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Small-scale faulting in the Upper Cretaceous of the Groningen block (The Netherlands): 3D seismic interpretation, fault plane analysis and regional paleostress

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A B S T R A C T

Over the last years, field-based studies have shown that fault surfaces can exhibit a considerable self-affine topography. It is reasonable to assume that similar undulations are also present in fault interpretations from 3D reflection seismic data, however both the interpretation uncertainty and geophysical resolution limits hinder their analysis. This study analyses a set of small-scale, non-reactivated faults in the Upper Cretaceous Chalk Group (Upper Ommelanden Formation) of the NW-part of the Groningen Block, the Netherlands, in a high quality Pre Stack Depth Migrated 3D seismic data set. The studied faults are fully contained inside the Chalk Group, in an area located between the major tectonic-bounding faults of the NW Groningen Block. Over 200 faults, with offsets in the order of 30–50 m, were interpreted across an area of ca. 150 km^2, showing a clear preferential orientation for strike, dip and dip-direction. Detailed interpretations and 3D fault plane analyses show undulations on the fault plane. We show that these undulations are not an interpretation or gridding artefact, and interpret these to indicate direction of fault slip. These results were used to calculate a paleostress tensor, using all faults to calculate a single stress tensor for the entire study area by Numerical Dynamic Analysis.

Based on the orientation, position and a thickness analysis, it is interpreted that these faults formed due to the tectonic reactivation of salt structures in the Latest Cretaceous. The calculated paleostress state shows a general NW–SE-extension, with a vertical maximum principle stress, and a stress ratio of about 0.3, indicating that the studied faults are not the result of dewatering. This interpretation agrees both with a nearby salt-tectonic reconstruction, as well as field-based paleostress results from the UK, Belgium and France. A first look at other surveys from the Dutch sector indicates that similar faults are present in other areas, with different orientations. We propose that a dedicated analysis of these faults across on- and offshore Europe would allow extending the stress map of the Late Cretaceous into areas where the Chalk is not outcropping.

1. Introduction

This work presents a detailed analysis of a set of small-scale faults interpreted on high-quality 3D seismic data of the Upper Cretaceous Chalk Group of the NW Groningen Block, the Netherlands (Fig. 1a). The interpretation results are compared with existing analyses of faults in the chalk of NW Europe, and used for paleostress analysis. Previous studies on small-scale faults in chalk strata have been controversial concerning the interpretation of the origin of faulting. Hibsch et al. (1995) and Hibsch et al. (2003) interpreted intra-Chalk faults to have formed by compaction. In contrast, Vandycke (2002) argued for tectonic deformation as the main cause of faulting observed in Chalk outcrops. The study presented here will help to distinguish between the two models.

Paleostress analyses provide information on the tectonic evolution of the crust and help to predict the location and possible orientations of fracture and fault systems below the resolution of seismic observation. In hydrocarbon exploration, these fracture systems can have economically viable permeabilities (Koestler and Ehrmann, 1991; Arnott and van Wunnik, 1996; van Konijnenburg et al., 2000; Smith and McGarrity, 2001; Otrtuno-Arzate et al., 2003; Casabianca et al., 2007); thus, the seismic-based paleostress-analysis approach can potentially impact oil and gas exploration and production in carbonate

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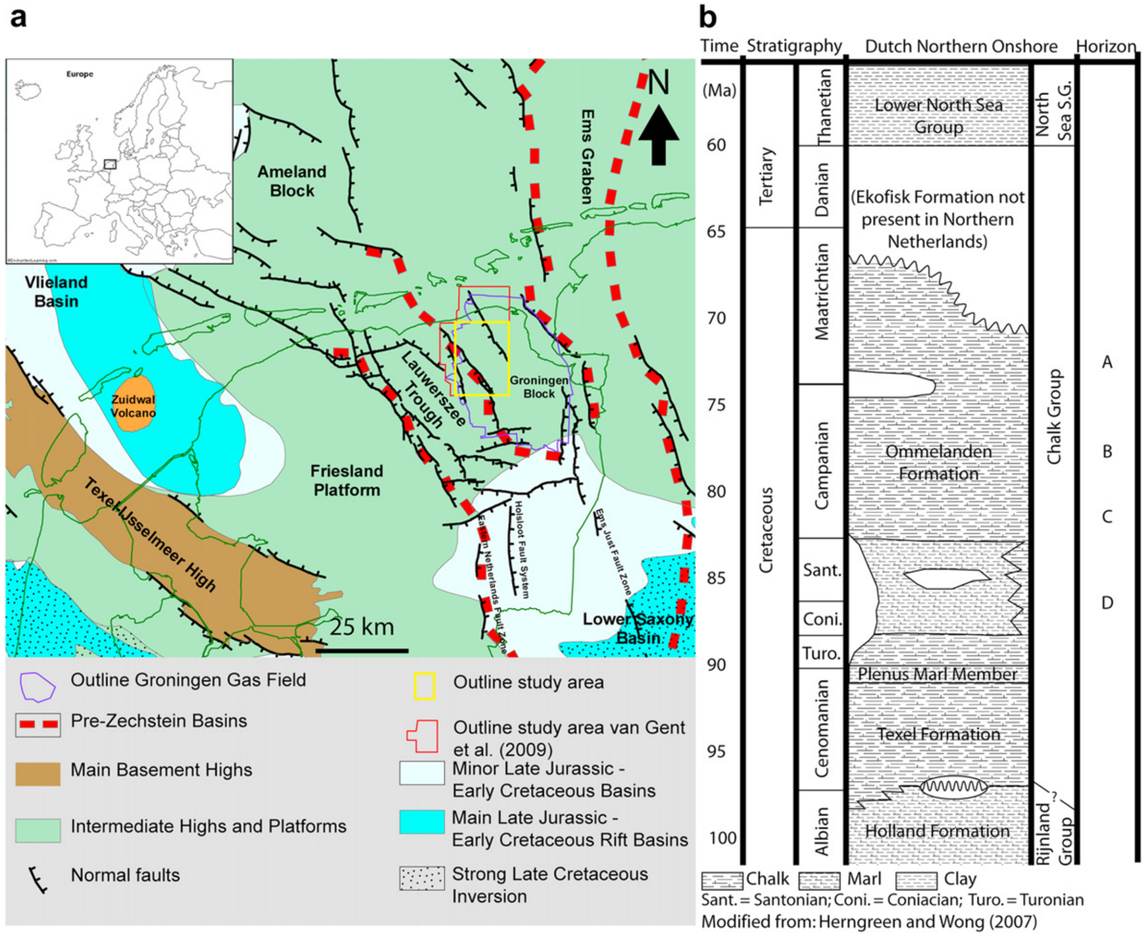

Fig. 1. (a) Location of the study area in the NW of the Groningen High, at the border of the Lauwerszee Trough. Image courtesy of NAM. (b) Simple stratigraphic column for the northern Netherlands. Modified from Herngreen and Wong (2007). Also indicated are the approximate stratigraphic positions of the four internal reflectors (A–D), see Table 1.

provinces in general. Paleostress analyses can be used to estimate the timing of the opening and closing of faults and fractures, and for analyzing and modelling the migration of geofluids (du Rouchet, 1981; Sapra, 1997).

Paleostress analyses are usually based on maps of fault systems at km-scale (e.g. Anderson, 1942; Michon et al., 2003), on the detailed mapping of fault surfaces and slip directions in outcrops at m-scale (Bergerat, 1987; Kleinspehn et al., 1989; Angelier, 1994; Hibsch et al., 1995; Delvaux, 1997; Saintot and Angelier, 2002; Vandycke, 2002; Caiazzo et al., 2006; Sippel et al., 2009), or on the analysis of calcite twins at mm-scale (Turner, 1953; Spang, 1972; Larroque and Laurant, 1988; Rocher et al., 2004). With the increased availability of industrial 3D seismic data for the scientific community, several attempts have been made to extract (paleo-) stress tensors from 3D seismic data (this does not include papers on seismic processing that constrain the orientation of either fractures or the present-day stress tensor, such as Neves et al., 2003). Seismic extraction of paleostress has the advantage that direct access to rocks is no longer required, so that sedimentary cover, or seawater coverage in offshore settings does not hinder paleostress analysis. Furthermore, the fact that seismic data is often available in areas of hydrocarbon exploration or production means that the results are directly applicable to aid the local exploration/production strategy (du Rouchet, 1981; Gartrell and Lisk, 2005; Henk, 2005; Lohr, 2007; Van Gent et al., 2009). For example, Gartrell and Lisk (2005) have used 3D seismic data to calculate the present-day stress field in the Timor Sea (N Australia). Lohr (2007) used 3D seismic data to constrain the stresses that caused deformation of the Top Rotliegend in the Central European Basin. Finally, Van Gent et al. (2009) showed how reactivated faults in reflection seismic data can be used to calculate paleostress stratigraphy in the NW part of the Groningen Block (Fig. 1) by using structural reconstructions, matching of horizon shapes across faults, and the analysis of undulations of fault planes.

In this study, a set of small-scale (on a seismic scale, the faults are actually roughly the same size as structures used in field-based paleostress study) faults (<50 m offset) of the Upper Cretaceous Chalk Group is interpreted and analyzed in detail (Figs. 2 and 3). These faults have low offset, are fully contained inside the Chalk Group, and not reactivated by later tectonic phases. To differentiate these small-scale faults from large, long-living, cross-formational faults, we use the term "Intra-Chalk faults". This term reflects that the studied faults do not penetrate Top or Base of the Chalk Group; but is not meant to imply syn-sedimentary faulting. Using several overlapping and detailed interpretations of a number of these faults, it will be shown that these faults commonly have a down-dip oriented undulation, which is not the result of imaging or interpretation artefacts. These undulations can be used to constrain the slip direction in the down-dip-direction (pure normal faulting). Assuming that all faults slipped in a similar fashion as the faults studied in detail, we used the orientation and related slip direction of all faults spread over the 10×15 km study area to calculate the regional paleostress tensor at the time of development of these faults. This approach differs from "normal" field-based paleostress