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6a.Restoration results

The restoration results are presented from present−day to the earliest Cretaceous, which is the order of the restoration sequence (Figures 5 & 6). The geological interpretation has been restored through six unfolding stages (Figures 5 & 6). The section illustrated in Figure 5 is representative of the evolution of the structure through time parallel to the maximum shortening direction (189^{o}). Decompaction at each restoration stage has produced an increase in volume (and hence cross−sectional area) of the structure as layers were backstripped (Figure 5).

By comparing the present−day palinspastic maps and cross sections with their latest Cretaceous counterparts, the structural−relief contours at Top Muschelkalk level are very similar (Figures 5a, 5b, 6a & 6b). The interpretation of the similarity of the maps is that during Tertiary there was very little growth of the folds (Figure 5g). However, regional tilting to the north did occur during this time.

The restorations to latest Cretaceous (Maastrichtian and Campanian deposition) show the progressive growth in amplitude of the anticline and flanking synclines, coupled with continued shortening (Figures 5b, 5c, 6b & 6c). In particular, the anticline grew in amplitude and broadened in the east. The growth of the fold is represented by thickness changes in the Maastrichtian and Campanian layers.

The latest Santonian restoration (83 Ma) suggests at Top Muschelkalk level the initiation of the fault−propagation fold (Figures 5d & 6d). The regional dip of the Top Muschelkalk surface during Santonian was towards the ESE. The majority shortening that produced the fault−propagation fold occurred during this time, as can be observed from the plot of cumulative shortening versus geological age (Figure 5g). The restoration to Early Cretaceous time (97 Ma) shows the regional dip of the Top Muschelkalk surface remained towards the ESE. The Lower Cretaceous rocks also thicken in this direction. Minor WNW−trending folds also remain present in the Muschelkalk surface as well (Figures 5e & 6e).

The restoration representing earliest Cretaceous time (146 Ma) shows the Top Muschelkalk surface with a change in the regional dip to the NE (Figure 5f & 6f) and with the Keuper unit thickening to the NE (Figure 5f). In addition to the regional dip, the Top Muschelkalk surface is also deformed by two minor, broad folds that trend between WNW and NW. In the final restoration in the sequence (not shown), the Top Muschelkalk surface was flexurally unfolded to a horizontal target surface to act as a reference for the shortening and area−based strain analyses.

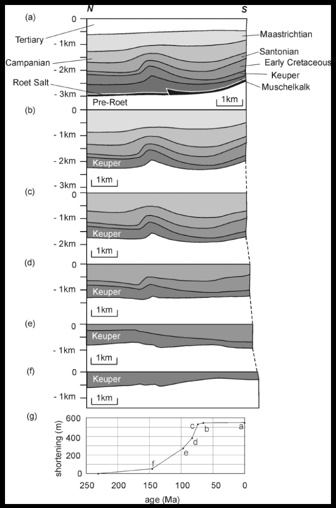

Figure 5. Sequential palinspastic sections extracted from the restored 3−D models depicting the structural evolution of the fold. Sections were extracted from the 3−D model parallel to the maximum shortening direction (189^{o}). The cross sections have no vertical exaggeration. (a) Present−day geometry. (b) Restoration of the Base Tertiary surface. (c) Restoration of the Top Campanian surface. (d) Restoration of the Top Santonian surface. (e) Restoration of the Near Base Cretaceous (or "Base Santonian") surface. (f) Restoration of the Base Cretaceous surface. (g) Plot of shortening versus geological age taken from restorations shown in (a−f). Age data are based on Harland et al. (1989). Note that the absolute age for the "Near Base Cretaceous" horizon has been taken to represent the Base Santonian (97 Ma).

6b. Restoration results

The loose lines for the cross sections that have been extracted from the 3−D model at each restoration stage show very little deformation (Figure 5). The map−view loose lines along the southern margin of the Top Muschelkalk surface at each restoration stage provide more information about the variability of horizontal shortening across the area (Figure 7).

The unfolding direction and the shortening measurement are oblique to the 3−D model boundaries, which reduces the amount of apparent shortening in the SE and NW corners of the model (Figure 7a) because the anticline is not intersected in the unfolding direction (Figure 7b at approximately 6300m along the E−W axis).

The map loose lines show a general apparent increase in shortening from east to west from approximately 250m to 590m (Figures 7a & b). This increase is a minimum shortening, as some of the minor folds are not represented across the whole model.

Taking the coverage into account, the local variability in shortening reflects real changes in fold geometry that might be produced by displacement or geometry changes along strike of the fault. These anomalies of the map−view loose line may represent zones of increased local deformation or may highlight areas where the interpretation requires adjustment. In either case, these regions are more easily recognised and adjusted with 3−D restorations in contrast to 2−D restorations.

The change in surface area of the Top Muschelkalk surface has been determined at each restoration stage (Figure 7c). The actual surface area of the Top Muschelkalk surface is interpreted to have decreased from the Mid-Triassic to the present−day based on the restorations, with the greatest magnitude of change occurring during the Cretaceous. Hennings et al. (2000) noted that surface−area changes produced by plane−strain flexural slip unfolding of a surface represent the deviation of the fold shape from a constant−amplitude, cylindrical fold.

In this study, the area change of the Top Muschelkalk is a product of:
1. the non−cylindrical nature of the structure,
2. the compaction of the sedimentary sequence through time,
3. the non−parallel geometry of the layers.

Area strains generated by using a slip system parallel to the uppermost (template) surface at each restoration stage relate not only to the local angular deviation between the template surface and the target surface, but also to the angular deviation of the passive surfaces and the slip system.

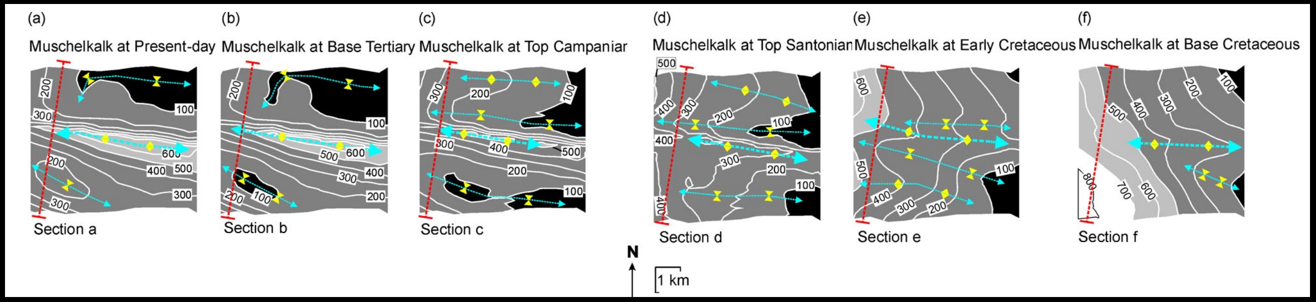

Figure 6. Structural−relief maps of the Top Muschelkalk surface at each stage of the 3−D restoration. Contours are relative to the lowest point on each horizon to show the comparative size of the folds through geological time. The darker shades show the lowest areas on each surface, whereas the lighter shades are the highest regions. Contour interval is 100m. Cross−section locations refer to the palinspastic sections in Figure 5. Arrows are used to highlight the fold axes, including the relatively minor features

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