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3.Application of the restoration technique

Our restoration technique has been applied to a contractional fold in the NW German Basin. The structure is located near the northern margin of the Jurassic to Early Cretaceous Lower Saxony Basin, which was inverted during Late Cretaceous time (Baldschuhn et al., 1991, Kockel et al., 1994; Figure 3a). Inversion is manifested by thrusting and thrust−related folding through the reactivation of former basin−bounding normal faults and by exploiting Permo−Triassic halite layers as detachment horizons.

The model used for this study was built from a depth−converted, 3−D seismic interpretation of the structure, based on unpublished hydrocarbon exploration data.

The model is approximately 6km by 6km in map extent, and 3km in depth. It contains eight surfaces that represent interpreted seismic horizons of different geological surfaces. From oldest to youngest they are: the Base Roet; Top Roet; Top Muschelkalk; Base Cretaceous; Near Base Cretaceous; Top Santonian; Top Campanian; and Base Tertiary (Figure 3).

The actual structure is an asymmetric, thrust−cored fold with thickness variations within most of the stratigraphic layers involved (Figure 3). At the base of the interpretation, the Lower Triassic Base Roet surface dips slightly to the north; elsewhere the Triassic Roet evaporite layer is folded along and is offset by a thrust fault (which strikes ESE−WNW parallel to the overlying folds). The overlying Triassic−age Keuper layer is folded and shows thinning to the south (Figure 3a). Lower Cretaceous strata also display thickness changes, but with thinning to the north. Above the Lower Cretaceous layer, the Upper Cretaceous units are all folded with thickness changes across the fold axis, whereas the overlying Tertiary is regionally dipping to the north and is not folded. The lowermost folded, but unfaulted, horizon is the Top Muschelkalk surface; it has a structural relief of over 600m (Figure 3b). The surface is deformed into an anticline with an E−W doubly−plunging axial trace that trends towards 098^{o}.

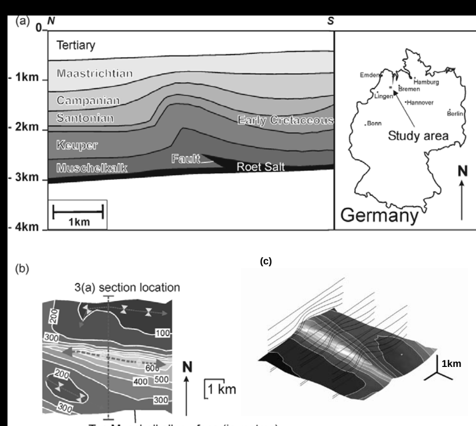

Figure 3. Present−day geometry of the contractional fault−related fold from the NW German Basin.
(a) Cross section, with 0m datum representing sea level, showing a representative geometry of the structure. Inset map illustrates the study area location of the fold.
(b) Map showing the present−day relative structural relief of the Top Muschelkalk surface and the location of cross section in Figure 3a.
The contour interval is 100m and relative to the lowest point on the surface in order to emphasize the relative structural relief. Arrows are used to highlight the fold axes, including the relatively minor synclinal features.
(c) Orthographic view of the Top Muschelkalk surface.

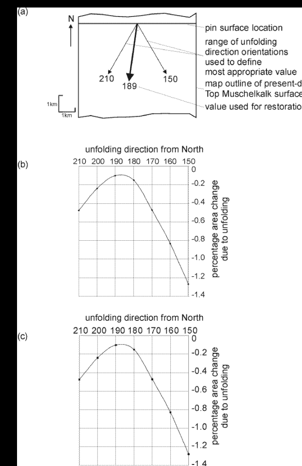

Figure 4. Unfolding direction sensitivity analysis.
(a) Map outline of the present−day Top Muschelkalk surface with the range of unfolding directions used to determine the most appropriate unfolding direction.
(b) Plot of the percentage area change due to unfolding versus unfolding direction from North. The pin surface was oriented E−W.
(c) Plot of the percentage area change due to unfolding versus unfolding direction from North. The pin surface was oriented orthogonally to the unfolding plane orientation. Note that this plot is almost identical to Figure 4b with the implication that the unfolding strain is insensitive to the pin surface orientation.

4. Restoration Methodology

The object of the restoration was to examine the temporal evolution of the fold.

We first sequentially decompacted the 3−D surfaces and then unfolded them to a horizontal datum using a vertical planar pin surface placed in the foreland of the fold. The 3−D decompaction utilised North Sea compactional values for the appropriate sedimentary units (Allen & Allen, 1990).

At each restoration stage, the uppermost stratigraphic surface was unfolded to the datum whilst the underlying surfaces were carried as passive objects.

Horizons below the Top Muschelkalk have not been restoredas it seemed inappropriate to restore faulted layers that involved evaporites using a flexural−slip mechanism.

5.Sensitivity testing of unfolding direction for 3−D restoration

Two analyses were carried out using the present−day Top Muschelkalk surface (Figure 4).

The first analysis was to test the sensitivity of total surface area change with variation of the unfolding plane orientation. Assumed that the most appropriate unfolding plane orientation will result in the minimum surface area change. The pin surface orientation of 090^{o} (E−W) was maintained, whilst the unfolding plane orientation was varied (Figure 4b).

The second analysis tested the sensitivity of the total surface area change to the pin surface orientation. The pin surface was kept orthogonal to the unfolding plane as the unfolding plane orientation was varied (Figure 4c).

The difference in percentage area change of the surface by using a constant or an orthogonal pin surface orientation is negligible compared to the area variation due to the change in unfolding plane azimuth.

The conclusion is that the unfolding process is not sensitive to the pin surface orientation (Figures 4b & c).

The optimal unfolding direction based on minimising the surface area change was determined to be 189^{o}. This orientation has been used throughout all the restoration stages. In addition, the pin surface orientation was kept at a constant 090o (E−W) orientation for all restorations.

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