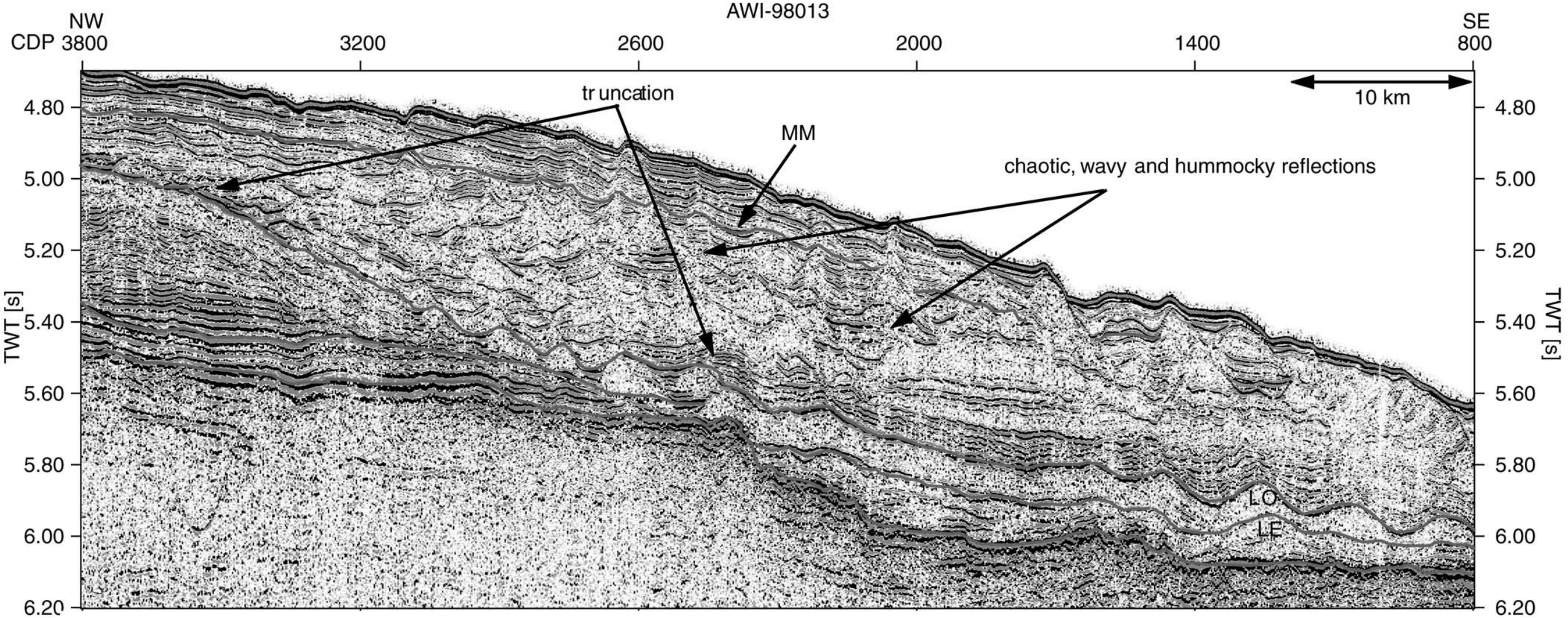

Figure 3. Eastern part of line AWI-98013. Here, we observe a distinctly chaotic, wavy and hummocky reflection pattern indicating shaping by currents. LE = Lower Eocene, LO = Lower Oligocene, MM = Middle Miocene.

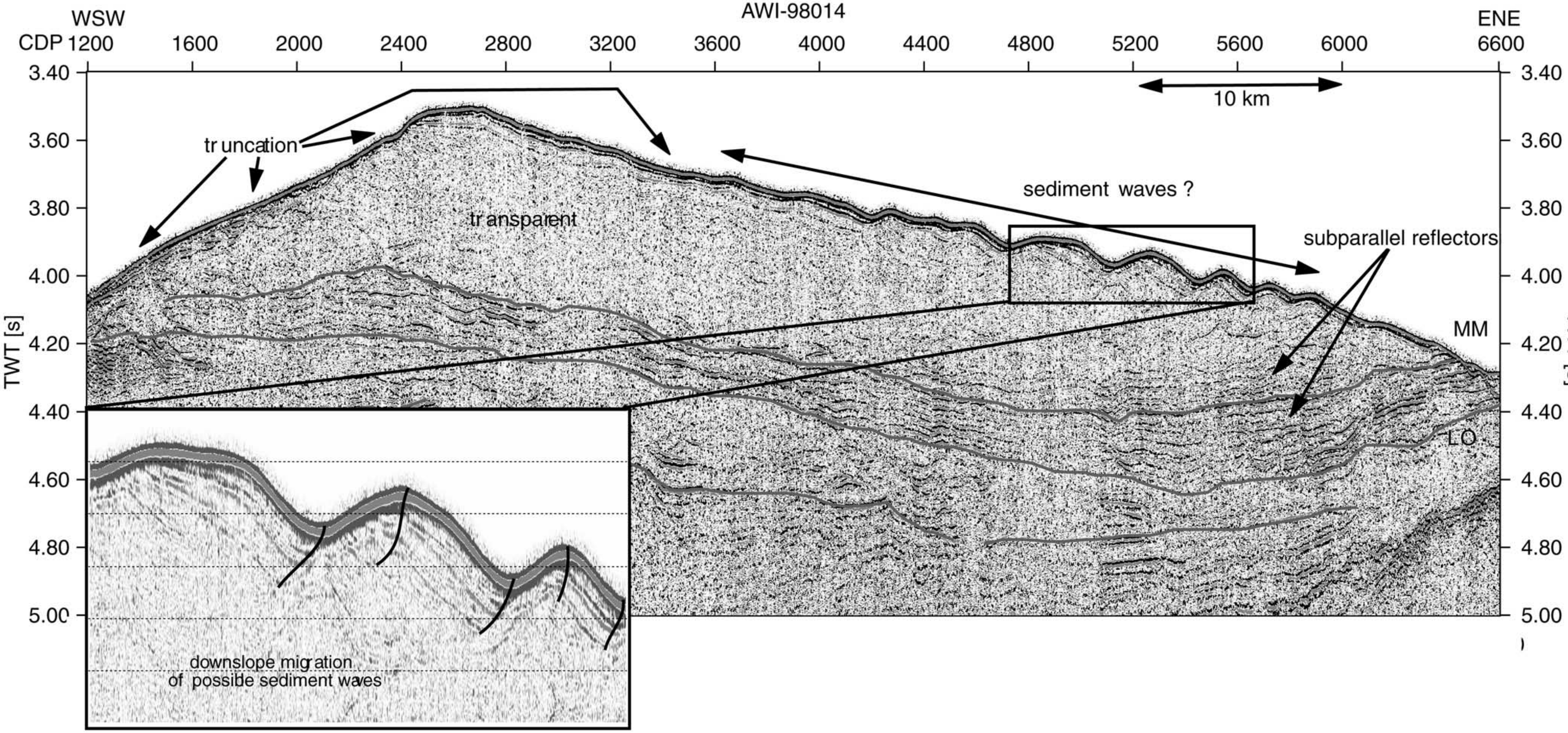

Figure 4. Western part of line AWI-98014. Note the mounded asymmetric geometry of the sediment drift which is covered by wavy structures (sediment waves?) in the east. The drift appears seismically transparent. The base is formed by a band of strong reflections. LO = Lower Oligocene, MM = Middle Miocene.

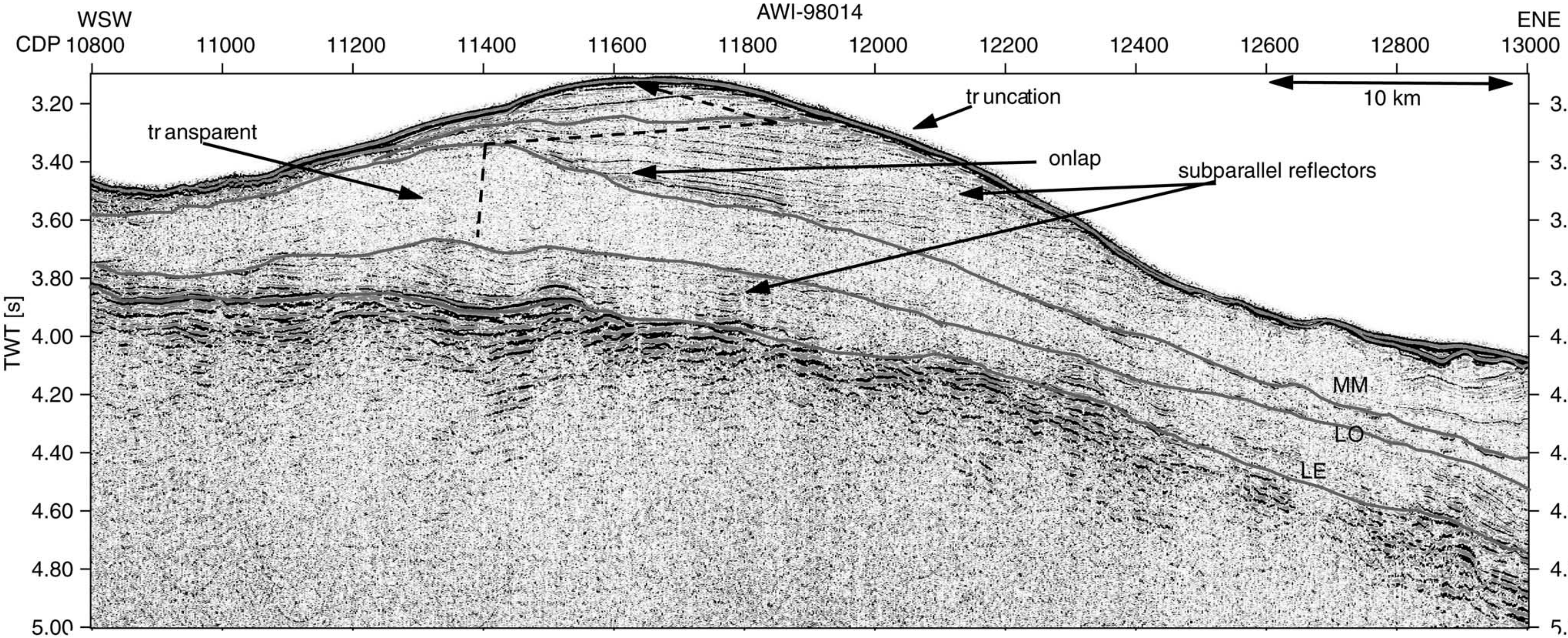

Figure 5. Eastern part of line AWI-98014. The seismic data reveal an asymmetric sediment drift. The crest of the drift moved from ~ CDP 11400 to ~ 11800. The drift distinctly shows changes in reflection pattern and truncation of the internal reflectors. LE = Lower Eocene, LO = Lower Oligocene, MM = Middle Miocene.

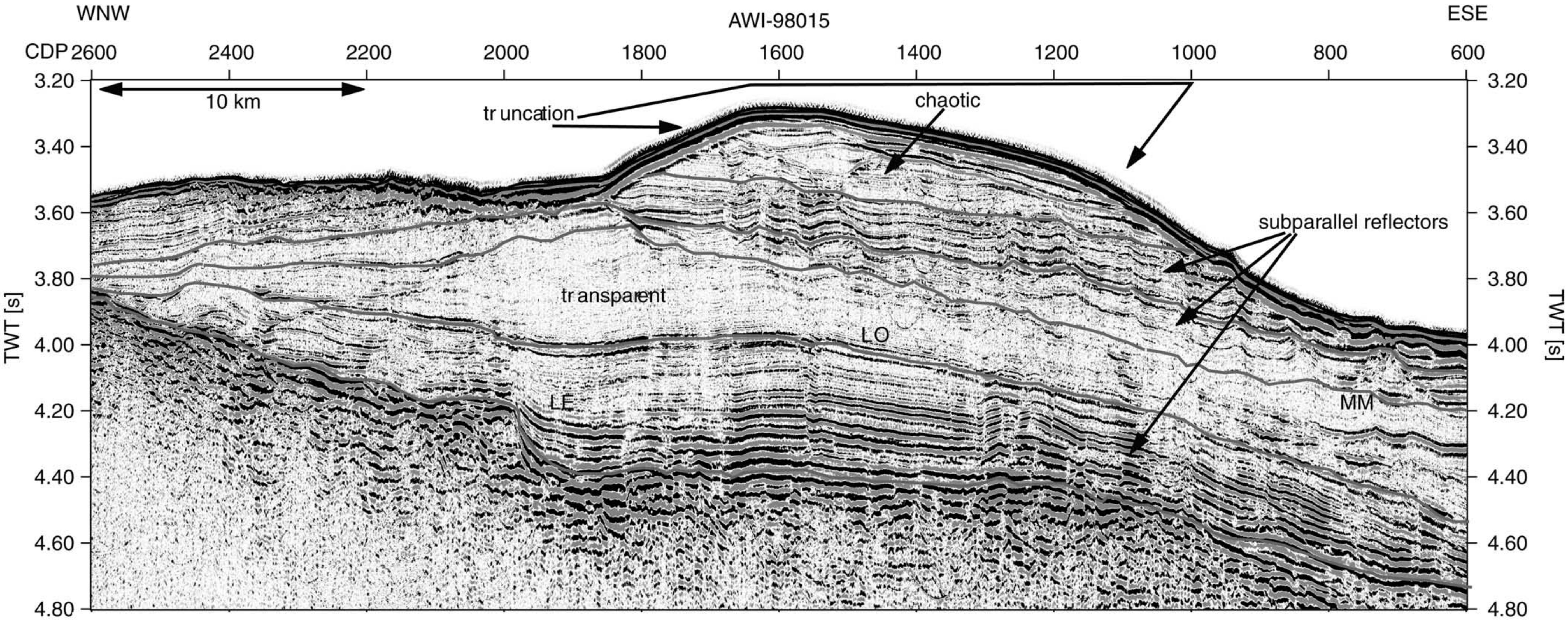

Figure 6. Line AWI-98015. The sediment drift on this line is characterised by strong changes in reflection pattern, truncation of the internal reflectors and strong discontinuities. LE = Lower Eocene, LO = Lower Oligocene, MM = Middle Miocene.

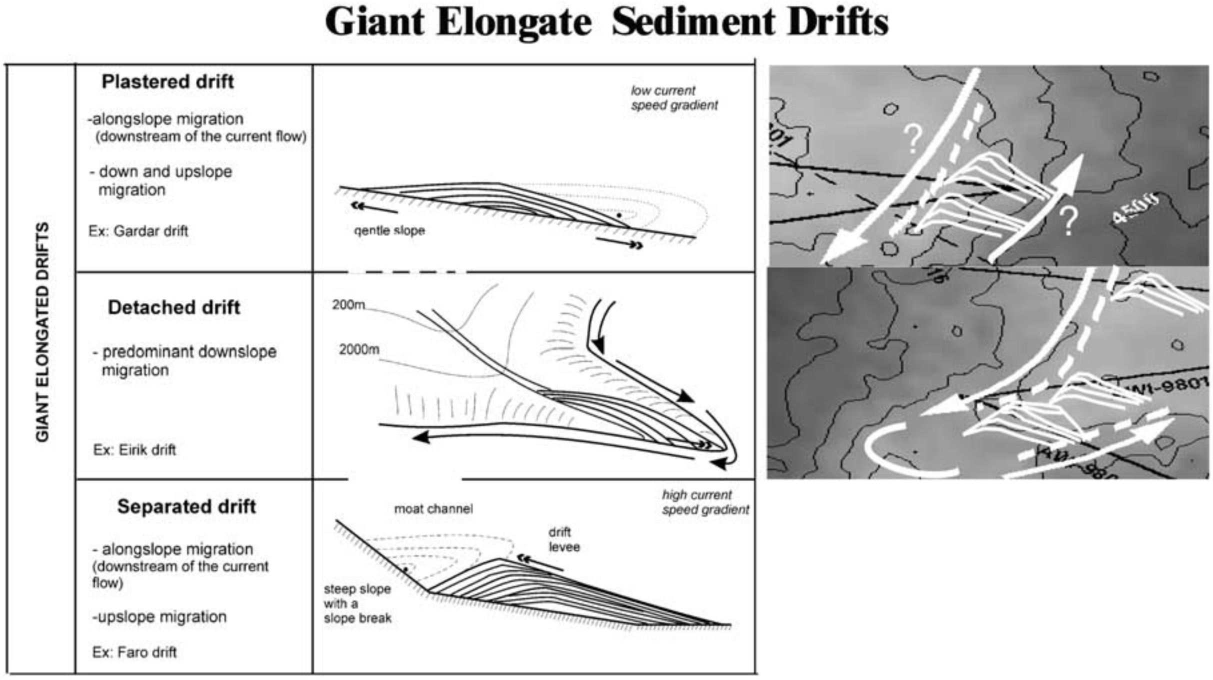

Figure 7. Compilation of the different types of giant elongate sediment drifts showing the general drift geometry and trend of migration (modified from Faugères et al., 1999). A drawing of the observed sediment drifts on the southwestern and eastern Agulhas Plateau were added as plastered and detached drifts, respectively. The dashed lines show the crest of the drift. Only giant elongate mounded drifts have yet been found on the Agulhas Plateau.

98014 (Figure 4, CDPs 2,400–4,000). There, at least the uppermost 100 ms TWT of the sediment drift show mounded reflectors as well indicating drift growth.

Sediment drifts at the Antarctic Peninsula show a similar geometry (Rebesco et al., 1996). There, the combined activity of turbidity and bottom currents led to the formation of a number of sediment drifts with a steep eroded flank and a gentler flank, where sediments are deposited.

The sediment drifts are characterised by discontinuities, which mark distinct changes in reflection pattern (transparent, subparallel, chaotic). Internal reflectors are truncated at the seafloor and at the discontinuities. The discontinuities correspond to major changes in flow pattern, links to ice sheet formations or to periods of major growth of Antarctic ice (Faugères and Stow, 1993). Those hydrological events changed the physical (salinity, density, velocity) and chemical properties of water masses thus modifying the biological productivity as well (Faugères and Stow, 1993; Faugères et al., 1999). Evidence for this was found in the cores taken in the 1970s where a clear distinction exists between the composition of calcareous components of Pliocene-Quaternary and pre-Pliocene sediments (Tucholke and Carpenter, 1977). This compositional change may reflect either changes in the composition of the surface water biocoenose or preferential dissolution of foraminifera in older samples. Tucholke and Carpenter (1977) thus favour the dissolution of the calcareous sediments due to changes in bottom water properties.

The seismofacies is also an indicator for grain-size and the depositional process, because this is reflected in different reflection patterns. A homogeneous sequence will show up as transparent to reflectionfree whereas strong variations lead to internal reflection and even a chaotic structure of a seismic unit. Three of the drifts show a transparent unit as their deepest part indicating that initially the sedimentation was uniform and continuous either due to a longer lasting calm period or increased sedimentation within a shorter period (spill-over at the rim of a 'calm' current?). With the onset of AABW, which formed reflector MM, deposition became more turbulent and episodic (overbank deposition?) leading to continuous high-medium amplitude subparallel reflectors. On line AWI-98015 this is topped by a third, more chaotic unit where channels are visible (Figure 6).This indicates highly episodical reworking of the sediments.

This kind of changing seismofacies was observed for both the drifts at the Antarctic Peninsula (McGinnis and Hayes, 1995; Rebesco et al., 1996) and the Feni drift (Stoker, 1998). There, the different seismofacies also represent different stages within the development of the drifts. Individual reflectors were reported to display either onlapping or downlapping terminations onto major discontinuities (McGinnis and Hayes, 1995). We observe onlaps and downlaps as well (Figures 2 and 4–6). Furthermore, the eastern drift on line AWI-98014 shows what may be interpreted as progressive onlap with a small moat describing upslope migration (Figure 5). According to McGinnis and Hayes (1995) this is another diagnostic criterion for sediment drifts.

A further characteristic of the observed drifts is their being aligned close to the flanks of the Agulhas Plateau and the fact that, if one connects the crests of the drifts, their trend follows the topography of the plateau. Sediment deposited by or significantly affected by the action of bottom currents and wind driven surface currents leads to the formation of drifts, which lie parallel to continental margins (Stoker, 1998; Rebesco and Stow, 2000). Hence, our drifts are interpreted to be the result of a south setting current (AABW?), which takes a turn to the east in deeper waters, on the western plateau and either a south setting or a prolongation of the northeast setting current on the eastern plateau. The situation in the east is not as clear as in the west.

Considering the definitions of giant elongate drifts as proposed by Faugères et al. (1999) the western drifts fall well into the detached drift category (Figure 7). The eastern drifts may qualify as either plastered drift (with a south setting current) or separated drift, if the northeast setting current built-up the drift from the east. There we cannot be definite without further seismic and bathymetric information.

Conclusions

A number of drifts were detected on the Agulhas Plateau aligned along the western and eastern flank, both alignments being oriented NNE–SSW. The drifts have a number of characteristics in common: they show an asymmetric mounded geometry; internal reflectors onlap and downlap distinct discontinuities and are truncated both at the seafloor and at those discontinuities; the discontinuities mark changes in seismofacies, which reflect different depositional processes and water mass properties; the drifts are aligned close to the flanks of the plateau and the trend of their crests follows the topography of the plateau.

As an origin for the western drifts a south setting current (AABW) is suggested. The situation in the east is equivocal. There, either a south setting current (deep reaching AC or AAIW) or the northeast setting AABW could be the generating current. In order to be more specific, additional data (seismic, bathymetric, oceanographic) are needed.

Generally, one can say that only the combination of seismic data with bathymetric, sedimentological and oceanographic information will represent a diagnostic frame for sediment drifts.

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