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Structure and Displacement Characteristics of the Brage Fault, Northern North Sea Sedimentary Basin

Adiotomre E. E.
Department of Geology, Delta State University P.M.B. 1, Abraka, Delta State, Nigeria

ABSTRACT
3-D seismic analysis of the Brage fault zone reveals it is over 21 km is strike length and has a maximum displacement of about 610 ms TWTT. The along strike trace of the Brage fault is characterized by four geometric fault segments identified as A, B, C, and D. Geometrical distribution, structural and displacement characteristics were use in delineating the fault segments along the fault trace. Geometric fault segments A and B are northern segments; segment C is a middle segment, and segment D is a southern segment. Geometric fault segment A occurs with a strike length of about 6 km from its northern tip and with a maximum displacement of 610 ms TWTT. Geometric fault segment B is about 4 km in strike length from its northern tip and with has a maximum displacement of 440 ms TWTT. Geometric fault segment C is about 5 km in strike length, and has maximum horizon offset of 330 ms TWTT. Geometric fault segment D has a length of about 7 km from its southern tip, and with a maximum displacement of 480 ms TWTT. Minima displacement and abrupt changes in fault strike marks the boundaries of the fault segments. Consequently, jog structures characterize the along strike traces of the Brage fault. A prominent structural feature associated with the southern and northern domains of the Brage fault is the Brage Horst that formed in the intervening blocks between the Brage fault and opposite dipping faults. The Horst structure tapers from its southern part where it is about 2.4 km wide to its northern region where it is about 300 m in width. The interaction between the geometric segments controls the present day structural geometry of the Brage fault.

KEYWORDS : *Brage fault, displacement, geometric fault segments, geoframe, horst structure, northern North Sea.*

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I. INTRODUCTION

The analysis of the structural geometry and displacement characteristics of fault zones is an important aspect of basin analysis probably because faults affect the geometry of structural closures of hydrocarbon units in sedimentary basins worldwide. Furthermore, faults may also ease or impede hydrocarbon migration in these basins. This is because the 3-D structural geometry of fault zones and the interaction between neighbouring faults, and the displacement variations along the fault zone impact the architecture of adjacent beds [1]. Previous studies on the pattern of displacement on fault surfaces suggests that displacement is greatest at the centre of the fault and diminishes to zero towards the fault tips, and that displacement distribution on a fault surface is in three dimensions [2, 3, 4, 5, 1, 6, 7]. Although this is what obtains for many faults, there are records of faults that deviate from this situation due to variations in lithology, differences in mechanical properties of rock units that relates to variations in seismic velocities [1].

The greatest displacement (D) on a fault scales with its largest strike length (L) in a way that $D = cL^n$, where c is a constant that relates to the properties of the rock type, and n vary between 1 and 2 [2, 4, 8, 9, 10, 11, 12]. In segmented discontinuous fault zones, displacement scales with the length of the entire fault zone in a way similar to that of a single segment. Also D-L profiles of the faults assume an asymmetric pattern characterized by steep slopes. These characteristics results from the mechanical interaction that occurs between each segment composing the fault zone before linkage. Another explanation is that the segmented fault zone behaves as a single fault with similar length as the segments array [13, 11, 12, 6, 14]. The Brage fault developed in the northern North Sea to the east of the Viking Graben, where it occurred with neighbouring faults such as Statfjord East fault and Oseberg fault on the west and east of the Viking Graben (Fig. 1) [15]. Whereas large amounts of useful data is available for the Statfjord East and Oseberg faults, scanty information is available on the structural geometry and displacement attributes of the Brage fault. Since the knowledge of the structural geometry and displacement characteristics of faults is of paramount importance in hydrocarbon play analysis, it is the purpose of the present study to unravel the structural attributes of the Brage fault to improve hydrocarbon exploration and production activities in the Brage area.

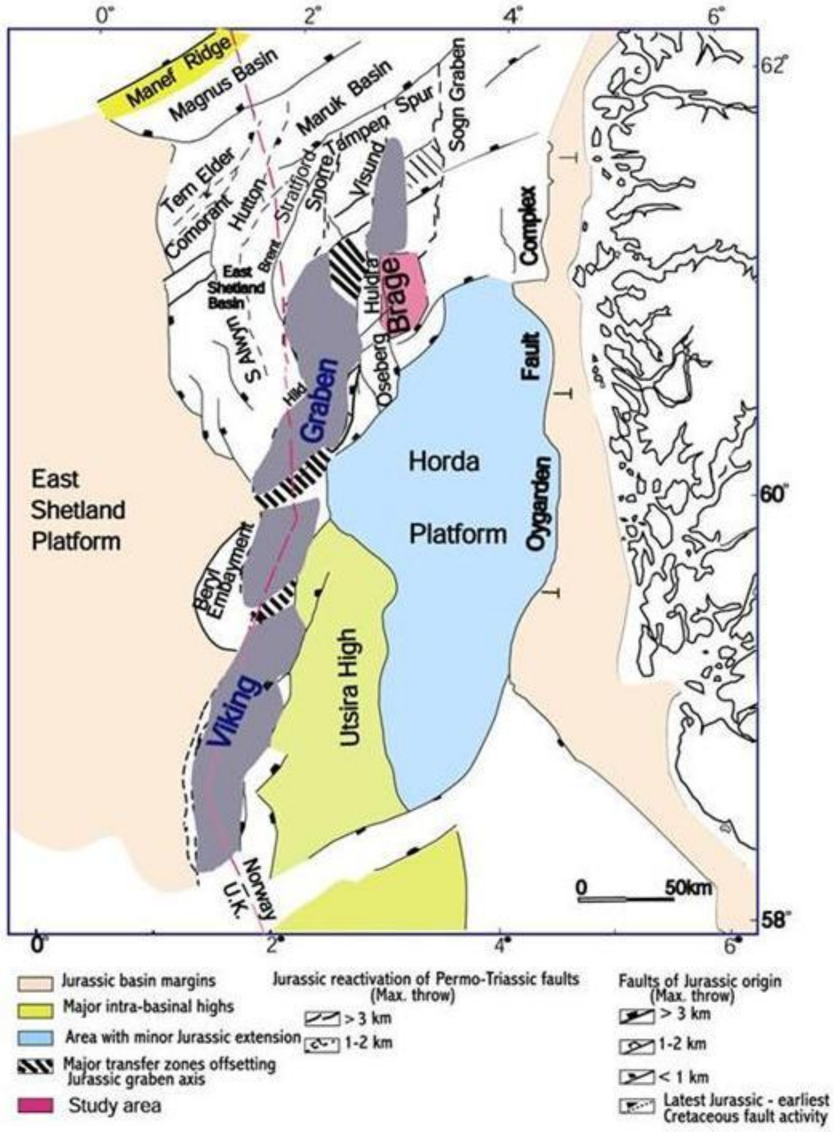

Figure 1: Map of the northern North Sea showing main structural elements and location of the study area [15].

II. MATERIALS AND METHODS

The northern North Sea 3-D seismic data set was use in the study of the Brage fault. The Schlumberger Geoframe software (version 3.8.1) was use to conduct the fault analysis in the Basin and Stratigraphic Laboratory of the University of Manchester, United Kingdom. Displacement, trace lengths, and positions of offset marker horizons in cross sections were measured along the trace of the Brage fault in two-way-travel-time (TWTT) of seismic waves. With the aid of offset marker horizons, displacement distribution profiles were generated for the Brage fault. The method used to compute displacement gradients (i.e. the change in displacement with respect to distance along the Brage fault) is similar to the method of [16] and [17].

III. NORTHERN NORTH SEA SEDIMENTARY BASIN

The Sedimentary Basin of the northern North Sea is a fault bounded extended crust that is N-S trending and 170-200 km in width. Its eastern limit is bound by the mainland of western Norway while its westerly margin is bound by East Shetland Platform [15]. Within the sedimentary basin, there are large normal faults which evolved during the Permo-Triassic extension and later reactivated by further rifting in the Jurassic. The faults show different trend directions that include a north-south, north-east, and north-west trend [18, 19, 20, 21, 22]. The Viking and Sogn Grabens that occur as a system of discrete rift segments represent the Jurassic rift in the northern part of the Northern North Sea [15]. The tectono-stratigraphy evolution of the northern North Sea Sedimentary Basin consist of three phases with reference to the period of initiation of rifting and these include pre-rift, synrift and post-rift phases (Fig. 2) [23, 15]. The synrift chronostratigraphic interval is the focus of the present study since it represents the phase when the significant extensional activity occurred in the northern North Sea. [23] and [15] offer comprehensive information on the stratigraphy of the northern North Sea.

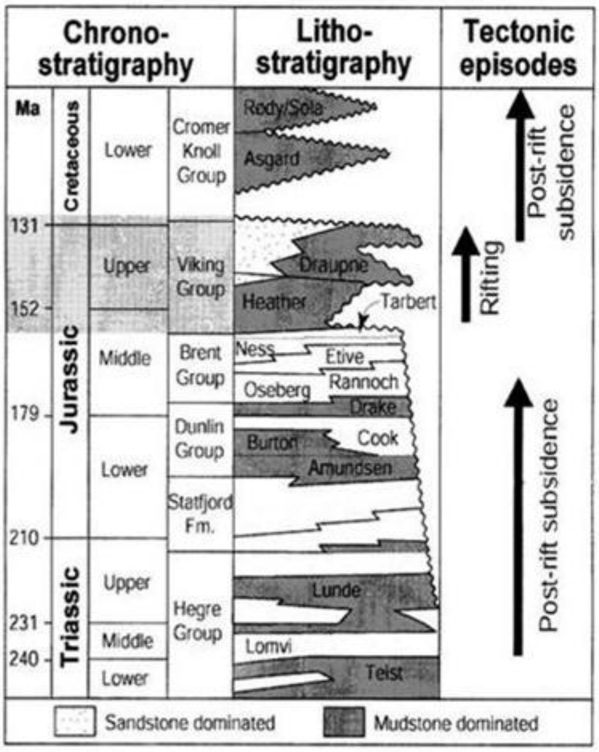

Figure 2: Stratigraphy of the North Sea showing the studied synrift interval [23].

IV. RESULTS AND DISCUSSION

Seismic Stratigraphy

Five regionally significant surfaces were mapped based on reflection character and terminations, and these include a top Brent unit (top pre-rift), top lower Heather unit, top upper Heather unit, top lower Draupne unit and top upper Draupne unit (top synrift) (Figs. 3). A high-amplitude reflection that is continuous throughout the seismic section characterizes the top Brent seismic unit. This reflection is a marked seismic onlap surface observed at 2450 ms TWTT and separates the high amplitude, sub parallel reflections of the pre-rift from the more complex seismic wedge packages of the synrift. It is therefore assumed as the top pre-rift in the study area (Fig. 3). Seismic reflection of moderate-high amplitude and excellent continuity characterize the top lower Heather unit. This reflection is the first prominent onlap on the top Brent observed at 2450 ms TWTT (Fig. 3), and this represents the boundary between the Brent Group and the overlying Viking or Humber Group. Moderate amplitude reflections that characterize the top Upper Heather seismic unit are poorly continuous. In the hanging-wall of the Brage East fault, the top lower Heather unit, locally onlaps the top Brent unit at 2150 ms TWTT (Fig. 3). The top lower Draupne is a low to moderate-amplitude reflection with excellent continuity. It locally truncates strong synrift reflections in the hanging-wall of the Brage East fault at 2050 ms TWTT (Fig. 3). The top of the synrift mapped as top upper Draupne is the base Cretaceous in the Brage area and is a high-amplitude reflection that is excellently continuous throughout the seismic section (Fig. 3). The strong reflection is as a result of the sharp impedance contrast between the carbonates in the lower part of the postrift Cromerknoll Group and the underlying synrift Draupne Formation [24].

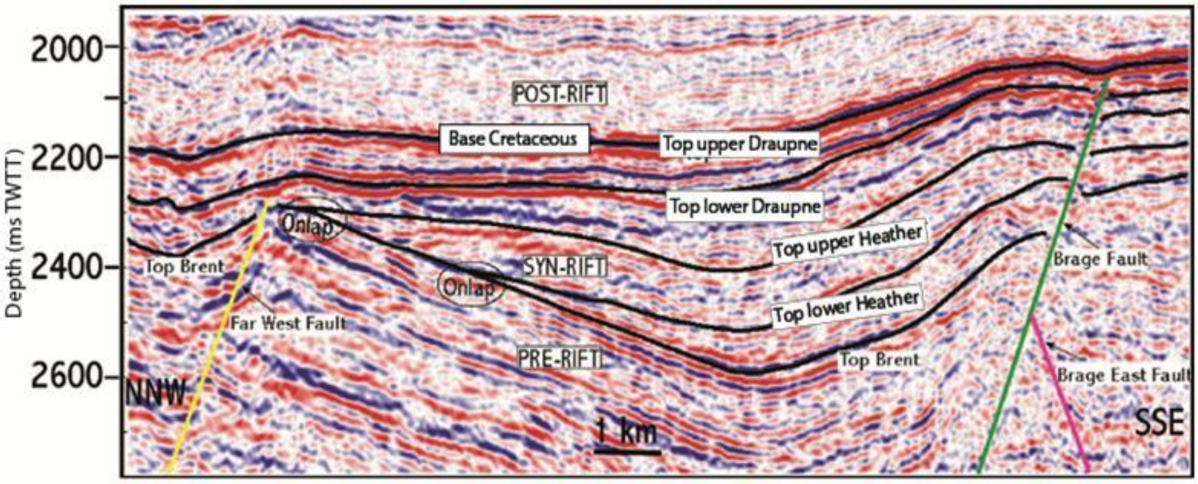

Figure 3: Cross section of interpreted seismic inline showing mapped stratigraphic horizons.

Structure of the Brage Fault Zone : The structure of the Brage fault is best illustrated by the top Brent horizon which separates units that show no thickness variation with respect to the synrift stratigraphic interval from those which diverge and thicken into the hanging-wall of the Brage fault zone. As a result, the top Brent horizon mark the beginning of significant activity in the Brage fault zone and provides information on the displacement that accumulates on the fault zone. The Brage fault is a north-south trending, west dipping fault that has a total length of about 21 km based on its trace on the top Brent horizon and it's comprised of 4 geometric segments that range between 4 and 7 km in strike lengths (Fig. 4). The fault segments (A, B, C and D) occur in three domains based on their geometric distribution along the Brage fault trace (Fig. 4). Geometric segments A and B are northern domain fault segments that are N-S and NW-SE trending. Geometric segment C is a middle domain fault segment that trends parallel to segment A, whereas segment D, a southern domain segment of the fault trace trends NNW-SSE (Fig. 4). The boundary of segments A and B is mark with a distinct jog where a change in fault strike from N-S to NW-SE occurred at about 6 km from the northern tip of the Brage fault trace (Fig. 4). A similar jog structure is also developed at the boundary of segments C and D that is mark by a slight change in fault strike from NW-SE to NNW-SSE (Fig. 4).

Eastwards of the southern domain of the Brage fault is a N-S trending fault, the Brage East fault. This fault is opposite dipping to the Brage fault and intersects its footwall to form a Horst structure (Figs. 4, 5 and 6). The Horst structure tapers from south to north; in the south where it is wider, measured width is up to 2.4 km on the top Brent horizon. The measured width of the northern part of the horst structure is about 360 m (Figs. 4, 5 and 6). A relatively smaller Horst structure (measured width is less than 0.3 km) is also developed in the northern domain of the Brage fault where geometric segment A occurs and it relates to a N-S trending fault which dips similar to the Brage East fault (Figs. 4, 5 and 6). The variation in the dimensions of the northern and southern Brage Horst structures may have resulted from a variation in the deformation that localized on the different domains of the Brage fault [e.g. 25, 26]. It is probable that in the northern domain, deformation localized early on the Brage fault as compared with the southern domain where deformation probably localizes late as the fault system evolved resulting in greater uplift of the footwall.

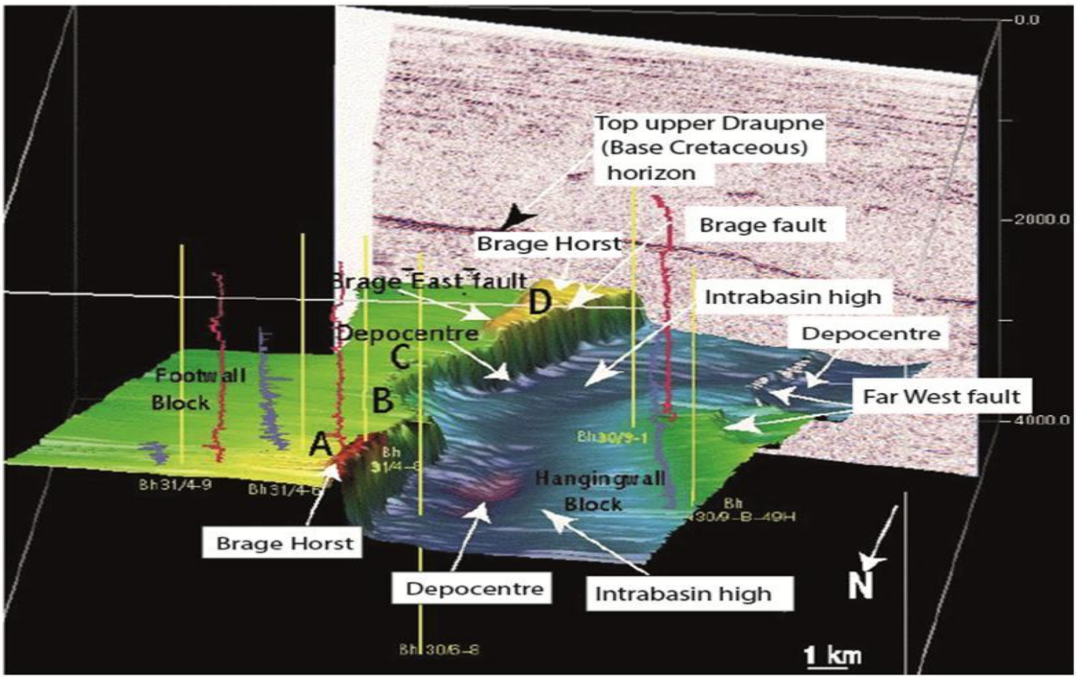

Figure 4: 3-D view of the Brage fault zone showing geometric fault segments (A, B, C, and D), Brage horst, depocentres and intrabasin highs. Note the wider southern part of the Brage horst structure. Seismic inline shows top Brent horizon in relation to the top upper Draupne (base Cretaceous) reflection. Bh=Boreholes drilled into footwall, hanging-wall and Brage horst.

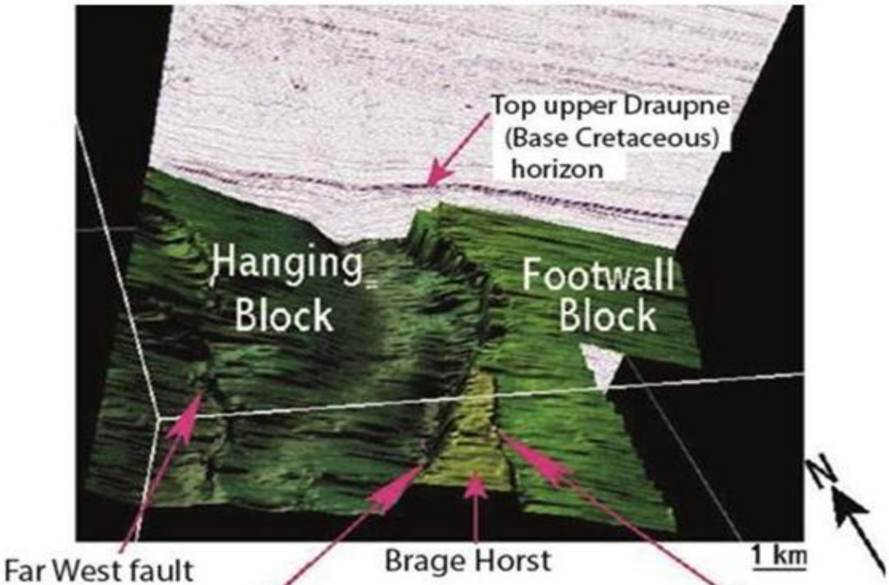

Figure 5: 3-D view of the top Brent horizon offset by the Brage fault. Seismic inline shows the top Brent in relation to top upper Draupne horizon.

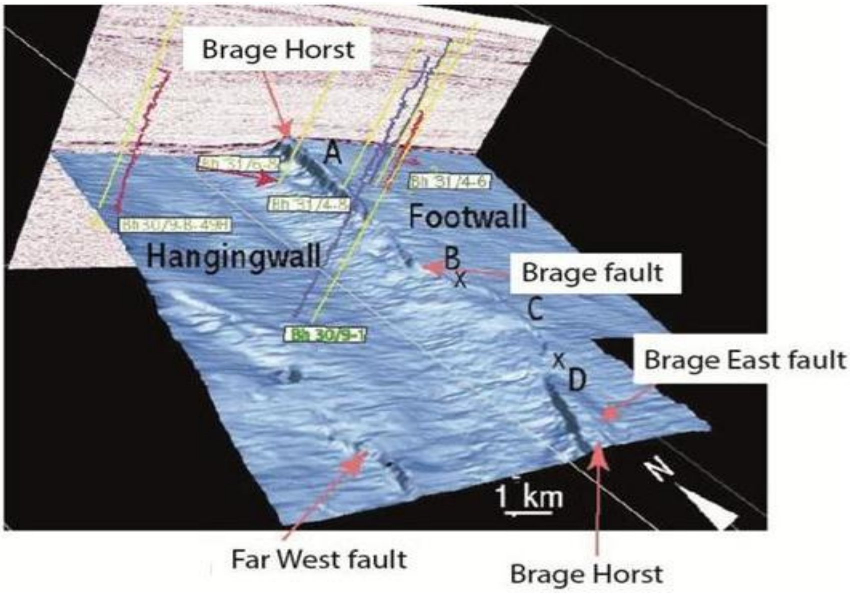

Figure 6: 3-D view of the top lower Draupne horizon offset by the Brage fault. A, B, C, D = geometric fault segments; Bh = boreholes drilled into footwall, hanging-wall and Brage horst; X = position of no offset of top lower Draupne horizon.

Fault Displacement Characteristics: The fault displacement (D) to distance (d) profiles generated for the top Brent and top lower Draupne seismic horizons illustrate a complex pattern with multiple displacement minima separated by local displacement maxima along the strike length of the fault (Figs. 7 and 8). A distance that varies from 1.5 to 4.2 km separates successive displacement maxima on the D-d profile generated for the top Brent seismic horizon while a distance, which varies between 2.0 and 3.2 km, separates successive displacement minima (Fig. 7). On the D-d profile generated for the top lower Draupne seismic horizon, successive displacement maxima occur at a distance that varies from 1.3 to 4.3 km, while a distance separates successive displacement minima that ranges between 2.2 and 4.7 km (Fig. 7). The D-d profiles when correlated with the fault trace in map view, illustrates areas where displacement minima coincide with locations of significant changes in fault strike (Figs. 6 and 7). These areas discriminate the four geometric segments illustrated in the map view as A, B, C, and D, and relate to different regions on the D-d profiles separated by displacement minima. A local displacement minimum is commonly associated with linked fault segments and occurs at the segment linkage site that is usually between two displacement maxima [27, 28, 11, 12, 17].

Based on the top Brent displacement-distance profile, the greatest displacement associated with the four geometric segments is: segment A (610 ms TWTT), segment B (440 ms TWTT), segment C (330 ms TWTT), segment D (480 ms TWTT). On the other hand, the D-d profile generated for the top lower Draupne shows that the greatest displacement for the geometric segments is: segment A (130 ms TWTT), segment B (70 ms TWTT), segment C (60 ms TWTT), segment D (100 ms TWTT). The greatest displacement (610 ms TWTT) associated with the top Brent seismic horizon occurred at 2600 km distance from the northern edge of the Brage fault trace while the greatest displacement (130 ms TWTT) related to the top lower Draupne horizon occurred at 837 m distance from the northern edge of the Brage fault trace (Figs. 6 and 7). An added characteristic of the D-d profiles obtained for the Brage fault is that areas of displacement high occur to the north and south of the profiles with intervening areas of relatively low displacement (100-480 ms TWTT) for both the top Brent and top lower Draupne horizons. In high displacement areas to the north and south of the Brage fault trace, two neighbouring N-S trending faults occur and intersect the footwall of the Brage fault (Fig. 6). One of these faults is Brage East fault, the trace of the second fault that developed in the northern domain is not clearly visualized in 3-D. The high displacement area that occurred to the north and south of the Brage fault D-d profiles is as a result of the positive stress feedback between ruptures on the Brage fault and aforementioned faults [e.g. 29].

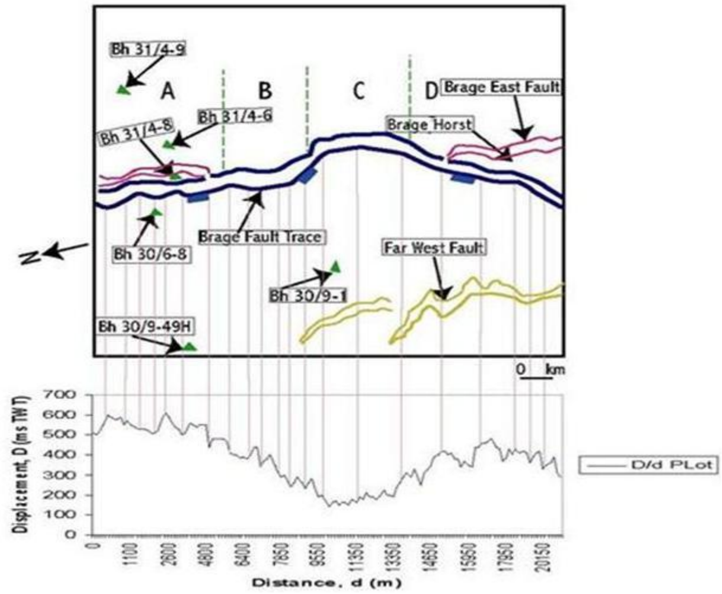

Figure 7: Brage fault trace related to the displacement-distance profile for the top Brent horizon. A, B, C, D = geometric fault segments; Bh = boreholes drilled into footwall, and hanging wall and Brage horst.

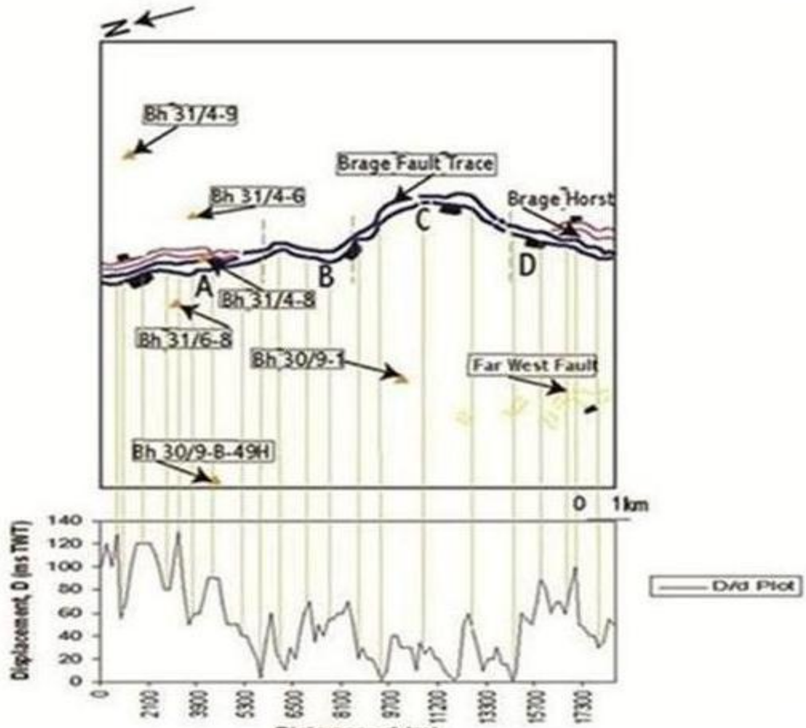

Figure 8: Brage fault trace related to the displacement-distance profile for the top lower Draupne horizon. A, B, C, D = geometric fault segments; Bh = Boreholes drilled into drilled into footwall, hanging wall and Brage horst.

V. CONCLUSION

The analysis of 3-D seismic data set from the northern North Sea Sedimentary Basin illustrates that the Brage fault consists of four geometric segments A, B, C, and D that occur in different domains along the Brage fault trace. These segments are of variable length and displacement attributes and have boundaries marked by displacement minimum that occurs between displacement maxima. The displacement pattern that characterized the D-d profiles generated for the top Brent and top lower Draupne horizons reveals high displacement in both north and south of the profiles with intervening regions where displacement is relatively lower. The enhanced displacement in these areas results from the positive stress feedback between the Brage fault and neighbouring faults in the northern and southern domain of the Brage fault trace. The Brage Horst structure in the southern domain is prominent and of larger dimension than the Horst structure in the northern domain probably due to variation in deformation and the time it localized from the neighbouring faults on the Brage fault.The interaction between the geometric fault segments and the associated along strike variations in displacement are important factors controlling the present day structural geometry of the Brage fault zone.

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