6. Paleostress analysis from 3D seismic data – an outlook

6.1. Introduction

Undulation of fault-surfaces is a commonly observed feature in 3D seismic data. The corrugations thereby identified on the fault-surfaces are assumed to result from the linkage of numerous smaller fault-segments through time (e.g. Walsh et al, 1999; McLeod et al., 2000; Mansfield and Cartwright, 2001; Marchal et al., 2003). Such undulating fault-surfaces have also been observed in the field, including features such as ribs, saddles, and depressions, which occur over a range of several scales (e.g. Wright and Turner, 2006; Sagy et al., 2007). Striation measurements on field-observed corrugations indicated that corrugations are parallel to fault slip (Hancock and Barka, 1987). Therefore, these corrugations observed in the field might be comparable to those observed in seismic data. Needham et al. (1996) suggested that fault-corrugations observed in the seismic data can indicate a movement direction parallel to the axis of corrugations because this movement direction will require least energy and therefore smallest strain.

In this study numerous normal fault-surfaces are interpreted from the 3D seismic data and their undulations are analysed in 3D. The axes of corrugations are then used as movement directions. The paleostress direction during Permian extension is finally derived.

6.2. Data base and methods

For this study we analysed a pre-stack depth-migrated 3D reflection seismic data set, provided by RWE Dea AG, Hamburg. Well data documented sandstone, conglomerates, and volcanic rocks, which were deposited synsedimentarily during the Permian. The seismic volume has a high resolution with a grid spacing of 25 m by 25 m, and approx. 30 m vertical resolution for the depth of the analysed faults. Detailed 3D fault interpretation is based on seismic picking of every third seismic line (75 m interval) perpendicular to fault-strike, numerous lines oblique to fault-strike, and horizontal correlations on depth slices. The seismic volume was interpreted with the Schlumberger software GeoFrame/IESX, and triangulation of fault-surfaces was carried out with the software package GoCad (GOCAD Consortium).

Ten normal faults have been analysed by applying the attribute curvature. Gaussian curvature at a given point is the product of the two principal maximum and minimum curvatures. By flattening the 3D triangular grid, positive curvature is defined by a gap forming between flattened triangles of a dome, whereas negative curvature is defined by an overlap forming between flattened triangles of a saddle or basin. Surfaces with a high Gaussian curvature like domes or saddles are non-cylindrical, whereas cylindrical surfaces like elongated folds and corrugations have a Gaussian curvature of zero (Lisle, 1994). For that reason the minimum or maximum Gaussian curvature can be used because it highlights well convex and concave areas on cylindrical surfaces.

6.3. Results

All Permian normal faults show a strong undulation of their surfaces because they developed as a result of propagation and coalescence of several small fault-segments through time, as demonstrated in chapter 4. Figure 6.1 shows all fault-surfaces colour-coded with depth and curvature. The general orientation of the faults is illustrated with the depth colour-code, whereas corrugations are well visible with the curvature attribute, changing from blue to red. The spacing between the here analysed corrugations is between 500 m and 2000 m.

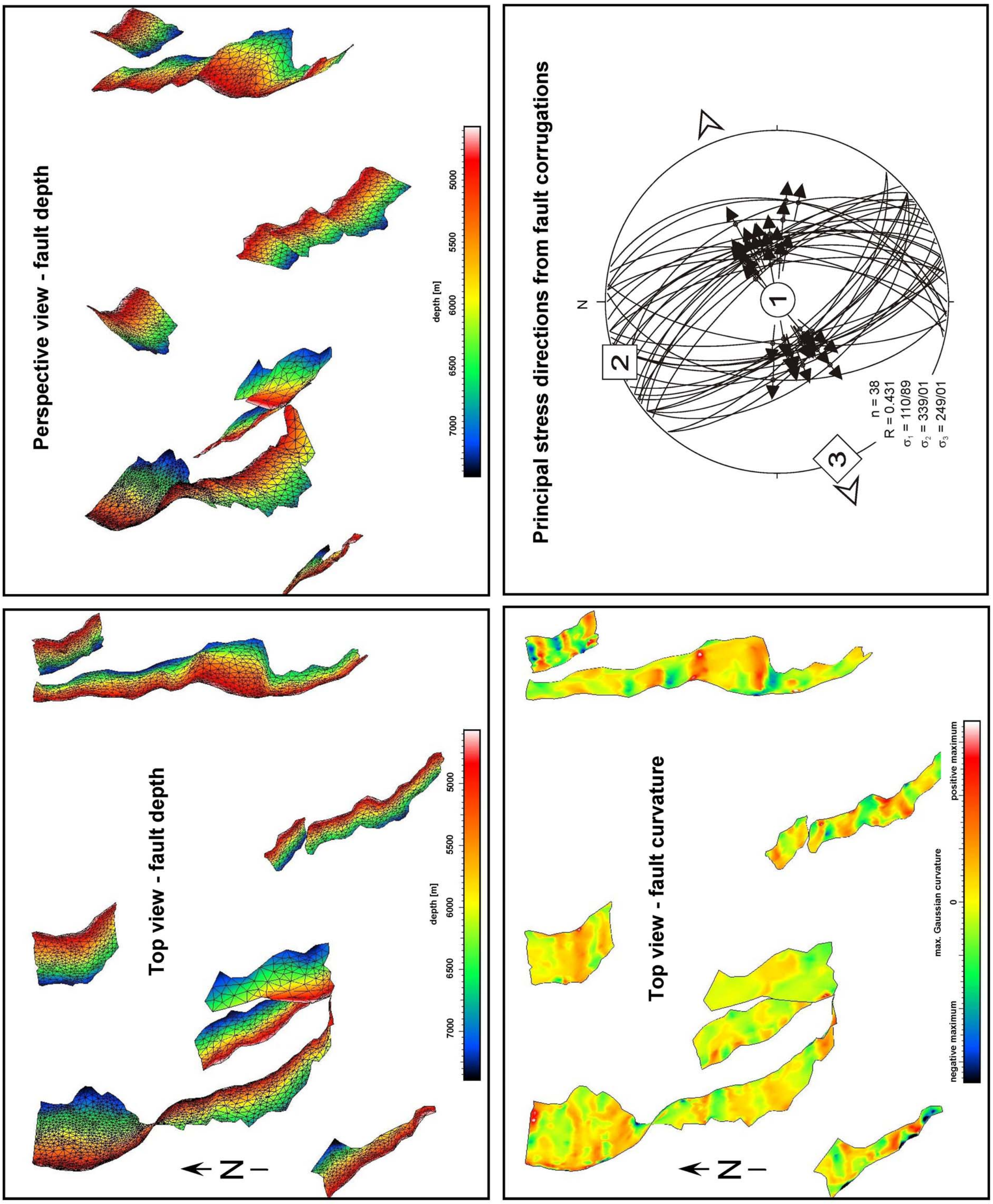

Figure 6.1: Permian normal faults in perspective and map view, coloured by depth (showing fault-orientations) and curvature (highlighting fault-corrugations). Area size: 17 x 22 km. Fault-corrugations axes are used as kinematic vectors, from which paleostress data have been derived. The plane-lineation-movement sense data and the principal stress directions are plotted in a Schmidt net, lower hemisphere, equal area projection. Used method is NDA, numerical dynamic analysis.

For paleostress analysis, the azimuth and dip of all triangles from each corrugation was measured, and the average value refers to the orientation of the corrugations axis, which was used as fault-surface azimuth/dip, and equally as bearing/plunge of the 'striae'. The sense of slip of the hanging wall was derived from the seismic data. Principal stress directions were calculated by using numerical dynamic analysis (Spang, 1972), and the associated computer program NDA (Sperner & Ratschbacher, 1994). Numerous corrugations (n = 38) have been measured for paleostress analysis (Fig. 6.1). The analysed data show a WSW-ENE directed extension during Permian times. From the plane-lineation-movement sense data, the NDA software calculates R, the ratio of the principal stress differences, with $R = (\sigma_2 - \sigma_3)/ (\sigma_1 - \sigma_3)$. In this data set R = 0.431 (Fig. 6.1), which refers to plain strain extensional deformation.

6.4. Discussion

The here described method of paleostress direction analysis from 3D fault-corrugation interpretation is presented for the first time. Estimates about the information content of subsurface data as related to a past stress regime have been derived usually from the strike of tectonic structure, interpreted from 2D or 3D seismic data. These measurements are not precise, since they represent only the orientation of faults but no indicators of movement direction on the fault-surfaces. The method suggested here is particularly useful in areas which are not assessable by field campaigns, and where paleostress data from subsurface strata need to be carried out.

The inferred WSW-ENE Permian extension direction fits the overall E-W extension direction proposed for the Southern Permian Basin region very well (e.g. Betz et al., 1997; Ziegler, 1990). However, in the published literature reliable paleostress data do not exist for the Permian within the North German Basin. Permian strata are usually not directly assessable due to its position in great depths between 3 and 9 km. Only in a few areas (e.g. Harz Mountains, Flechtlingen High) Permian strata have been exposed on the surface, but they are either strongly overprinted by exhumation processes, or relevant measurable Permian fault-surfaces are missing. 2D seismic lines, which are numerous available for studying subsurface Permian structures, are subject to spatial artefacts and are therefore not suited for 3D paleostress measurements. However, depth-migrated 3D seismic data sets are rarely available in the North German Basin, but they are the only data which allow paleostress analyses of faulted strata in the subsurface.

In this study we present for the first time stress data derived from 3D seismic data for subsurface Permian strata within the North German Basin, and it is therefore an important contribution not only methodologically, but also for paleostress analysis within the Southern Permian Basin.