Quaternary Science Reviews 101 (2014) 217–233

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Response of salt structures to ice-sheet loading: implications for ice-marginal and subglacial processes

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ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form
22 July 2014
Accepted 31 July 2014
Available online 29 August 2014

Keywords:
Salt structures
Ice-sheet loading
Finite-element modelling
Central European Basin System

ABSTRACT

During the past decades the effect of glacioisostatic adjustment has received much attention. However, the response of salt structures to ice-sheet loading and unloading is poorly understood. Our study aims to test conceptual models of the interaction between ice-sheet loading and salt structures by finite-element modelling. The results are discussed with regard to their implications for ice-marginal and subglacial processes. Our models consist of 2D plane-strain cross-sections, which represent simplified geological cross-sections from the Central European Basin System. The model layers represent (i) sedimentary rocks of elastoplastic rheology, (ii) a viscoelastic diapir and layer of salt and (iii) an elastoplastic basement. On top of the model, a temporarily variable pressure simulates the advance and retreat of an ice sheet. The durations of the individual loading phases were defined to resemble the durations of the Pleistocene ice advances in northern central Europe. The geometry and rheology of the model layers and the magnitude, spatial distribution and timing of ice-sheet loading were systematically varied to detect the controlling factors. All simulations indicate that salt structures respond to ice-sheet loading. An ice advance towards the diapir causes salt flow from the source layer below the ice sheet towards the diapir, resulting in an uplift of up to +4 m. The diapir continues to rise as long as the load is applied to the source layer but not to the crest of the diapir. When the diapir is transgressed by the ice sheet the diapir is pushed down (up to −36 m) as long as load is applied to the crest of the diapir. During and after ice unloading large parts of the displacement are compensated by a reversal of the salt flow. Plastic deformation of the overburden is restricted to the area immediately above the salt diapir. The displacements after unloading range between −3.1 and +2.7 m. Larger displacements are observed in models with deep-rooted diapirs, thicker ice sheets, longer duration of the loading phase, thicker salt source layers and lower viscosity of the salt. The rise or fall of diapirs triggered or amplified by ice-sheet loading are likely to affect glacigenic deformation, erosion and deposition above the diapir and within the rim synclines. Ice-load induced uplift in front of an ice sheet will provide favourable conditions for the formation of push moraines, for example by creating a topographic obstacle and inclining potential detachments. Subglacial subsidence of salt structures will enhance erosion by providing a preferential drainage pathway and fracturing of the overburden of the salt structure and thereby contribute to the incision of tunnel valleys. However, the resulting displacements are probably too low to have a marked effect on the advance or retreat pattern of the ice sheets.

1. Introduction

A correlation between subsurface tectonic structures, such as faults zones and salt structures, and Pleistocene glacigenic features, such as ice-marginal valleys, terminal moraines, tunnel valleys and river courses, has been recognised along the margins of the Fennoscandian ice sheets in the Central European Basin System (Fig. 1; Gripp, 1952; Liszkowski, 1993; Piotrowski, 1993; Schirrmeister, 1999; Pedersen, 2000; Sirocko et al., 2002, 2008; Kurzawa, 2003; Reicherter et al., 2005; Ber, 2009), but also from the margins of the Laurentide ice sheets in the Michigan Basin in the northeastern USA (White, 1992). These correlations are interpreted as pointing to an interaction between the ice sheets and the subsurface tectonic structures (cf. Sirocko et al., 2008). The interaction between ice-sheet loading–unloading and tectonic processes has received much attention since the concept of glacioisostasy was first introduced in the 19th century (see overview by Stewart et al., 2000).

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http://dx.doi.org/10.1016/j.quascirev.2014.07.022

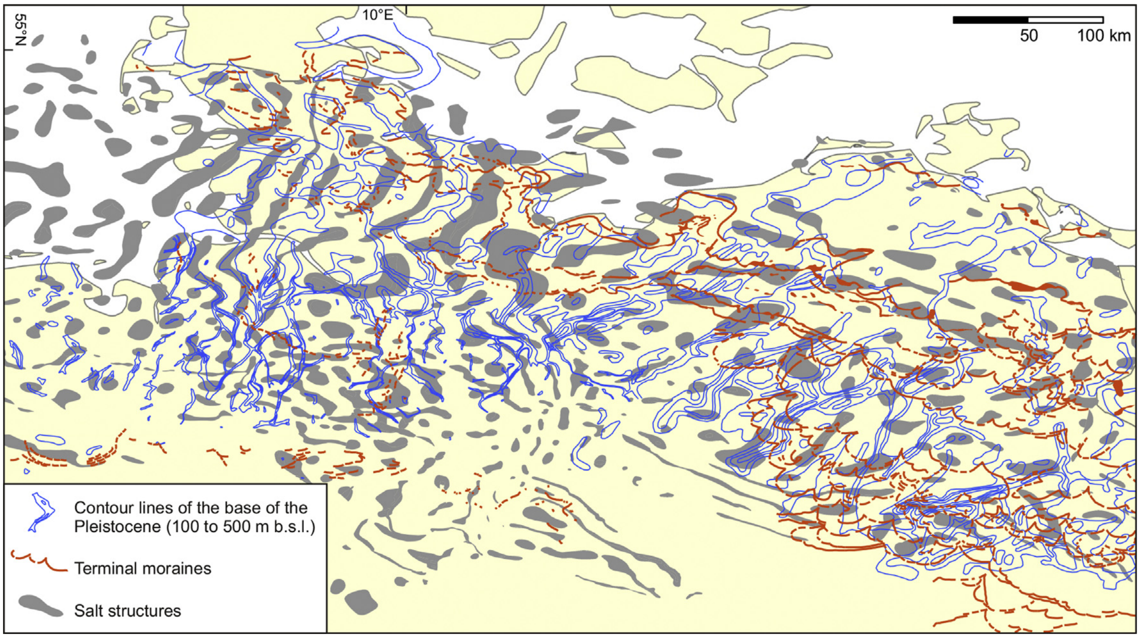

Fig. 1. Map of the salt structures, terminal moraines and tunnel valleys in the German part of the Central European Basin System. Terminal moraines are locally aligned parallel to salt structures. Tunnel valleys commonly follow the trend of salt structures, change their course when encountering a salt structure or have their deepest parts located above salt structures. Data are compiled from Reinhold et al. (2008), Stackebrandt et al. (2001) and Ehlers et al. (2011).

During glaciations the stress field in the lithosphere is strongly affected by the stress applied by ice-sheet loading. The interactions between ice sheets and crustal deformation are complex and depend on the thickness and extent of the ice sheet, the position of an area relative to the ice margin and the pre-existing tectonic stress field (Johnston, 1987; Wu et al., 1999; Stewart et al., 2000; Hampel and Hetzel, 2006; Hampel et al., 2009).

Geological process models related to glacio-isostatic rebound need to take into account that deformation will be focussed along pre-existing zones of weakness, such as faults (Liszkowski, 1993; Brandes et al., 2011). This is especially important for areas that have a complex deformation history and experienced repeated reactivation of fault zones, as the Central European Basin System (e.g., Maystrenko et al., 2008). Salt structures also represent zones of weakness within basin fills that accumulate strain during phases of deformation (Hudec and Jackson, 2007) and perturb the regional tectonic stress field (Brandes et al., 2013).

During the Pleistocene large parts of the Central European Basin System were affected by multiple advances of the Fennoscandian ice sheet during the Elsterian, Saalian and Weichselian glaciations (Ehlers et al., 2011; Houmark-Nielsen, 2011; Laban and van der Meer, 2011; Marks, 2011; Lee et al., 2012; Roskosch et al., 2014). Evidence for seismicity triggered by ice-sheet loading and unloading is known from regions that were beneath the ice sheets (Dehls et al., 2000; Mörner, 2004) as well as proglacial and periglacial regions (Brandes et al., 2011, 2012; Hoffmann and Reicherter, 2012; Brandes and Winsemann, 2013).

1.1. Salt–ice interaction

The main driving force of salt movement is differential loading, which causes viscous flow from areas of higher load to areas of lower load (Hudec and Jackson, 2007). Gravitational differential loading of a salt layer is caused by the infill of supra-salt mini-basins (e.g., Waldron and Rygel, 2005; Brandes et al., 2012) or by the progradation of sedimentary wedges above a salt layer (e.g., Wu et al., 1990; Vendeville, 2005). Salt flow driven by the differential thickness of the overburden does not require the overburden to be denser than the salt and may be induced by very small differential loads (Jackson and Talbot, 1986; Cohen and Hardy, 1996; Gemmer et al., 2004, 2005). The salt flow rate, the efficiency of salt expulsion from the source layer and the resulting geometries depend primarily on the salt viscosity, the thickness of the source layer and the rate of progradation of the overburden (e.g., Cohen and Hardy, 1996; Koyi, 1996; Gemmer et al., 2004, 2005; Vendeville, 2005). The advance of an ice sheet into a salt-bearing basin may cause differential loading comparable to a prograding sediment wedge (Jackson and Talbot, 1986) and can therefore be expected to induce salt movement although glacier ice is less dense than sediment.

Based on field observations conceptual models for the interaction of the load applied by ice sheets and salt diapirs were proposed (Liszkowski, 1993; Stackebrandt, 2005; Lehné and Sirocko, 2007; Sirocko et al., 2008). The load applied by an ice sheet advancing towards a salt diapir is interpreted to reactivate or accelerate the rise of the diapir and subsidence of the rim synclines (Fig. 2A; Lehné and Sirocko, 2007; Sirocko et al., 2008). Glacigenic successions, which are deposited between the diapir and the ice margin, may be deformed into push moraines during ongoing ice advance (Sirocko et al., 2008). If the ice sheet transgresses the diapir the load will impede further rise or even force the diapir to subside (Fig. 2B; Liszkowski, 1993). The subsequent removal of the ice load during deglaciation will then allow the diapir to rise once again (Fig. 2C; Liszkowski, 1993; Sirocko et al., 2008). Faults above the crest of the diapir may be reactivated during the loading and unloading cycle, although the sense of fault slip may switch during different stages of the process (Liszkowski, 1993; Lehné and Sirocko, 2007; Sirocko et al., 2008).

To evaluate the conceptual model of ice–salt interaction, we apply finite-element models to simulate the response of salt structures to ice-sheet loading and unloading (Fig. 3). Based on our modelling results we quantify the spatiotemporal evolution of the salt diapir and its host sediments with respect to the vertical and horizontal displacements. The model set-up and input parameters are systematically varied to determine the controlling factors of the