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Intense salt deformation in the Levant Basin in the middle of the Messinian Salinity Crisis

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ABSTRACT

While numerous studies have shown that salt related deformation in the Levant Basin began in the Late Pliocene or Early Pleistocene, here we show that the first salt related deformation event occurred 3–4 myr earlier, in the middle of the Messinian Salinity Crisis. Considering that the entire crisis lasted only about 650 kyr and that halite deposition in the deep basin may have lasted only ∼50 kyr, this deformation event must have been very short. At some point after deposition of nearly half of the evaporitic sequence, the upper 200 m thick clastic-rich layer glided downdip and formed a series of steep contractional ridges on the deep basin floor. However, unlike the recent salt motion, which is derived from northwestward tilting of the Levant continental margin towards the Cyprus Arc and by basinward progradation of the Nile-derived overburden, the short intra-Messinian deformation event is enigmatic. It predates the Nile-derived overburden and its direction does not match northwestward tilting. We postulate that it may reflect the uplift of the Carmel block northeast of the study area and possibly the entire north Levant coast. In a wider view, intra-Messinian deformation is a circum-Mediterranean phenomenon, possibly reflecting reorganization of the Africa–Eurasia boundary.

1. Introduction

The evaporitic sequence of the Levant basin accumulated during the Messinian Salinity Crisis (MSC) when the Mediterranean sea-level dropped drastically and evaporites were deposited throughout the entire Mediterranean region (e.g., Ryan et al., 1973; Hsu et al., 1973). The entire crisis lasted ∼650 kyr (Krijgsman et al., 1999; Manzi et al., 2013), but the massive halite sequence in the deep Mediterranean basins probably represents only ∼50 kyr (Roveri et al., 2008; Krijgsman and Meijer, 2008) or even less (Manzi et al., 2012). In particular, the deep Levant Basin salt sequence is nearly 2 km thick (Ryan and Cita, 1978; Mart and Ben-Gai, 1982).

In numerous studies, extending over four decades, the deformation of the overburden in the Levant Basin was described and explained in terms of salt tectonics (Neev et al., 1976; Ben-Avraham, 1978; Garfunkel et al., 1979; Almagor and Hall, 1983; Garfunkel, 1984; Garfunkel and Almagor, 1985; Mart and Ben-Gai, 1982; Tibor et al., 1992; Gradmann et al., 2005; Frey-Martinez et al., 2005; Bertoni and Cartwright 2006, 2007; Netzband et al., 2006; Loncke et al., 2006; Hubscher and Netzband, 2007; Mart and Ryan, 2007; Hubscher et al., 2008; Cartwright and Jackson, 2008; Clark and Cartwright, 2009; Cartwright et al., 2012). However, the internal deformation within the salt layer itself received much less attention. Several early studies (Garfunkel et al., 1979; Garfunkel, 1984) identified internal reflectors within the Messinian sequence. But these reflectors were not clear enough to describe the internal structure of the salt and were mainly discussed within a lithological context, that is, whether they reflect inter-bedded clastics (Garfunkel et al., 1979; Garfunkel, 1984) or anhydrite layers (Gradmann et al., 2005; Netzband et al., 2006; Cartwright and Jackson, 2008).

Later advances in seismic imaging enabled several studies to show that the seismic reflectors within the evaporitic sequence are unconformable with the overlying Pliocene strata and are truncated by the top of the Messinian evaporites angular and erosional unconformity. In particular, Netzband et al. (2006) and Bertoni and Cartwright (2007) documented strong deformation of an intra-evaporitic layer that its structure is clearly different from shallower deformed layers in the overburden. They suggested that in addition to the post-Messinian deformation phase that affected the salt and the overburden, another earlier syn-depositional deformation event may have occurred in the Messinian times.

On the other hand, in a recent study (Cartwright et al., 2012) the same dataset was interpreted differently, arguing that the intra-evaporitic layer was deformed together with the Pliocene overburden in a single phase of deformation, which occurred in the Late Pliocene and Pleistocene. According to this interpretation,

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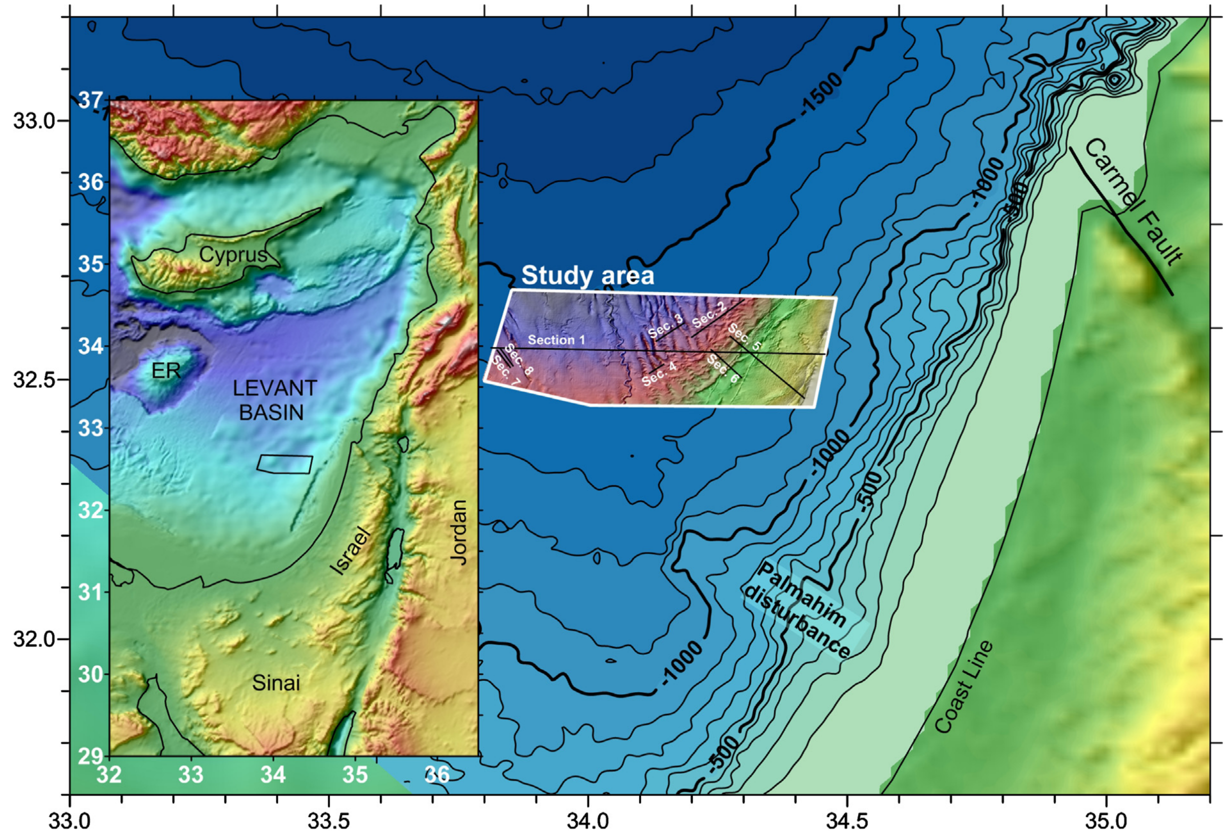

Fig. 1. Location map. Regional relief from ETOPO 11 (Amante and Eakins, 2009). Levant Basin bathymetry from Steinberg et al. (2011). Bathymetry of the study area from this study (larger picture in Fig. 6A). ER – Eratosthenes Seamount.

these units deformed differently at the same time, because of their different mechanical behavior. This argument was supported by a set of laboratory experiments demonstrating that when a multilayer model deforms, each mobile layer flows faster than its adjoining competent layers. Therefore, they conclude that within a single event, strain in evaporites can be far greater than in the overburden.

Regardless of the question whether or not such a mechanical process is possible, the question of what actually happened remains. Here we present a newly-acquired high-quality seismic survey in which weak reflectors that were not coherent enough in previously acquired datasets are clearly seen. These weak, yet observable, reflectors opened the gate for classical stratigraphic analysis that enables distinguishing between syn- and post-depositional deformations. We show that in this case deformation was syn-depositional and occurred during the Messinian Salinity Crisis. This interpretation reopens another question regarding the observed SW–NE shortening direction, which is approximately orthogonal to the gliding direction expected from the northwestward tilting of the basin. Whereas previous studies (Cartwright and Jackson, 2008; Cartwright et al., 2012) related this shortening direction to salt flow away from the Nile Cone, our data indicate that deformation predates the accumulation of the Nile Cone and therefore requires a different explanation.

2. Data and methods

The seismic reflection survey we use extends over a rectangular area, 60 km long (EW) and 24 km wide (NS), that begins about 50 km offshore central Israel at the foot of the continental slope, where water depth is 1100 m, and extends westwards to waters of 1500 m depth (Fig. 1). The survey was acquired with a 25 m trace interval on both in-line and cross-line. It was pre-stack depth migrated using a Kirchhoff-based method (Reshef, 1997). Accordingly, all seismic sections, interpretational work, and the resulting maps are presented in the depth domain. Since data were collected for industrial targets below the Messinian evaporites, the volume was cut off at just below the base of the evaporite unit. Prior to the migration, standard marine processing procedures were applied, with particular attention to multiple suppression. In addition to the conventional surface-related multiple elimination (SRME), methods targeting inter-bed and diffraction multiples were also executed. Interval velocity analysis was based on standard reflection tomography.

We focus on a strongly deformed layer in the middle of the Messinian sequence (defined below as Unit 3), where deformation is clearly different from the deformation observed in the overlying layers. To determine whether the deformation of this layer occurred before or after its burial, we carefully analyze the layer just above it, which is characterized by weak reflections that were not identified in older surveys. We examine whether these weak reflections express a pattern indicating: gradual burial of a deformed seafloor (onlap); post-depositional deformation similar to underlying strata; or maybe flow structures. We also produce structural and isopach maps of several units and examine the fault and fold directions, cross cutting relations and thickness variations. Interpretation of these parameters is used to reconstruct the deformation history and, accordingly, the driving forces.

3. Results

3.1. Seismostratigraphy

Based on seismic character and continuity, we divide the Messinian evaporite unit to six sub-units (Fig. 2A) that approximately correlate with the 6 units of Hubscher et al. (2007, 2008)