Tectonophysics 637 (2014) 354–369

Contents lists available at ScienceDirect

Tectonophysics

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

Influence of pre-existing salt diapirs on 3D folding patterns

Naiara Fernandez *, Boris J.P. Kaus

Institute of Geosciences, Johannes Gutenberg University of Mainz, Germany

ARTICLE INFO

Article history:
Received 24 June 2014
Received in revised form 20 October 2014
Accepted 26 October 2014
Available online 30 October 2014

Keywords:
3D folding
Fold patterns
Salt diapirs
Numerical modeling

ABSTRACT

The 3D detachment folding instability gives rise to a wide variety of fold shapes (e.g. from dome shape structures to long en-echelon or straight anticlines) as a result of interactions between growing fold segments. The 3D growth of these folds, as well as the wavelength and lateral propagation of folds, is controlled by the physical parameters of a detachment layer and its overburden. However, the existence of initial heterogeneities, such as pre-existing salt plugs within the sedimentary cover, might affect fold development as well.

We use numerical modeling to investigate how the fold pattern is affected by pre-existing salt structures. High-resolution 3D folding simulations (with and without pre-existing salt structures) were performed, in which we varied the shape, height and spacing of pre-existing diapirs. In a first geometric setup, we employed a multilayer setup and synthetic diapir distributions in order to study the influence of diapir spacing on fold spacing and patterns. In a second geometric setup, we use a diapir distribution that fits the observed exposed diapir distribution in the southeastern Zagros.

Results show that the presence of diapirs does not considerably change the wavelength of the folds, which is in all cases close to the dominant folding wavelength that develops in the absence of diapirs. Yet, the presence of pre-existing structures speeds up the folding instability in those locations and also affects folding patterns as the diapirs localize the initial deformation by accommodating folding above them, which results in the diapirs being located in the core of the folds. If diapir spacing is much smaller than the dominant folding wavelength, diapirs are located in different structural positions such as fold synclines or flanks.

1. Introduction

The role of a weak basal detachment level composed of a viscous material (e.g. salt) on the style of deformation in fold-and-thrust belts has been studied since decades. A viscous detachment results in lower taper angles than in the case of a frictional detachment, as well as in faster propagation of the deformation front (Davis and Engelder, 1985), which can also lead to simultaneous evolution of the structures at different positions (Costa and Vendeville, 2002). In most studies, the basal weak layer is considered to have a more or less regular geometry, although gradual spatial changes in thickness and/or different extent of the basal layer have also been addressed by analogue modeling (e.g. Bahroudi and Koyi, 2003). However, the topography of this basal layer can be far from regular, and could potentially include abrupt changes in thickness prior to the compressional stage. An example is when a halokinetic phase predates the formation of the fold and thrust belt, where the topography of the basal salt layer can include the many different salt structures described in Hudec and Jackson (2007), ranging from buried salt domes, to salt walls or salt plugs, etc.

Compression of salt diapirs has been recognized in different geological settings, that range from passive margins and extensional basins (e.g. Rowan and Vendeville, 2006) to convergent settings (e.g. Letouzey et al., 1995). The Zagros is an example of the latter case (Bahroudi and Koyi, 2003; Letouzey and Sherkati, 2004), where the relation between folds and diapirs has drawn the attention of several works in the area (e.g. Colman-Sadd, 1978; Kent, 1958, 1979). Although it had previously been proposed that salt could have moved previous to the main folding events (e.g. Ala, 1974; Kent, 1958, 1979), the idea that most of the salt structures were exposed or shallowly buried at the time of the onset of the Zagros main folding event was recently reinforced by Jahani et al. (2007). Jahani et al. (2007) made an attempt to classify the salt plugs of southeastern Zagros with respect to folding in the area. While Letouzey and Sherkati (2004) showed that in the central Zagros the salt diapirs are associated with major strike slip and tear faults and tend to localize the position of faults, the diapirs of the southeastern Zagros are mainly related to anticlines (Jahani et al., 2007) (see Fig. 1a). Estimating an exact age of the initiation of salt diapirism in the southeastern Zagros is difficult but the presence of recycled debris of the salt that cores the diapirs, as well as thinning or sedimentary gaps close to the diapirs, indicates early salt mobility in the area previous to the Zagros folding (Kent, 1958). The identification by Jahani et al. (2009) of halokinetic sequences

* Corresponding author.
E-mail address: fernande@uni-mainz.de (N. Fernandez).

http://dx.doi.org/10.1016/j.tecto.2014.10.021
0040-1951/

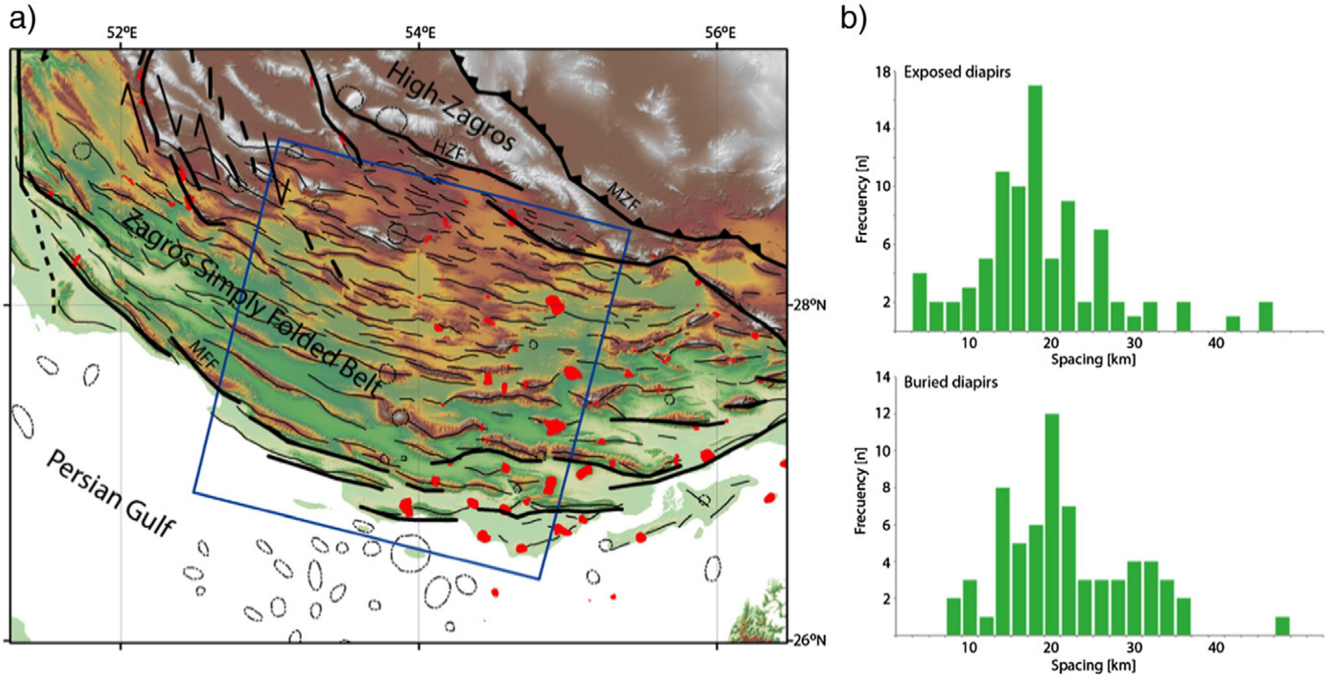

Fig. 1. a) Digital elevation model (lower heights shown in green, higher heights shown in brown/white) of the southeastern Zagros showing the axial traces of the anticlines (thin black lines) and the exposed (in red) and buried diapirs (dashed lines), from different sources (geological maps of Iran, scale 1:250,000, Jahani et al., 2007, 2009). Thick black lines indicate inferred basement faults compiled from Berberian (1995) and Talebian and Jackson (2004) with the following abbreviations: Mountain Front Fault (MFF), High-Zagros Fault (HZF) and Main Zagros Thrust (MZT). b) Histogram plot of spacing of the exposed and buried salt diapirs shown in the map of a).

(as defined in Rowan et al., 2003) flanking the diapirs in southeastern Zagros and recycled debris salt material within the growth strata indicate that most diapirs were active prior to the initiation of folding in the area.

Some analogue modeling studies address the shortening of salt diapirs subjected to compression (e.g. Callot et al., 2007; Dooley et al., 2009; Koyi, 1988; Roca et al., 2006; Rowan and Vendeville, 2006). They show that it is common that anticlines or synclines are first localized above pre-existing diapirs (Callot et al., 2012; Jahani et al., 2009; Koyi, 1988). However, the initial geometry of the diapir might also cause differences in the deformation style from one diapir to another. The width of the compressed diapir, for example, can affect the amount by which the roof rises above it (Vendeville and Nilsen, 1995). Differences in shapes and heights of the diapirs with respect to the sedimentary cover may also favor welding, thrusting or folding (Callot et al., 2007). Most of the mentioned analogue experiments employ a brittle overburden. However, it has been argued that folding and thrusting dominated deformation are two end-member modes of fold and thrust belts (Ruh et al., 2012; Yamato et al., 2011). Therefore, experiments with a purely brittle and thrusting-dominated deformation might not be representative of the mechanics of the folding dominated belts such as the Zagros Simply Folded Belt (Fig. 1a).

Our aim is to study the effect of pre-existing salt diapirs on the overall folding pattern of an area, and for this reason we mainly focus on regular patterns of salt diapirs as well as on a southeastern Zagros-like diapir distribution, rather than on single diapirs. Regular map view patterns in salt diapirs are recognized in many of the well-known halokinetic regions (e.g. Rowan and Vendeville, 2006), but also in the southeastern Zagros (Kent, 1979). In several cases, the regular distribution of the salt structures has been associated with basement faults that may have controlled the salt deposition thickness (e.g. Kent, 1979). However, analogue and numerical models have shown (e.g. Kaus and Podladchikov, 2001; Talbot et al., 1991) that diapirs rising from a constant thickness buoyant underlying layer can also develop regular patterns.

On the other hand, the folding instability itself also results in a characteristic spacing (wavelength) as a function of physical and geometrical parameters. Such parameters include the effective viscosity ratio between the overburden and basal salt layer or the thickness ratio between the two layers, among others. It is therefore of interest to study whether the folding wavelength adjusts to the spacing of pre-existing salt diapirs, or whether it is unaffected.

For this purpose, we analyze how different patterns of regularly spaced diapirs (six different distributions) and a southeastern Zagros-like diapir distribution influence the folding patterns. The results of simulations with pre-existing diapirs are compared to reference models without pre-existing diapirs, but which employ the same random noise distribution. In order to test how robust our findings are with respect to differences in the viscosity structures, we use two rheological setups (referred to as setups 1 and 2). These two rheological setups have parameters that result in different fold wavelengths (but in both cases close to the 14–15 km observed in the area, e.g. Yamato et al., 2011) and growth rates. We also relate the effect of the diapirs to the folding growth rate vs. wavelength diagram of each of the setups.

2. Method

We use a continuum mechanics approximation where the equations used to describe geological processes consist of a set of balance equations for mass and momentum together with their constitutive relationships.

Conservation of mass and momentum for slowly moving incompressible fluids are given by

$$\frac{\partial v_i}{\partial x_i} = 0 \tag{1}$$

$$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} = -\rho g_i \tag{2}$$