Generation of accommodation space around the D-1 fault during the Oligocene , Danish North Sea

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Abstract

Implications of a sequence stratigraphic study of the Oligocene sediments in the Norwegian-Danish Basin around the D-1 well are presented. The study is based on seismic mapping, log interpretations and detailed dating. This paper focuses on the evolution of the accommodation space along and across the D-1 fault since the fault generated deviations in the available accommodation space and has a significant influence on the depositional geometry of the sequences. The results show that displacement across the D-1 is fairly constant along strike during deposition of the older Oligocene sequences. This is in contrast to the youngest Oligocene sequence which has a higher displacement rate and thus significant variations along strike. This emphasises, that the understanding of the structural evolution of local faults in a basin dominated by clastic sediment infill as the Tertiary North Sea has to be as detailed as the sequence stratigraphy, because the fault may have had a significant influence on the depositional geometry, and hence the complete sequence stratigraphic interpretation.

Introduction

The general objective of this sequence stratigraphic study was to map the Oligocene succession in order to create a reliable stratigraphic framework for a future modelling of the parametres controlling the Oligocene sequence development in the Norwegian-Danish Basin (fig. 1). The present paper describes the sequence development controlled by the D-1 fault, which throw affect the entire Tertiary succession. The D-1 fault is a NNE-SSW striking listric fault dipping to the north and detaching along a Zechstein salt surface (Petersen et al., 1992, 1993, Clausen et al., 1993). Displacement of the D-1 fault creates deviations in the subsidence pattern by generating a local accommodation space in the hangingwall of the D-1 fault. Control on the displacement history of the D-1 fault is of great importance as an input to the future sequence stratigraphic modelling of the evolution in the Norwegian Danish Basin, since generation of the accommodation space has influence on the sequence geometry. A detailed seismic mapping of sequences is performed to describe variation in sequence geometry. Decompaction and backstripping of selected profiles are carried out to describe the displacement history of the D-1 fault.

Materials

The PH-n85, DCS and RDT81 surveys were used to map the sequences. The seismic interpretation was tied to the L-1, Inez-1, Ibenholt-1 and F-1 wells (fig. 2), enabling dating of the sequence boundaries (fig. 3). The dating in these wells is based on the coccolith zonation by Erik Thomsen (pers. com.), which gives a very detailed chronostratigraphic subdivision of the Oligocene sediments. Biostratigraphic dating in the D-1 well was avoided since the Oligocene deposits in this well are affected by the faulting.

Regional geology

During the late Palaeozoic and Mesozoic, the North Sea region (fig. 1), was dominated by two east-west trending basins, the Northern Permian Basin (including the Norwegian-

Danish Basin) and the Southern Permian Basin, separated by the Ringkøbing-Fyn High and the Mid North Sea High trend. This trend was cut by the north-south oriented Central Trough and the Horn Graben.

During the Cenozoic time, the North Sea region constituted a large epicontinental basin with a north-south axis above the older Central Trough structures (Nielsen et al., 1986). The Cenozoic deposits in the central part of the North Sea Basin reach a thickness of more than 3000 m, representing most of the erathem. The Upper Palaeocene and Eocene deposits comprise clays, deposited in a distal position. The sediment transport seems to have been from the north and the west. The depocentres of the Upper Palaeocene and lower Eocene are located north of the Danish sector, and the depocenter of the Middle to Upper Eocene section is found at the western border of the Danish Central Trough. The Oligocene and Miocene sediments consist of clay with an upward increasing amount of silt and mica, and sand bodies are present in the eastern part of the study area. The sediment transport was mainly from the north and northeast. The depocentres of the Oligocene to Middle Miocene sequences are located in the Norwegian-Danish Basin and on the Ringkøbing-Fyn High, and the depocenter of the Middle to Upper Miocene deposits in the Norwegian Central Trough (Michelsen et al., in press).

The D-1 fault is located at the northern flank of the Ringkøbing-Fyn High (fig. 2), in the distal part of the Oligocene depocenter. The base of the Zechstein salt is here dipping to the north, whereas the Upper Cretaceous - Lower Palaeocene Chalk Group has a westward dipping surface. The fault is located above a Zechstein salt structure, which was initiated during the Triassic and was an active diapir during the Tertiary. Salt migration from the hangingwall to the footwall controlled the shape of the fault and the displacement along the fault (Petersen et al., 1992, 1993, Clausen et al., 1993).

Sequence stratigraphy

The sequence stratigraphic subdivision

The Cenozoic succession in the southeastern North Sea has recently been subdivided into 7 major sequence stratigraphic units, which are further subdivided into sequences. In total, twenty-one sequences were identified in the Danish offshore area (Michelsen et al., in press.). The major sequence stratigraphic unit 4 comprises four sequences, 4.1 to 4.4, and represent the main part of the Oligocene deposits.

Additional sequence stratigraphic studies of unit 4, carried out by the present authors, have indicated that eight seismic sequences, O.1 to O.8, can be identified whith in the depocenter (fig. 3). The studies are based on the principle of Vail et al. (1977), and the eight sequences are defined as unconformity bounded units, which have a chronostratigraphic significans. Basinwards shift of onlaps occurs at the lower seqence boundarie. The uppermost sequence, O.8, is furthermore characterised by distinct erosional features at the lower and upper boundaries. These features occur approximately 2-3 km west to northwest of the D-1 fault, but there is not recognised erosive feature at the crest of the footwall.

Location of depocentres

Variation in thicknesses of the sequences are illustrated by the seismic section DCS 27 and DCS 31 (figs 4a and 4b). The two sections crosses the central and eastern marginal parts of the fault, respectively (fig. 3).

Sequences O.1-O.5 are represented by distal deposits in the area around the D-1 fault, and the corresponding sequence depocentres are located east-northeast of the fault. The thickness of each of these sequences is very small, and the five sequences are, therefore, treated as one stratigraphic unit in the area close to the fault.

The depocentres of sequences O.6, O.7, and O.8 migrate successively westwards into the area north of the D-1 fault. The depocenter of sequence O.8 is located just northwest of the seismic section DCS 27, which explain the larger thickness of sequence O.8, seen on this section compared to that seen on the seismic section DCS 31 (see figs 4a and 4b).

Each of the sequences O.1 to O.7 shows a minor individual thickness variation across the fault. A pronounced and consistent change in thicknesses along the fault is evident for sequence O.8 (figs 4a and 4b). On the hangingwall, sequence O.8 shows a reflection pattern typical of a normal growth fault with maximum subsidence at the fault (fig. 4b). 1-2 km in front of the fault zone, there is a small synform, indicating that salt has migrated from the hangingwall into the fault plane. On the seismic section DCS 27, the reflectors suggest the presence of a roll-over anticline on the hangingwall, resulting from salt migration into a small dome under the D-1 fault plane, which also amplifies the footwall crest.

Since the goal of the present paper is to analyse the difference in rate of displacements at the central and the marginal parts of the fault, we have decided to treat sequences O.1 - O.7 as one group and sequence O.8 as another group. By doing so, the differences in displacement between the two parts of the fault and the change in displacement rates during the main part of Oligocene are emphasised.

Fault displacement

Methods

Estimates of the displacement rates of the D-1 fault are based on rather simple geometric considerations assuming that the top of a sequence was continuous across the fault during deposition. The thickness variations across the fault, therefore, reflect the displacement which took place during deposition of the sequence. The depth and isopach values at several location on the hangingwall and the footwall were measured in order to construct backstripped and decompacted sections. The reference point for the depth during the backstripping is located at the sea floor assuming that the palaeo-depth of the Oligocene North Sea Basin was constant in the area around the D-1 fault. The depth conversion is based on a simple depth-dependency velocity, based on a simple linear regression through the Tertiary succession. The decompaction is based on the algorithm given by Allen and Allen (1990). This algorithm is a mathematical attempt of sliding the sedimentary layer up along an "exponential porosity - depth" curve, the solution to which is found by forward numerical iteration. The principle is based on Sclater and Christie (1980). Values for the sedimentary composition taking into account surface porosity and porosity/depth ratios are from Sørensen (1986).

The backstripped and decompacted sequences are then related to geological time so that the displacement during deposition of each sequence can be calculated. The displacement rate (v) is determined by the following relation:

$$v = \frac{\Delta Z_{decom}}{Time}$$

where ΔZ_{decom} is the decompacted thickness after backstripping to the relevant horizon and *Time* is the geological time interval (fig. 3) for deposition of the decompacted sequence. The unit for is thus metres/1000 years.

Displacement variations along the D-1 fault
The seismic sections DCS 27 and DCS 31 have been depth converted using an interval velocity of approximate 1900 m/sec for the sediments on top of sequence O.8 and approximate 1950 m/sec for sequences O.1 to O.8. This relative low velocity gradient is partly derived from the sonic log of wells in the study area (L-1, Inez-1, Ibenholt-1 and F-1) and partly from the sedimentary composition. The gamma ray logs of the wells indicate, that the older Oligocene sediments are dominated by fine-grained sediments but there is an upward increase in the relative amount of coarse-grained clastic sediments.

The depth conversion and the subsequent backstripping/decompaction was performed at 10 pseudo-wells along each seismic section. The decompacted sections show the Oligocene evolution of the D-1 fault across the centre of the fault (fig. 5a) and across the more eastern marginal section (fig. 5b). The decompacted sections emphasize that the compaction of the underlying sequences constitutes a major part of the differential subsidence across the fault as argued by Petersen et al. (1993).

The true decompacted displacement across the D-1 fault on the seismic sections DCS 27 and DCS 31, during the periods represented by sequences O.1 - O.7 and O.8, is shown in figure 6. The uncompacted thicknesses in the footwall and in the hangingwall indicates the size of the displacement at the time when the upper sequence boundary was horizontal. The displacement was smaller at section DCS 31, than at DCS 27, during both periods examined here, and the difference is more pronounced during the deposition of sequence O.8.

Figure 7 shows the fraction of the accommodation space generated by displacement across the D-1 fault in relation to the total accommodation space generated during the Oligocene. It is evident that the D-1 fault has large influence on the accommodation space at the centre of the fault.

The dating of the sequence boundaries (fig. 3) gives the following ages: base O.1 - 36 Ma; top O.7 - 28.8 Ma and top O.8 - 26.5 Ma. These values are used to calculate the displacement rate across the fault on the given sections, and the values are shown in figrue 8. It shows that the displacement rates were higher at the centre of the fault during both periods, represented by O.1 - O.7 and O.8, and the displacement rate was highest during deposition of O.8.

Discussion

The total displacement and therefore also displacement rate are minimum values since the generated accommodation space is assumed to be filled continuously during deposition of the actual sequence. However, if erosion of the sequence in the footwall took place the displacement and thus displacement rate achieved would be overestimated. In the study area there is no seismic evidence indicating that the area was suffering from sediment starvation and the assumption of continuous sediment infill in the fault-generated accommodation space seems to be valid. Furthermore, if the sedimentary input direction (north to northeast) is taken into to account, the presence of sequences O.1-O.7 and O.8 on both the footwall and the hangingwall of the D-1 fault indicates that there was enough clastic material available for keeping pace with the fault-controlled generation of accommodation space. The erosion on the footwall, described earlier, does not influence the estimates of displacement since the thicknesses measured are at locations where there is no seismic indication of erosion.

This analysis does not take into account the compaction of the underlying sequences. This means that the displacement and displacement rate includes both the tectonic and compactional differential subsidence across the D-1 fault. To differentiate between these two,

causes of subsidence, would require a complex decompaction including the sediments in the footwall (Petersen et al., 1993), which is beyond the scope of this study.
The location of the depocentres north of the D-1 fault may have enhanced the movement of salt from the hangingwall into the footwall of the D-1 fault. This would have a major influence on the evolution of the D-1 fault since salt movement is the major cause for faulting along the D-1 fault (Petersen et al., 1992, 1993). However, the removal of salt from beneath the hangingwall would create local accommodation space, which with enough sediment available would enhance the removal of salt from the hangingwall to the footwall and so on. The location of the depocentres may thus be controlled by the salt removal, but the salt removal is also enhanced by the deposition in the hangingwall.

Conclusion

The preliminary results of this study shows that :

i: The fault-generated accommodation space at the D-1 fault varies systematically both in time and space. The major generation, of space, is at the centre of the fault where it constitutes up to 25 % of the available accommodation space in contrast to the more marginal sections where it constitutes less than 20%.

ii: The displacement rate varies only a little along the strike of the fault during the deposition of sequence O.1-O.7 whereas the displacement rate is significantly higher and has higher lateral variation during the deposition of O.8.

iii: The location of depocentres seems to be related to the displacement on the D-1 fault, since the depocentres are located at the hangingwall of the D-1 fault and occur contemporaneously with an acceleration in displacement rate.

iv: A detailed sequence stratigraphic mapping is valuable as a basis for a detailed geometrical analysis of faulting and displacement rates.

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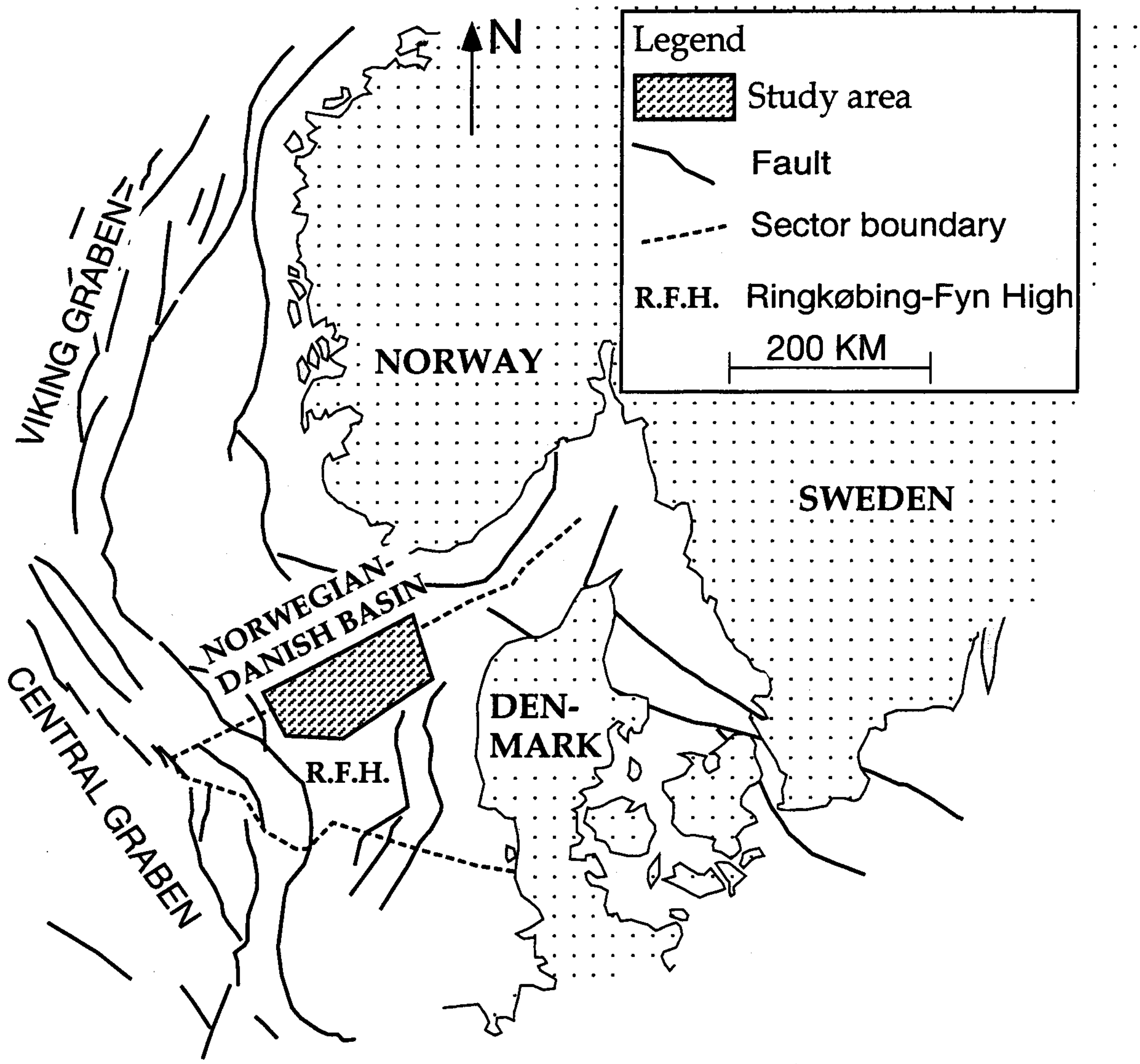

Fig. 1 Tectonic framework and location of the study area (after Ziegler 1982).

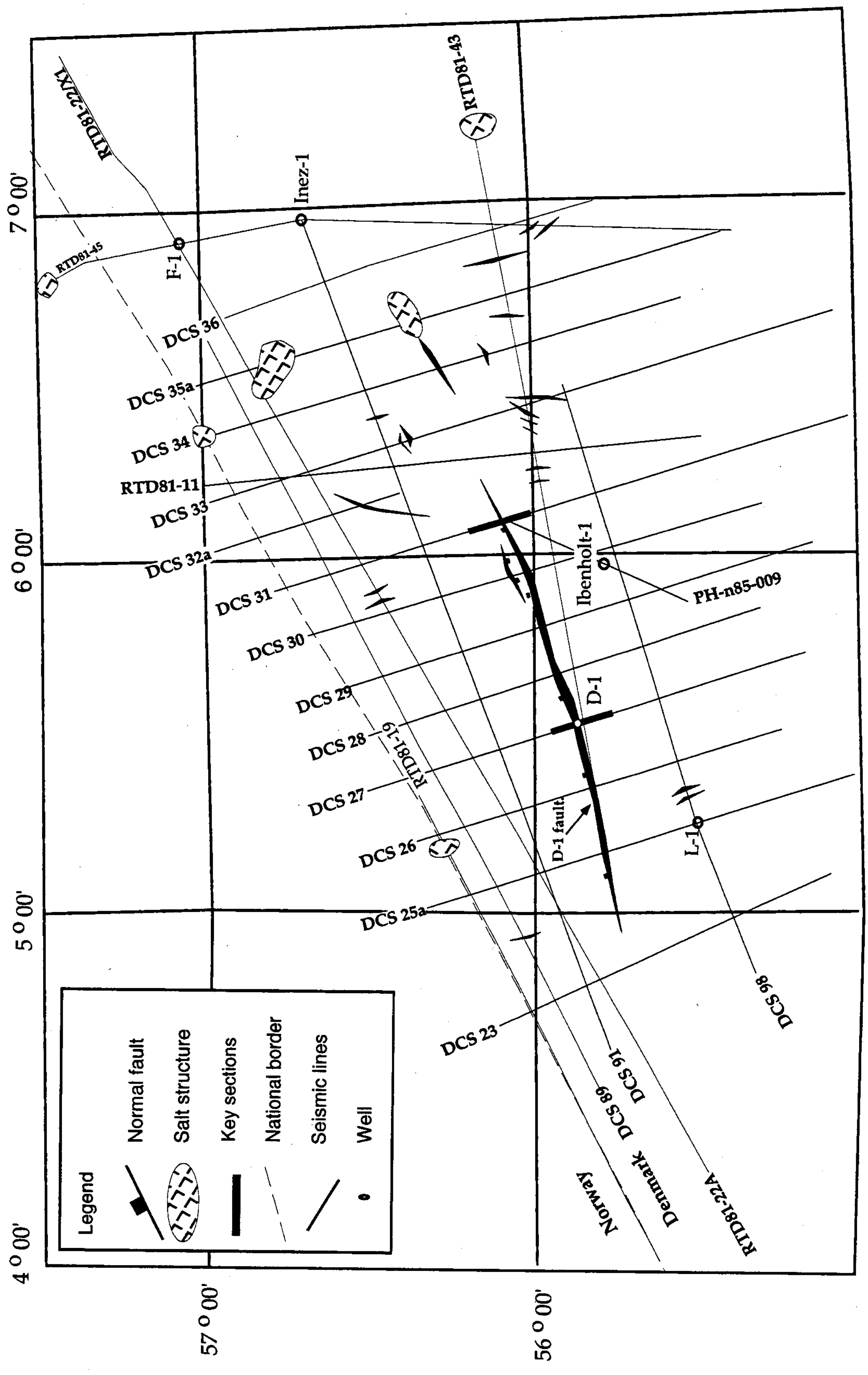

Fig. 2 Location of the seismic sections and the wells used in this study. The key sections DCS 27 and DCS 31 are emphasised by a bold line.

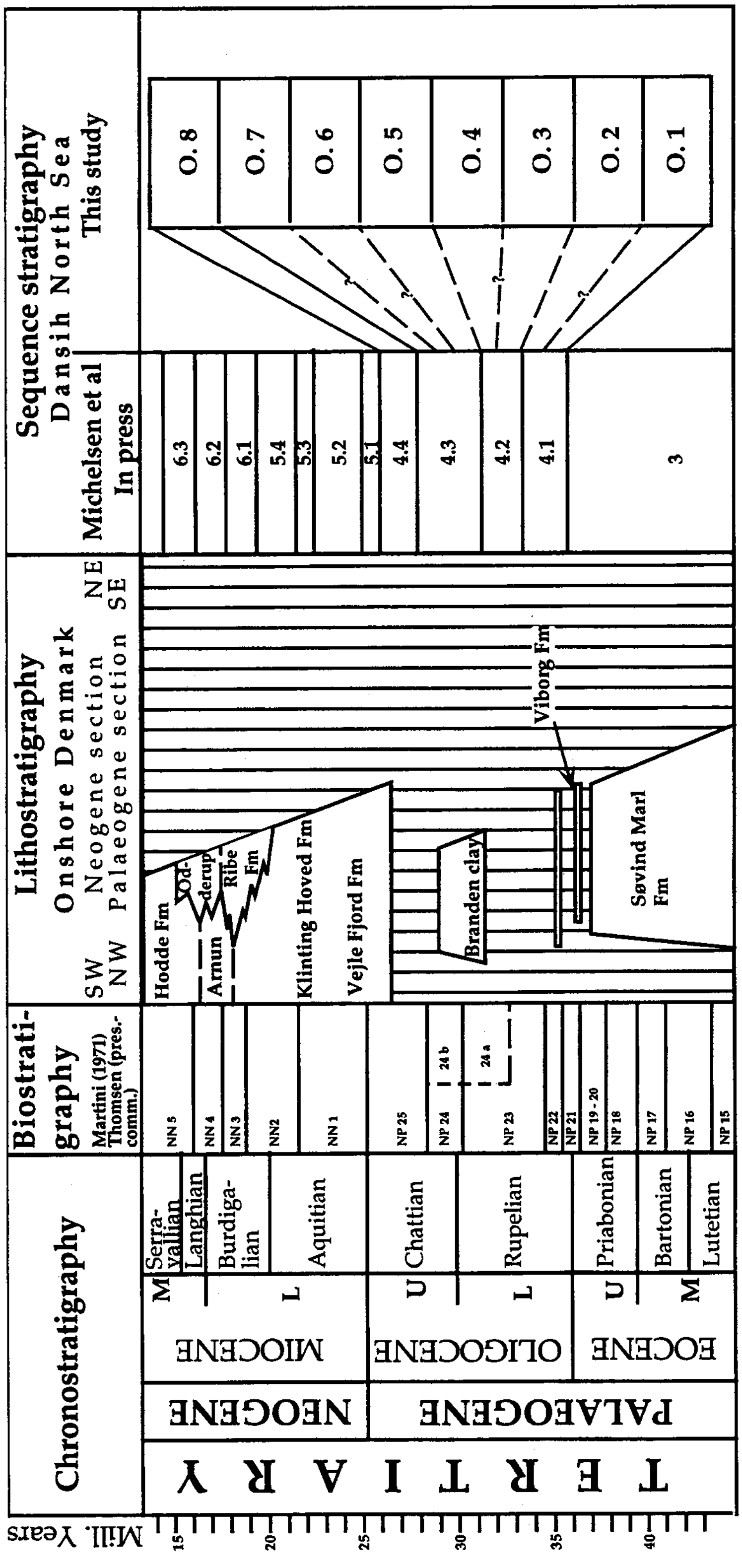

Fig. 3 The interpreted sequence stratigraphic subdivision related to the chronostratigraphy and to theTertiary lithostratigraphy in the North Sea and the Danish onshore area (from Michelsen et al., 1993).

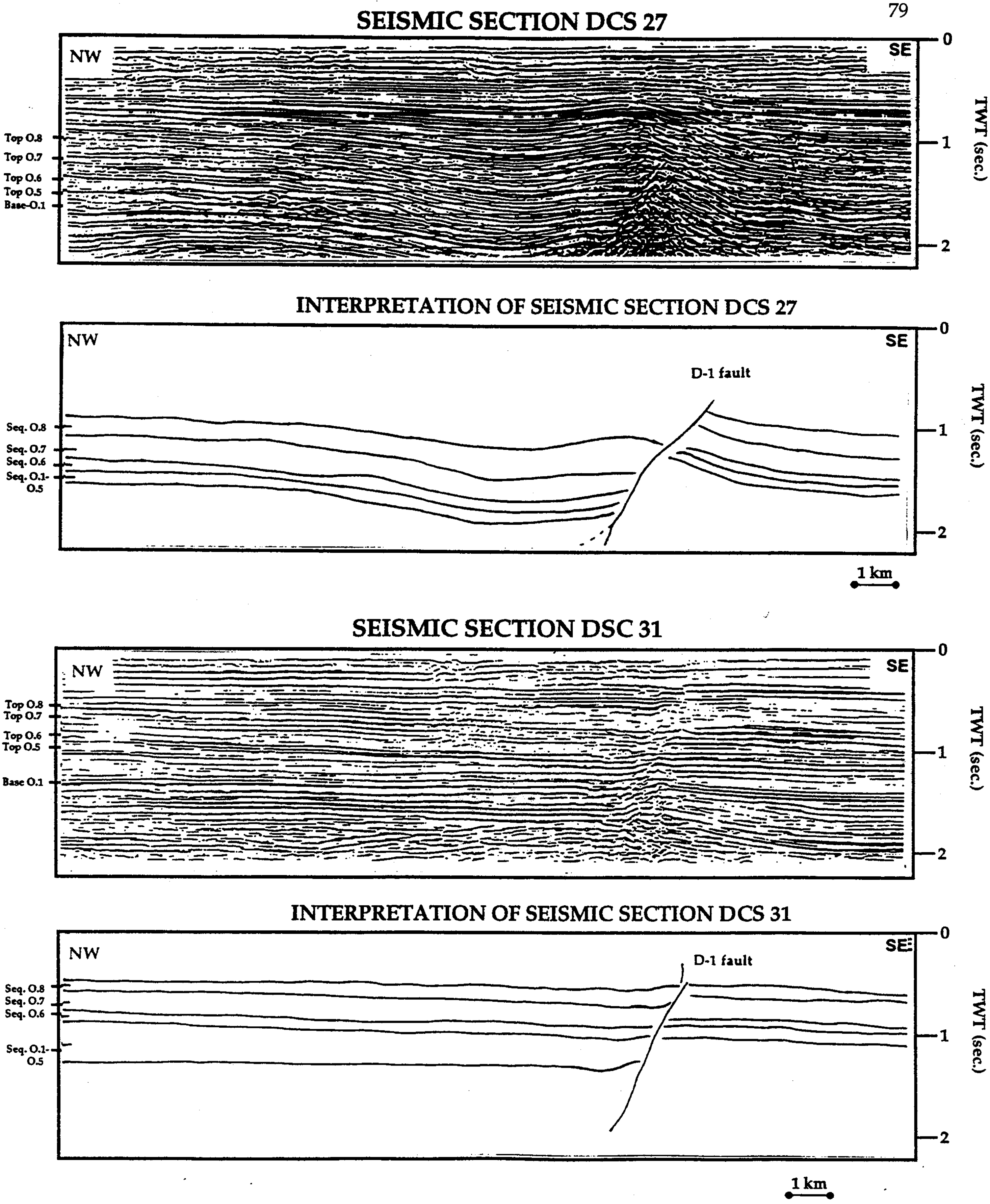

Fig. 4 Seismic sections DCS 27 (a) and DCS 31 (b) and corresponding line drawing of the interpreted sequence boundaries. For location of the sections see figure 2.

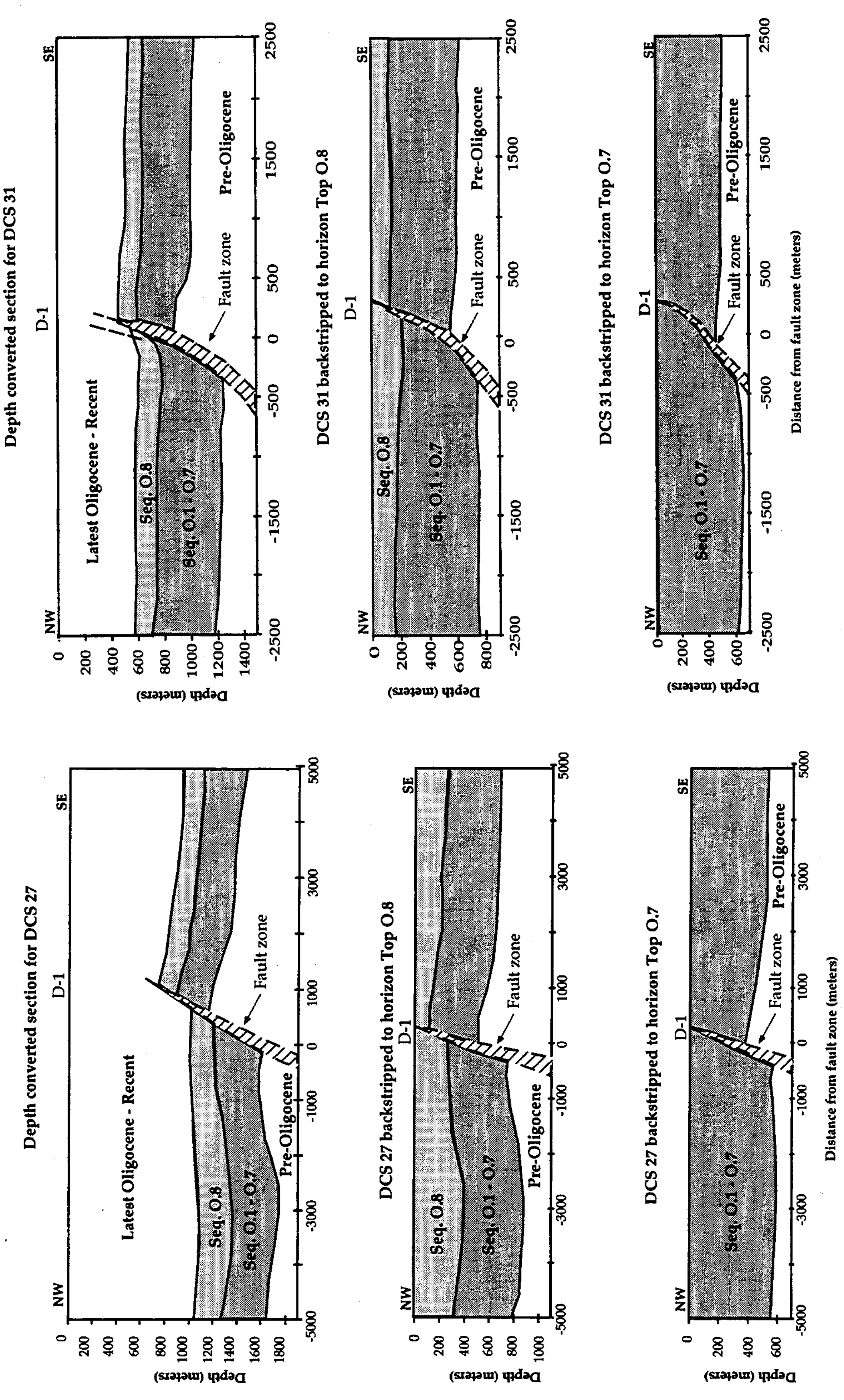

Fig. 5 Decompaction and reconstruction of Oligocene sequences on the sections DCS 27 (a) and DCS 31 (b). The evolution of the accommodation space across the D-1 fault is clearly indicated. The fault is regarded as a fault zone and thus not represented as a single plane.

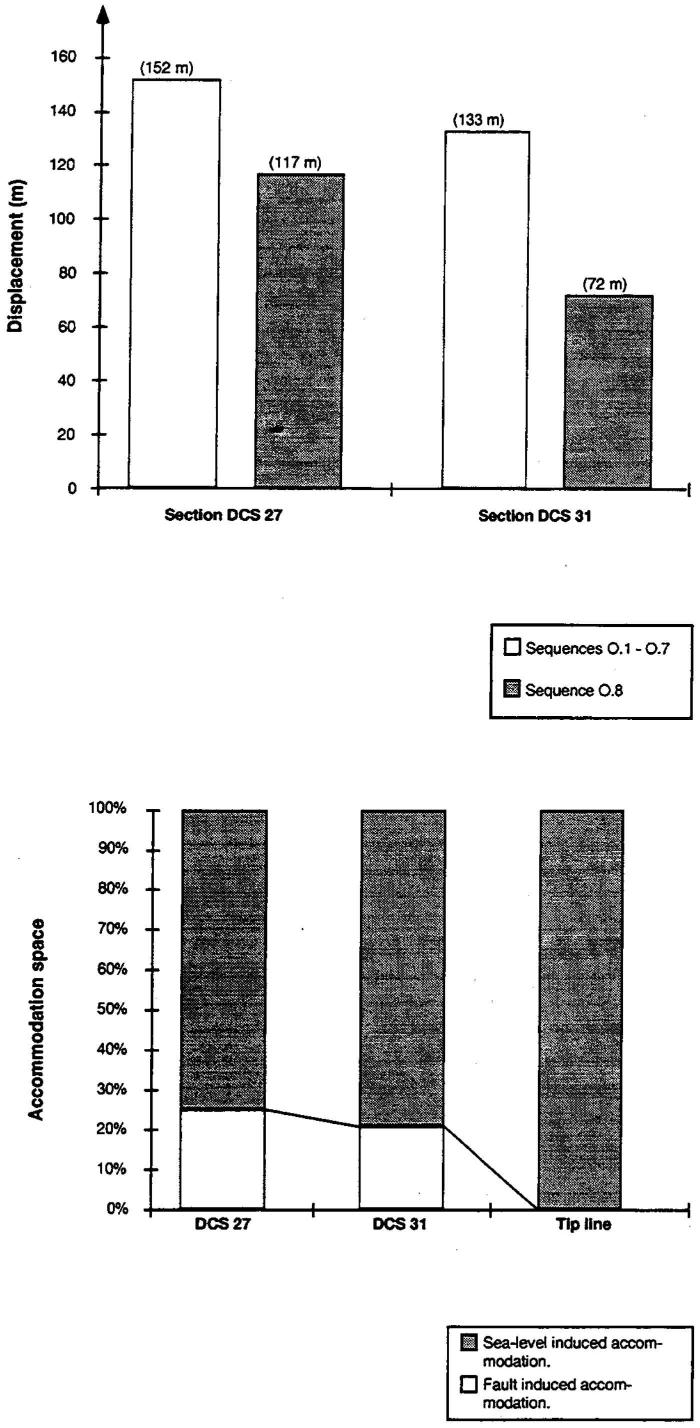

Fig. 6 Graph showing the uncompacted thickness difference (at two seismic sections) between the footwall and hangingwall (= displacement) across the D-1 fault at the time where the top of the sequence was continuos and nearly horizontal.

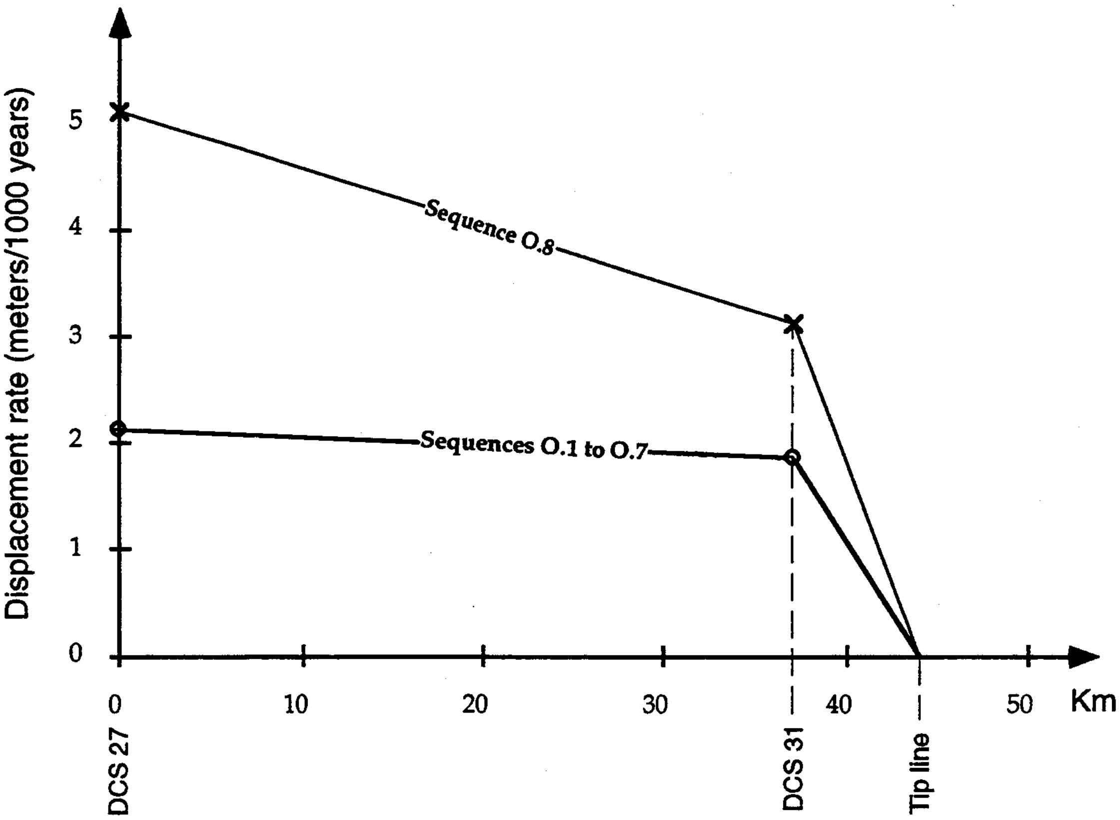

Fig. 7 The fault-generated accommodation space as a normalised fraction of the total accommodation space along strike of the D-1 fault (at relative locations along the fault).

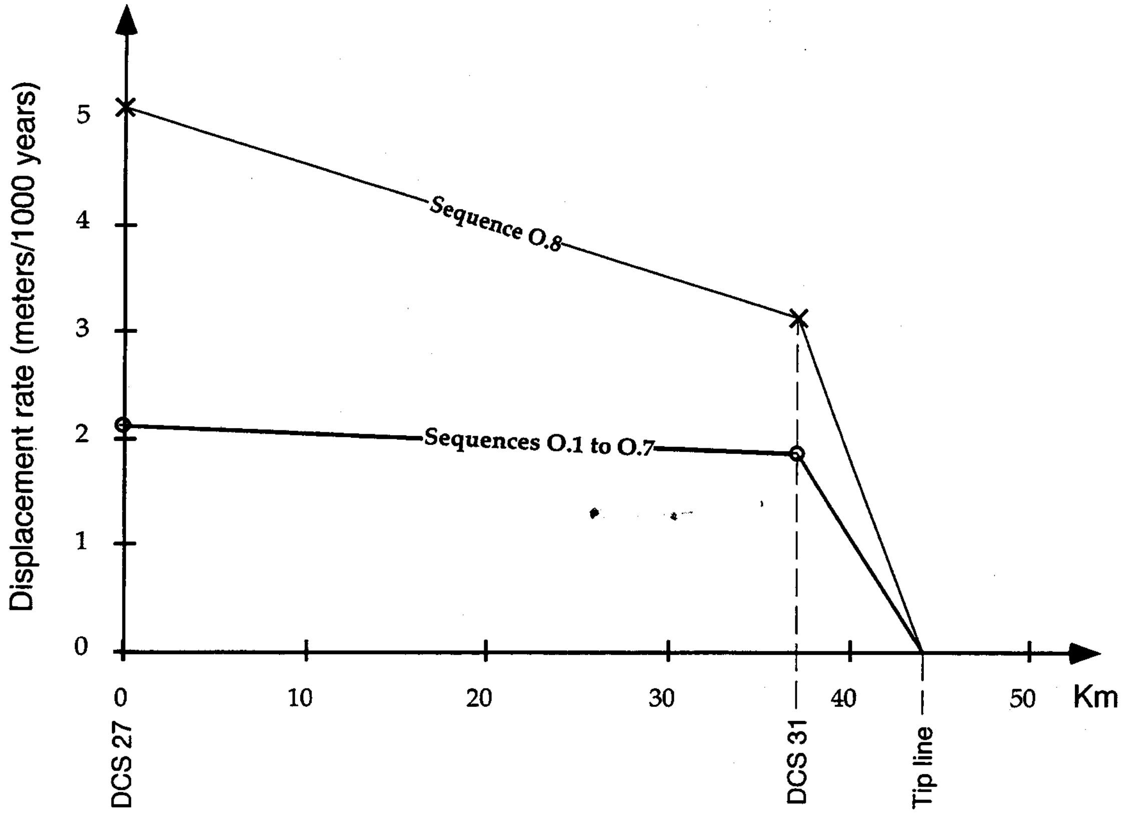

Fig. 8 The variations in displacement rate along the strike of the D-1 fault.