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Structural evolution of the Witch Ground Graben

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SUMMARY: The Witch Ground Graben is a NW–SE trending extensional basin in the central part of the northern North Sea, lying between the Moray Firth and the Viking Graben. NE–SW extension occurred from Triassic to Cretaceous times. Extension took place on listric normal faults along the SW margin, with downthrow to the NE, giving rise to the asymmetry of the basin. One of the principal phases of fault-controlled subsidence occurred in the Lower Cretaceous, from the Valanginian to Albian. Compilation of biostratigraphic data from this interval shows the development of an increasing number of stratigraphic breaks across the basin from SW to NE, these breaks increasing in time span also in this direction. This is a result of rotation of the subsiding fault block on the listric extensional faults. The rotation is recorded in dipmeter data, and occurred in several distinct episodes—the Triassic, the Volgian and the Valanginian to Aptian. In reconstructing a cross-section of the basin, the interpreted fault curvature is constrained by the observed rotation of bedding surfaces, and the amount of extension across the listric faults is constrained by the observed basin subsidence. A depth to décollement for the faults of 4 km below sea level and an extension across the basin of 40% are estimated.

The simple stretching model for the initiation and evolution of certain sedimentary basins proposed by McKenzie (1978) has been successfully applied to the analysis of the basin subsidence in several recent studies (e.g. Sclater & Christie 1980; Christie & Sclater 1980; Sawyer *et al.* 1982). The model involves a stretching of the continental crust with subsidence taking place as light continental crust is replaced by dense upper mantle material in the thinned zone. This initial subsidence is followed by a more gradual subsidence caused by the cooling and contraction of the hot upper mantle material. The initial subsidence may account for up to 40% of the total basin subsidence, and the thermal subsidence generally occurs during 100 Ma after stretching.

In the upper crust, stretching occurs by movement on extensional faults, which are usually steeply dipping near the surface, but become concave with depth to a decoupling zone (e.g. Le Pichon *et al.* 1982; Proffett 1977; Davies & Hardy 1981; Wernicke & Burchfiel 1982). The Witch Ground Graben is an extensional basin in the northern North Sea lying between the Viking Graben and Outer Moray Firth (Fig. 1), bounded by a major NW–SE extensional fault zone along its SW margin (Johnson & Dingwall 1981; Ziegler 1981; McQuillin *et al.* 1982). Extensional subsidence of the basin may have occurred during the Permian and Triassic, but is most conclusively recorded by Upper Jurassic and Lower Cretaceous sequences. The effects of post-extensional thermal subsidence are seen in the Upper Cretaceous sequences (cf. Sclater & Christie 1980). Examples of sections across extensional, fault-controlled sedimentary basins may be found in Royden *et al.* (1983), Effimoff & Pinezich (1981), Wernicke & Burchfiel (1982). The structure of these basins is analogous to that of the Witch Ground Graben outlined below.

This paper examines the geometry and stratigraphic development of the Witch Ground Graben as a specific example of an extensional basin in such a way that the applicability of McKenzie's (1978) theoretical model for the development of such basins may be judged.

Structural cross-section

Figure 2 presents a SW–NE section across the Witch Ground Graben. A major gently dipping zone of listric normal faults forms the SW margin of the basin. These faults are shown to flatten out into a basal fault or decoupling zone at about 4 km below sea level. The sedimentary sequence thickens from NE to SW towards this fault zone, and growth of the stratigraphic section across the zone in Permian, Triassic, Jurassic and Cretaceous times is seen. In general, faults within this zone became active at progressively younger times in going from the hanging-wall block to the footwall block. The faults are drawn as concave listric structures as this provides the mechanism for progressive rotation to southwesterly dips in the hanging-wall block. The amount of fault curvature is constrained by the fact that successive stratigraphic horizons in the hanging wall must restore to their pre-faulting configuration in the footwall. Further, cross-sectional area balance must be maintained. Whilst these constraints have been upheld, the geometry will have been modified by post-faulting subsidence and compaction, as recorded, for example, by the shape of the base Tertiary reflector. Restoration of this has not been attempted.

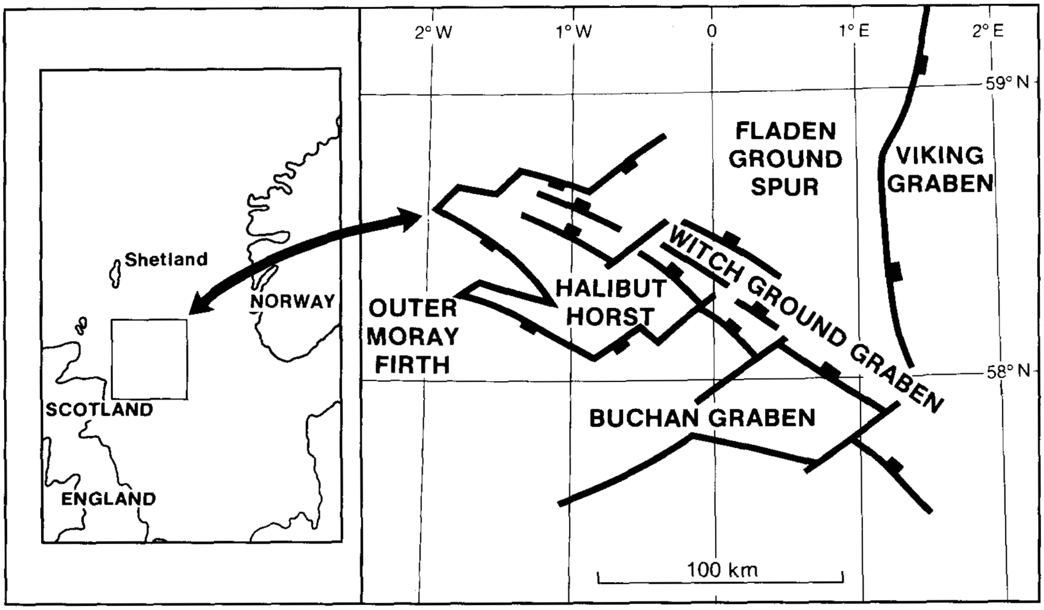

FIG. 1. Location of the Witch Ground Graben, showing the principal extensional normal faults and transfer faults active during the Jurassic–Cretaceous, based on Johnson & Dingwall (1981).

One consequence of extensional listric faulting is the necessary change in shape of the hanging-wall block as it conforms to the curved fault shape. Indeed, it is the latter which enables an interpretation of the former to be made on seismic sections. At shallow crustal levels this is largely accommodated by the development of antithetic faults, dipping steeply to the SW in Fig. 2, and terminating at the master synthetic fault. As growth of the sedimentary section occurs through time, antithetic faults penetrate upwards to progressively younger stratigraphic horizons, and early faults become rotated into steeper positions. Most of the faults shown in Fig. 2 terminate upwards at or near the top of the Lower Cretaceous, whilst a few persist upwards to affect the base of the Tertiary.

Rotation of the hanging-wall block during extension not only gives rise to a subsiding basin but may also cause uplift, stratigraphic thinning and erosion away from the fault zone. This is seen in Fig. 2 where in a NE upflank direction, the Triassic sequence thins and is truncated at the base Jurassic reflector; the Jurassic sequence thins beneath the base Cretaceous reflector; and the Lower Cretaceous thins beneath the Upper Cretaceous.

Rotation may be recorded in suitable dipmeter data. For example, Fig. 4 shows a record of gradual change in regional dip from a location on the up-flank side of the basin, where a thinned Jurassic sequence rests on rocks of Permian age. The oldest Jurassic rocks here are Early Volgian, and from Fig. 4 it is seen that regional rotation was not continuous from this time, but was separated into an Early to Middle Volgian phase, a late Ryazanian to late Aptian phase, and a minor Cenomanian/Turonian phase. Each phase is inferred to correspond to an episode of extension on the listric faults.

A further record of the timing and duration of fault movement is provided by growth curves for the major extensional faults, in which the thickness of the stratigraphic sequence on the downthrown side of the fault is plotted as a percentage of the thickness on the upthrown side, for successive stratigraphic intervals. A general compilation of data for the Witch Ground Graben is shown in Fig. 5, based on data averaged from 10 wells on the downthrown side and from 6 wells on the upthrown side. Two major periods of syn-faulting stratigraphic growth are seen, during the Volgian (approximately 6 Ma) and from the Hauterivian to Barremian (approximately 7 Ma). From the latter phase, the curve tails off gradually through to the Cenomian as fault movement ended and compaction of the underlying sequences occurred.

The section shown in Fig. 2 allows estimates of extension at different stratigraphic horizons to be made. For example, at the base of the Cretaceous, extension is approximately 15%; at the base of the Jurassic it is approximately 25%; and at the base of the Permian it is approximately 40%. Fault-controlled subsidence in a basin is related to extension across the basin, and the values of extension from interpreted cross-sections should be consistent with amounts of subsidence measured from well data. Using the model

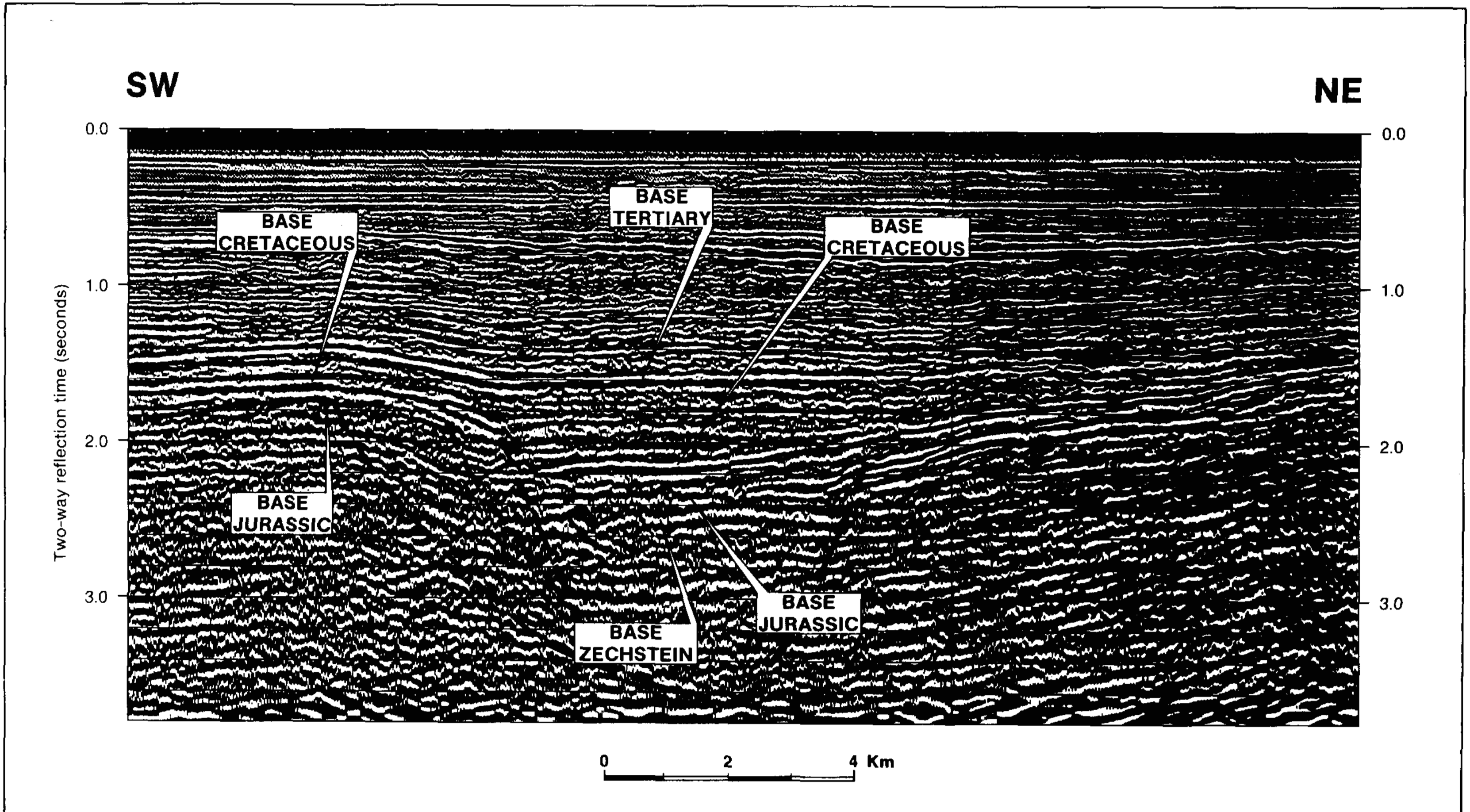

FIG. 3. Part of a seismic section across the Witch Ground Graben to illustrate the type of data used to construct Fig. 2. Principal stratigraphic markers are labelled and the principal fault interpretation is shown. Individual sections such as this often raise problems of overall balance that suggest that out-of-section strike slip movements may have occurred on either or both sets of faults marked. Fig. 2 is a generalized section generated from seismic data. Vertical scale in seconds, two-way time; horizontal scale in km.

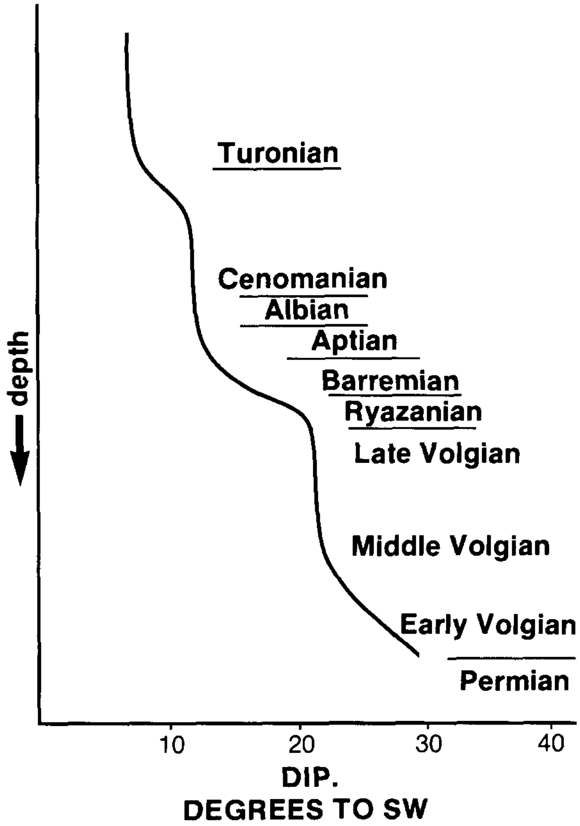

FIG. 4. Fault block rotation in the Witch Ground Graben recorded by the regional dips in a well dipmeter from an upflank location, where Jurassic and Lower Cretaceous sections comprise Early to Late Volgian, Ryazanian, and Early Barremian to Late Albian Strata. All dips are to the SW.

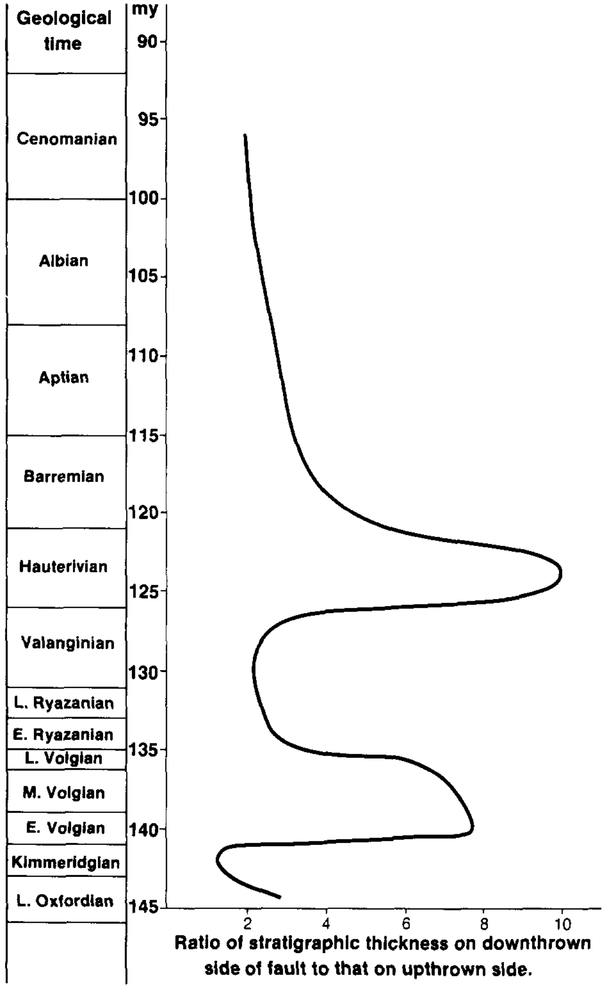

FIG. 5. Stratigraphic growth curve for the Witch Ground Graben, plotted as the ratio of stratigraphic thickness on the downthrown side to that on the upthrown side of the major boundary fault, through geological time from Late Oxfordian to Cenomanian. The curve is averaged from 10 wells on the downthrown side and 6 wells on the upthrown side.

of McKenzie (1978), elaborated by Sawyer *et al.* (1982), the theoretical relationship between basin subsidence and extension is shown in Fig. 6. Curve **a** relates subsidence to extension in the absence of sedimentation, whereas curve **b** adds to this a correction for isostatic loading of the 'syn-faulting' sediments. A sediment density of 2.6 gm^3 and a crustal thickness of 30 km have been used (see Christie & Sclater 1980).

From the data used to compile Fig. 5, the average thickness of the syn-faulting sediments in the Upper Jurassic and Lower Cretaceous is 950 m, which corresponds to an extension 60% on Fig. 6. This is considerably higher than the value of 25% interpreted on the structural cross-section (Fig. 2). Clearly the seismic interpretation could be overestimating the inclination of the extensional faults, since the measured extension is very sensitive to fault dip. It is considered that the seismic data used would not allow reinterpretation of fault dips to such a degree as to raise the extension at base Jurassic to 60%.

Modification must be made by considering the sedimentary thickness at the time of deposition. A present measured thickness of syn-rifting sediment of 950 m can be restored to the uncompacted thickness at the time of deposition using the methods of Magara (1978). However, a more rapid approximation can be made in the Witch Ground Graben. The crest of the footwall block was eroded during Lower Cretaceous times (see Fig. 2) and was emergent until Late Albian

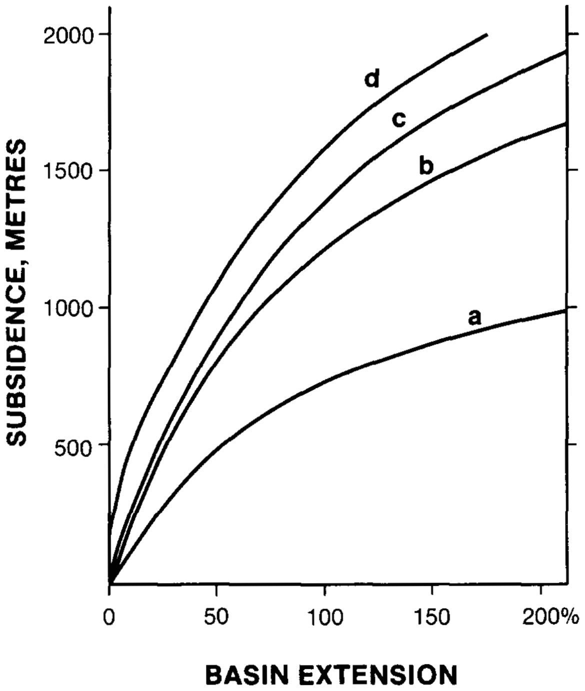

FIG. 6. Relationship between the extension and the subsidence in a basin, based on McKenzie (1978) and Sawyer *et al.* (1982). Curve **a** is the subsidence resulting from crustal extension, while curve **b** shows the subsidence plus the isostatic correction for the sediment loading, using a crustal thickness of 30 km and a sediment density of 2.6 g cm^3 (compacted sediment, present day thicknesses). Curve **c** adds a further correction to allow for uncompacted sediment at the time of deposition; this curve assumes that all sediment was claystone with initial porosity of 0.4, and uses the relations given by Magara (1976). Curve **d** shows the addition of 200 m thermal contraction subsidence, resulting from the previous Upper Jurassic extension, that may have been superimposed on extensional subsidence in the Lower Cretaceous.

times, when marine sediments covered the block. Using this measure of sea level, an isostatic correction for 950 m of compacted sediment plus 325 m of water has to be applied to the subsidence curve **a** in Fig. 6. This is shown as curve **c** in Fig. 6, and the measured syn-rifting sediment thickness now corresponds to an extension of approximately 50%.

In addition, it should be noted that the model from which curve **a** in Fig. 6 was derived involved instantaneous stretching and subsidence (McKenzie 1978). However, this is not the case in the Witch Ground Graben, where a Lower Cretaceous stretching followed about 15 Ma after an Upper Jurassic stretching. This suggests that the Lower Cretaceous rifting subsidence was superimposed on a post-Upper Jurassic thermal contraction subsidence that already amounted to 1–200 m (McKenzie 1978; Sawyer *et al.* 1982; see also Fig. 6, curve **d**). This result ignores any effect of post-Triassic thermal subsidence. If stratigraphic thicknesses obtained from well logs are decompacted and if allowance is made for the time-span of rifting events and the duration from the previous event, reasonable accord between measured subsidence and extension should be obtained. The prediction of overall basin extension from observed subsidence is an important aspect of basin interpretation and the theoretical relation established by McKenzie (1978) must be used with care and greatly modified to allow for the specific geological evolution of individual basins. Construction of a separate subsidence-extension relation for each basin results from this and represents the product of the iterative procedure of checking observation against modelling. At this stage, Fig. 6 achieves an acceptable precision in predicting extension to the nearest 10%.

Combining the data on the extension across the faults and the subsidence during extension, derived from Fig. 2, it is possible to estimate the depth to decoupling of the hanging-wall block. Thus, both the curvature of the listric faults and the depth at which they flatten out can be constrained by data obtained directly from seismic sections, and the interpretation of the fault geometry from seismic reflections corroborated.

The method utilizes a technique previously applied in overthrust belts (see Hossack 1979, fig. 1 and discussion; Gibbs 1984). The area (defined by integrating the subsidence at a chosen stratigraphic level over the length of the section), divided by the extension (measured at the same stratigraphic level and over the same length), equals the depth to the level of decoupling. The latter is measured from the initial depth of the stratigraphic horizon chosen and the section is one in which cross-sectional area is conserved during extension. Applying this method to the section in Fig. 2, it is found that the listric extensional fault system flattens out at a depth of about 2 km below the base of the Permo-Trias on the footwall block seen at the SW end of the section.

However, the depth of decoupling of the extensional faults controlling the development of the Witch Ground Graben does vary along the strike of the basin. For example, Fig. 2 is representative of the northern part of the basin, whereas in the southern part of this basin, decoupling is thought to have occurred at about 10 km depth. Such changes in structure along strike are thought to occur across significant transfer faults (see Gibbs 1984) that divide the basin into separate compartments (transfer faults are the extensional analogue to sidewall ramps in thrust belts, see Elliott & Johnson 1980).

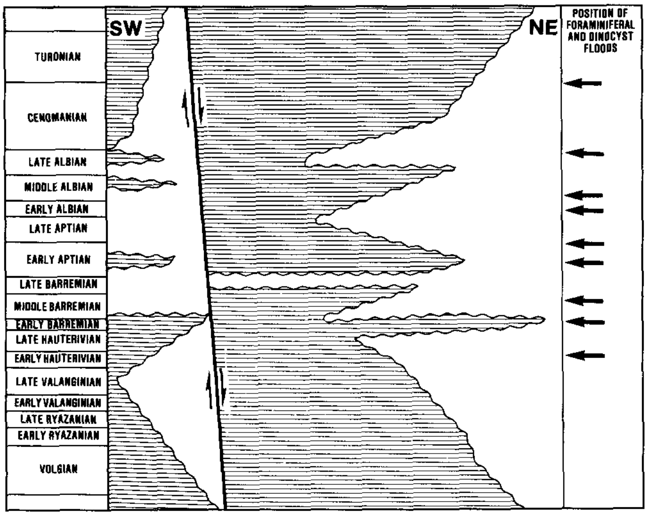

FIG. 7. Time–stratigraphic section across the Witch Ground Graben. The timing, duration and correlation of stratigraphic breaks were assessed using 41 foraminiferal and dinocyst markers in the Ryazanian to Cenomanian section. The position of the boundary fault is shown. Section present is ruled; section missing is left blank.

Time–stratigraphic section

Figure 7 has been compiled from well data where the positions and durations of stratigraphic breaks have been interpreted using 41 biostratigraphic markers (foraminifera and dinocysts) identified from the base of the Ryazanian to the top of the Cenomanian. The position of the major fault forming the SW boundary to the basin is indicated. The most continuous sections are found immediately on the downthrown side of this fault. Stratigraphic breaks gradually increase in number and duration in a northeasterly direction until only a very small part of the Lower Cretaceous section is represented. A repetition of the pattern seen on the NE side of the basin is found on the upthrown side of the fault (Fig. 7).

This pattern of stratigraphic breaks is interpreted to result from the rotation of the fault block on a listric fault during extension. Subsidence is greatest, and therefore sequences are most continuous, close to the fault. Farther away, where rotation tends to cause uplift, thinning and discontinuity of the sequence increase upflank of the fault block.

Discussion

The data presented show that there was a close relationship between the structural and stratigraphic development of the Witch Ground Graben during the Jurassic and Cretaceous. Systematic development of stratigraphic breaks and sediment thicknesses relate closely to the extensional, fault-controlled geometry of the basin. A complex pattern of regional rotation, stratigraphic truncation and onlap results from the asymmetric subsidence, the interaction of fault controlled subsidence with thermal subsidence from earlier extension episodes, and the consequent sea level changes.

In cross-sections of the Witch Ground Graben, Jurassic and Cretaceous strata progressively onlap in a NE direction (cf. Figs 2 & 7). Vail & Todd (1981) relate such onlap to sea level changes, generally considered to be global in distribution and eustatic in origin. More recently Watts (1982), Steckler & Watts (1981) and Watts *et al.* (1981) have demonstrated that onlap is a logical consequence of the McKenzie (1978) model during the post-extensional lithospheric cooling stage, and these authors largely reject the global sea-level curve of Vail & Todd (1981).

The Witch Ground Graben shows episodic onlap (Fig. 7) onto the Fladen Ground Spur (Fig. 1) during the Cretaceous. Little of this can be attributed to global sea-level changes. For example, Hancock & Kauffman (1979) consider an Albian to Early Turonian sea-level rise to be global in extent, Jenkyns (1980) a worldwide existence of black shales in the Aptian–Albian and the Cenomanian–Turonian to correspond to global transgressions, and Summerhayes (1981) a distribution of black shales in the North Atlantic to have a similar origin.

In detail, the positions of foraminiferal and dinocyst floods within the Lower Cretaceous sequences of the Witch Ground Graben (Fig. 7) are considered to indicate episodes of transgression and/or rise in sea level, producing an increase in marine shelf area, with rapid single species dominance following this environmental change (cf. Haig 1979). A group of Late Valanginian to Early Hauterivian floods correspond to the onset of extensional faulting, with late Hauterivian to Middle Barremian floods occurring later in this faulting phase (Figs 5 & 6). Aptian floods may be partly fault-controlled, related to early post-tectonic subsidence superimposed on post-Jurassic rifting subsidence. In the Aptian–Albian, floods occur during periods of general offlap and onlap. A smoothed curve from Aptian to Turonian in Fig. 7 indicates a gradual onlap in response to the thermal contraction subsidence following rifting (McKenzie 1978; Sclater & Christie 1980; Watts 1982). Global eustatic rises in sea level in this period (Vail & Todd 1981; Hancock & Kauffman 1979; Jenkyns 1980; Summerhayes 1981) are not discernible in the data presented.

In conclusion, stratigraphic onlap in the Cretaceous rocks of the Witch Ground Graben is seen to have a complex pattern and origin. Onlap occurred both in response to fault block subsidence during extensional faulting and to post-faulting thermal subsidence. Periods of active uplift on the NE side of the basin may interrupt onlap during basin subsidence. They are related to the geometry of the sole fault across which the hanging-wall block is moving during extension, and suggest that this fault may be undulating (cf. De Charpal *et al.* 1978).

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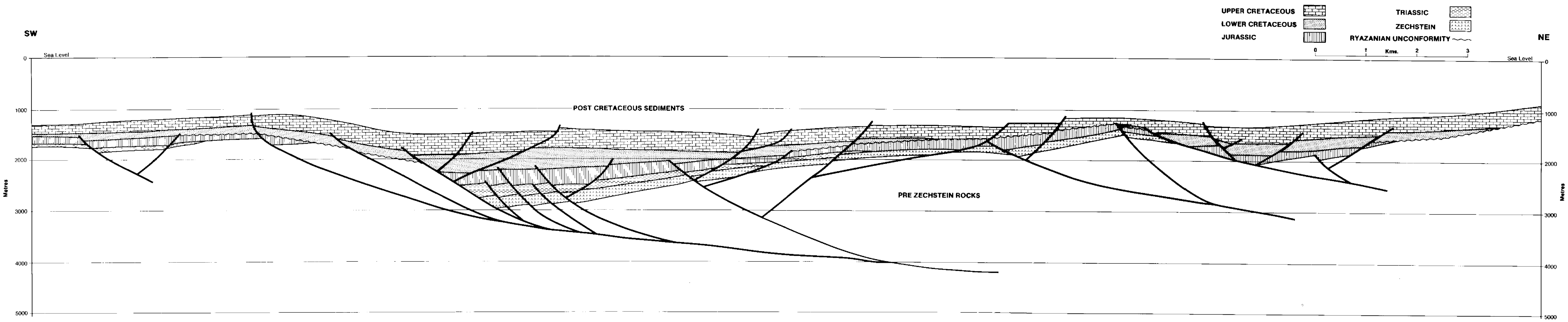

FIG. 2. Structural section across the Witch Ground Graben, showing the major extensional listric fault zone at the SW margin; related antithetic faults; a subsidiary fault zone to the NE; the change in thickness and truncation of stratigraphic units; and Cretaceous onlap. This section has been constructed from seismic sections with well ties to principal seismic markers of Permian, Triassic, Jurassic and Cretaceous age (see Fig. 3). The interpretation of the deeper part of the section, especially the depth of fault flattening, is controlled by two observations at shallower levels, viz. the amount of stratigraphic growth and bed rotation into the major fault, and the distance away from this fault that rollover dies out (cf. Gibbs 1984).