Self-similarity of intrasalt thrust faults: Lessons from offshore Levant Basin and the Dead Sea

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1. INTRODUCTION

The Levant Basin in the eastern Mediterranean Sea developed during rifting episodes occurring from Permian to the Early Jurassic (Netzeband et al. 2006; Gardosh et al. 2010), and has been a deep-water basin with a passive continental margin at least since the Cretaceous (Gardosh et al. 2008). Thick sequences of halite and interbedded shales (stringers) were deposited during the infamous Messinian Salinity Crisis (5.96-5.33 Ma). Salt-rich passive continental margins facilitate complex deformation of both the mobile salt and the surrounding rock mass (Allen et al. 2016, Cartwright et al. 2012). The weak salt will mobilize as a response to differential loading (gravity spreading) or tilting of the basin (gravity gliding), and intricate strains within the package may be observed due to the difference in AI between the halite and the stringers.

This study compares large-scaled intrasalt thrust systems interpreted on high quality 3D seismic data from offshore Israel (Kartveit et al. under review) with recently published outcrop analogies in gravity-driven mass transport systems near the Dead Sea (Alsop et al. 2017a, Alsop et al. 2017b) in order to evaluate the multi-phase deformation history in the basin.

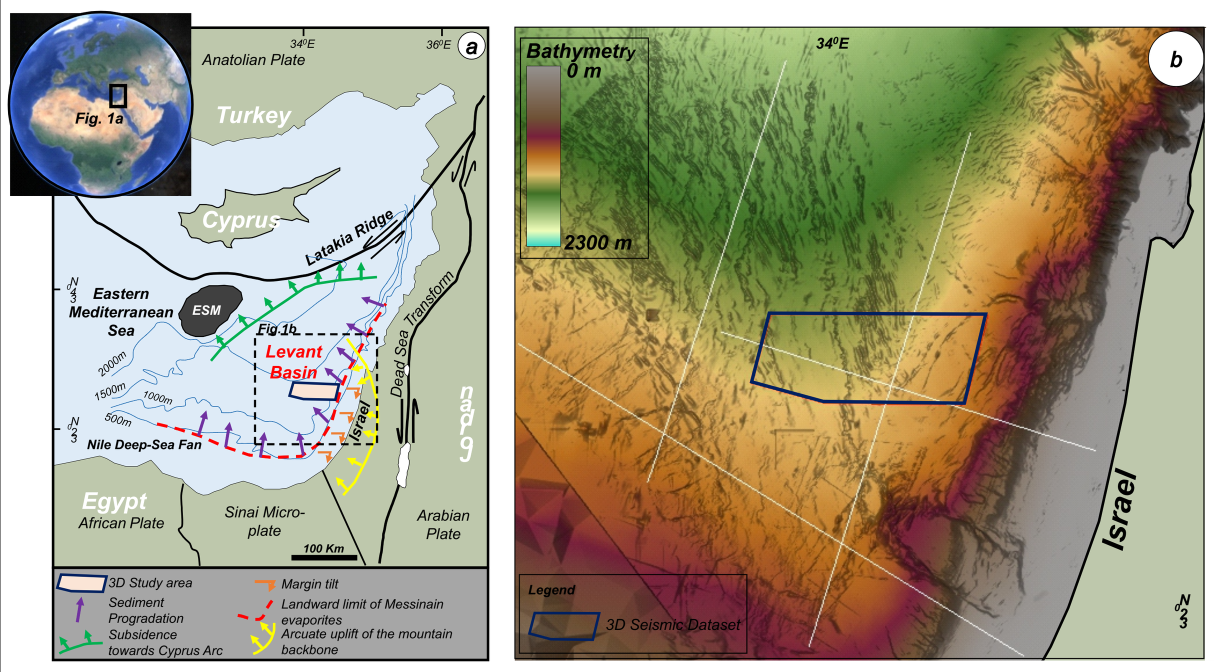
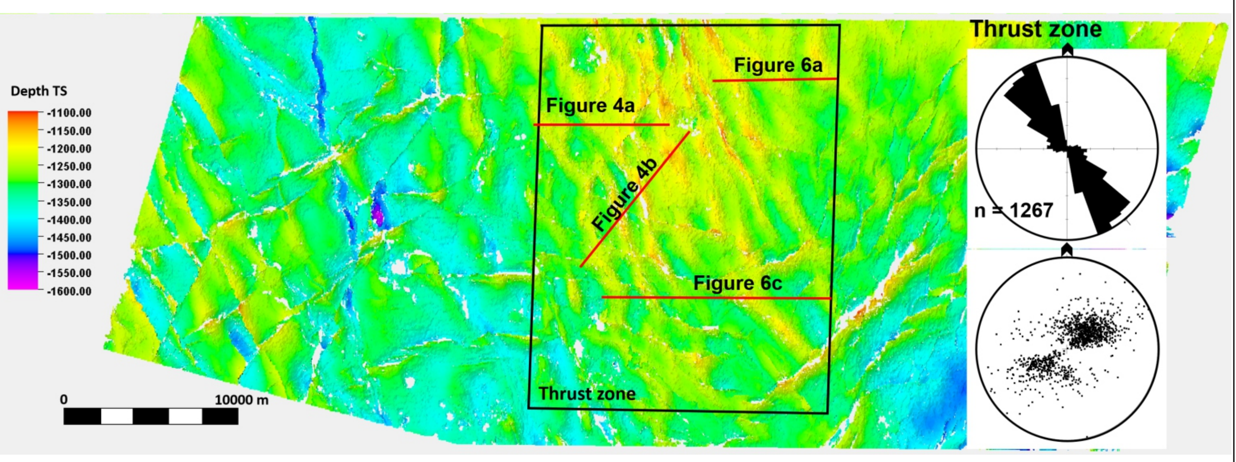


Figure 1: a) Tectonic map of the Eastern Mediterranean Sea indicating active regional fault systems and sediment progradation. b) Bathymetric map of the Levant basin showing the seismic dataset utilized in this study.

2. METHODS

This study utilizes a pre-stack zero-phase, depth migrated 3D seismic reflection survey with crossline (N-S) and inline (E-W) spacing of 25 m and 12.5 m, respectively. All seismic data are displayed with a normal SEG polarity, where a downward increase in acoustic impedance correspond to a positive (red) reflection. Multiple seismic attributes have been used in this work and are summarized in Figure 3.



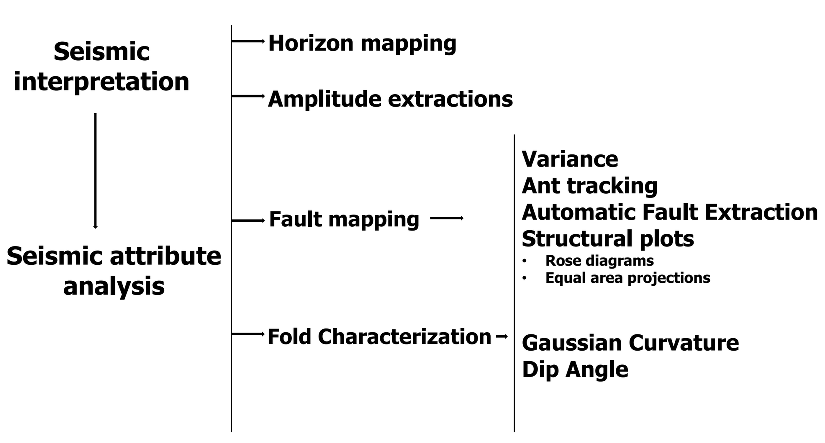


Figure 2 (above): Depth map of the Top Salt horizon in the study area. The dominant thrust zone, seismic sections, rose diagram and dip plot in the study area are indicated.

Figure 3: Schematic illustration of the approach used in this study.

3. RESULTS

3.1. DIFFERENT THRUST SYSTEMS

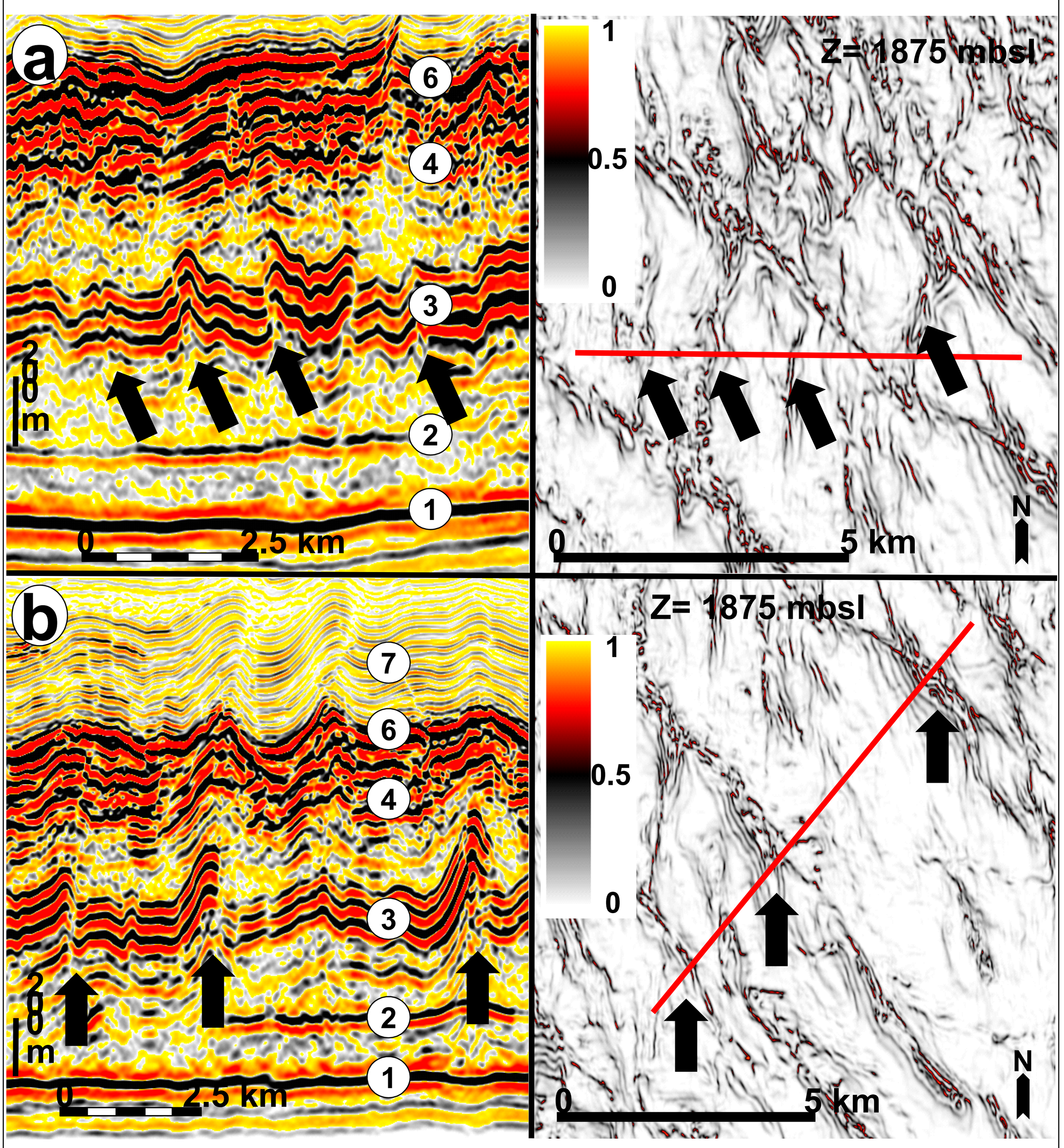


Figure 4: a) N-S oriented train of thrusts displaying a vergence towards the west and b) NW-SE oriented train of thrusts displaying a vergence trend to the northeast. Variance maps at the depth of 1875 m corresponds to the local depth of the MC1 package and the faults are easily observable. Note that the pop-up structure in figure a) is caused by the presence of a dominant, NW-SE oriented, thrust fault cutting through the N-S trending train of thrusts.

Our work demonstrates three different thrust fault types, where the dominant one being NW-SE oriented and the other two N-S and NNW-SSE thrust faults, respectively. However, only the N-S and NW-SE oriented deformational features are believed to be syn-Messinian structures; the NNW-SSE trending thrusting was likely initiated at a later stage. This is best visualized in seismic sections (Figure 4) and on depth- and dip illumination maps (Figure 5): At lower stratigraphic levels, the dominant intrasalt thrusts progress from the NW-SE trend seen in the seismic package 3 (MC1) to a NNW-SSE trend in the seismic package 4 (MC2) and on the Top Salt (TS) reflector. The extensive NW-SE faulting in MC1 induce NW to NNW-SSE trending folding in MC2 and on the TS reflector. Although the MC2 package and the TS surface are folded similarly, they are not conformably deposited. The MC2 is much more deformed by folding and faulting than the overlying erosional surface indicating that some salt deformation occurred before the end-Messinian erosion event. An important observation is that the smaller scaled N-S oriented structures have a general vergence to the west, while the dominant NW-SE trending deformation is verging to the NE. This is indicative of a polyphase deformation history, and cannot easily be explained simply by a rotation of the deformational trend.

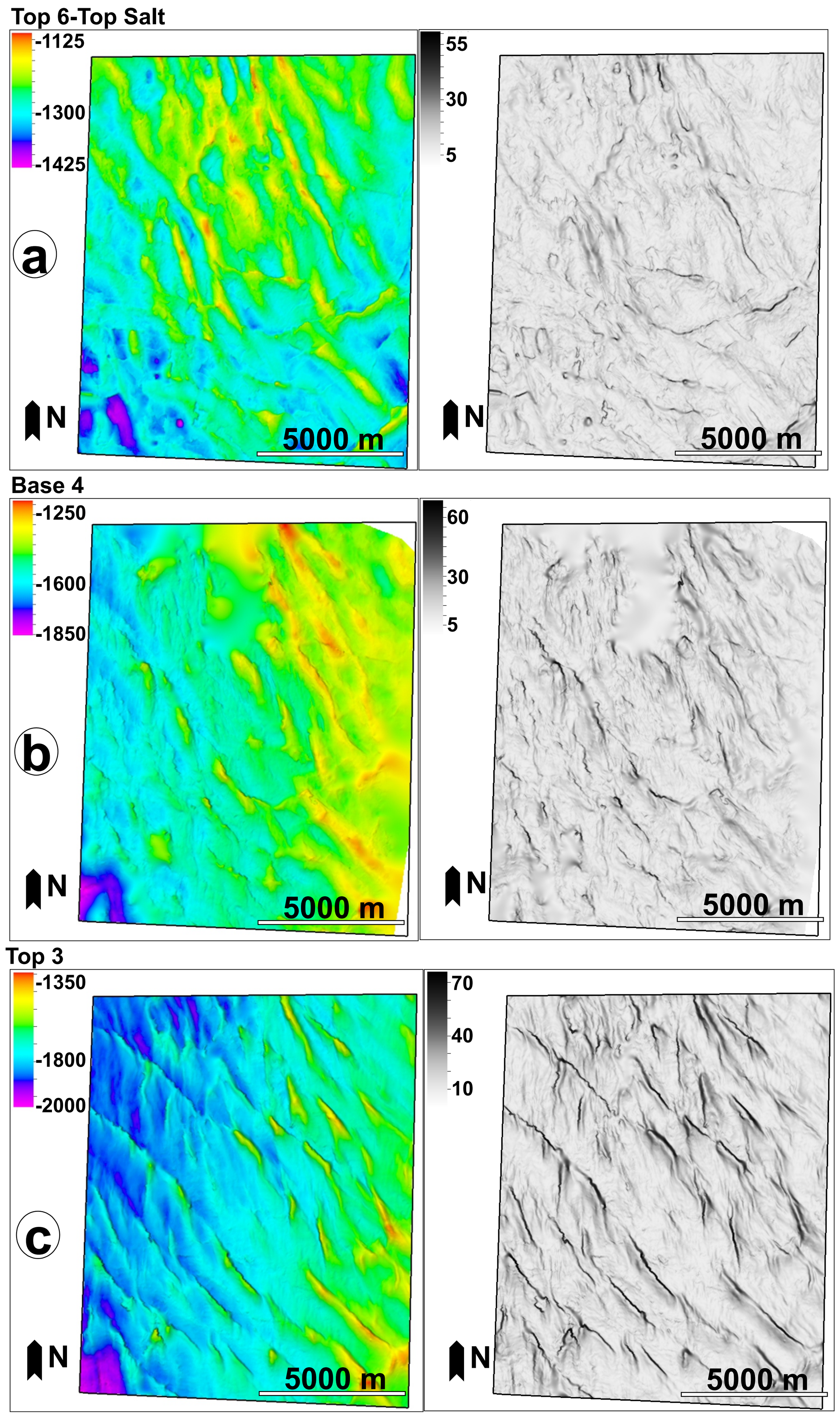


Figure 5: Depth and dip illumination maps of a) the TS reflector, b) the base of MC2 and c) the top of MC1. A clockwise rotation of the dominant deformation structures can be seen from the MC1 to the TS, as well as the N-S trending thrusts in the MC1 sequence.

3.2. DETAILED INTERPRETATIONS

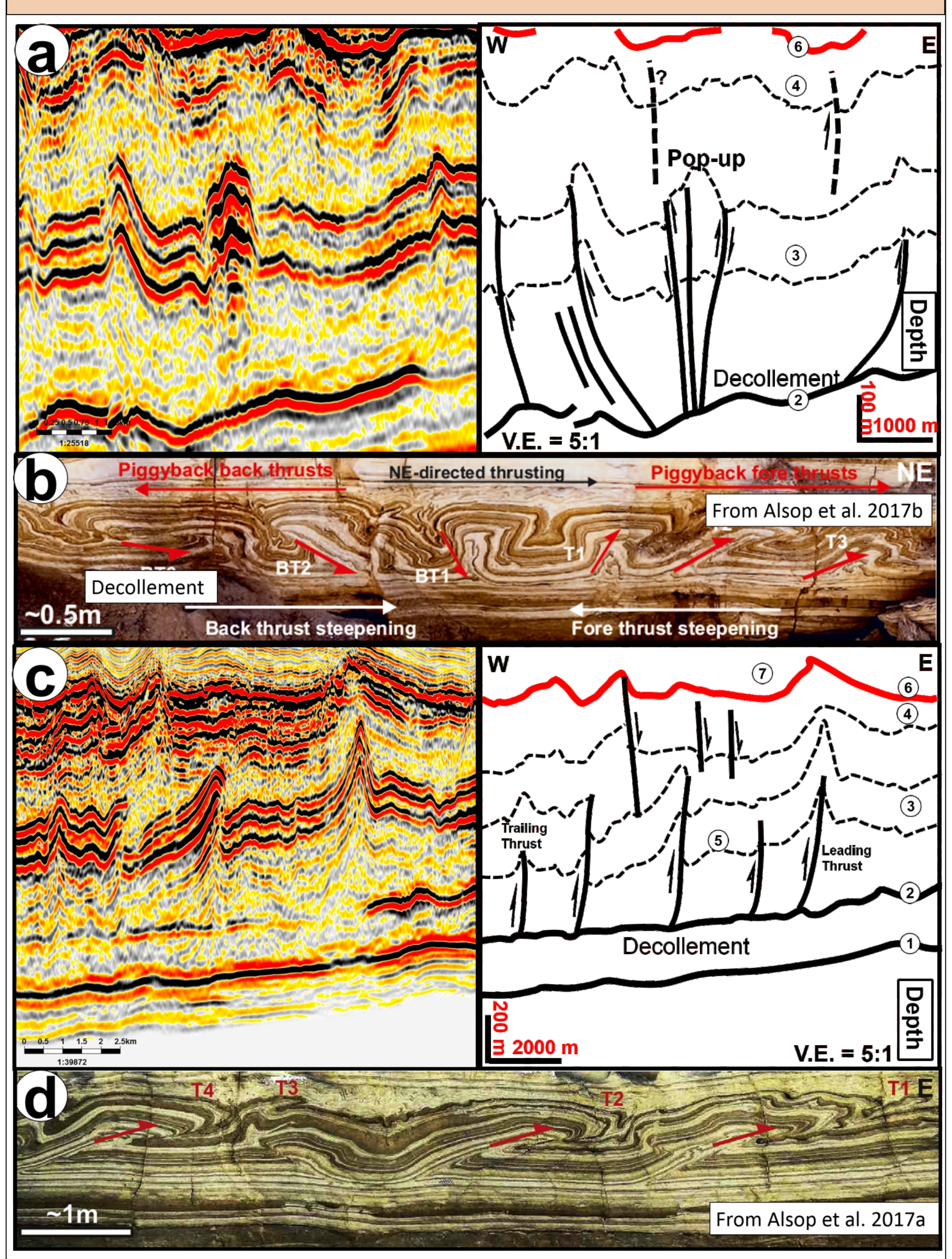


Figure 6: a) Interpreted seismic section from the northeastern part of the thrust zone. Note the presence of fore- and back thrusts in the piggyback sequence displaying a steepening trend towards the pop-up structure. b) Outcrop analogue of a piggyback sequence in the Dead Sea Basin taken from Alsop et al. 2017b. The slump system has been transported towards the northeast. c) Interpreted seismic section from the central part of the thrust zone showing a train of fore thrusts. Note the discontinuous deformation trend between the MC1 and MC2 strata. d) Outcrop analogue showing a thrust train in the Dead Sea Basin subparallel to the local transport direction. Taken from Alsop et al. 2017a.

3.3 FAULT PROPAGATION

The N-S oriented west-verging fault trains are believed to be fore thrusts, indicating a westwards transportation direction. An alternative interpretation is that they represent an upslope-directed train of back thrusts, but as no significant steepening of older master thrusts occurs, we see this as unlikely.

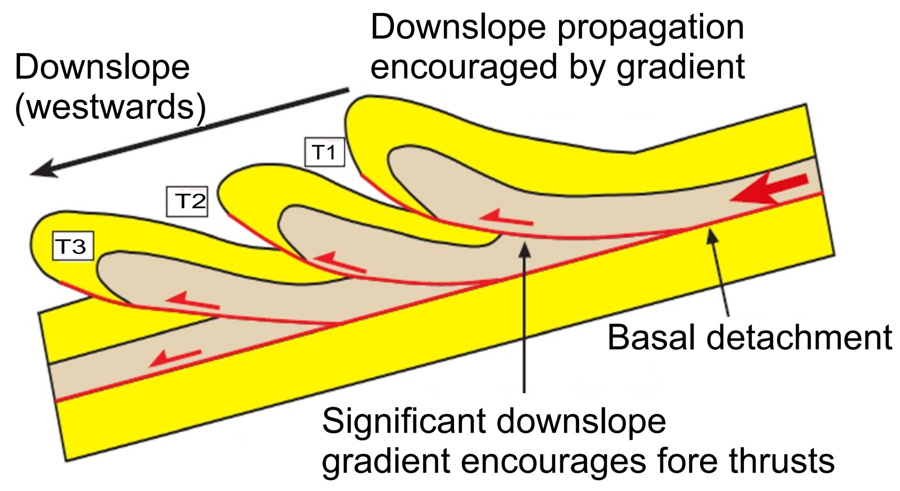


Figure 7: Downslope propagation of fore thrusts model, modified from Alsop et al. 2017b.

The dominating NW-SE oriented thrusts exhibits a striking similarity to the thrust systems described by Alsop et al. 2017b. Even though the thrusts show a general vergence to the NE, a considerable number of faults display an opposite verging trend. This can be explained by the 'downslope-directed underthrust model' as presented by Alsop et al. 2017b. The presence of a basal detachment, steepening of back thrusts and hanging wall thickening supports this model. We propose that the presence of older syn-Messinian faults act as buttresses and encourage the development of piggyback sequences within the evaporites.

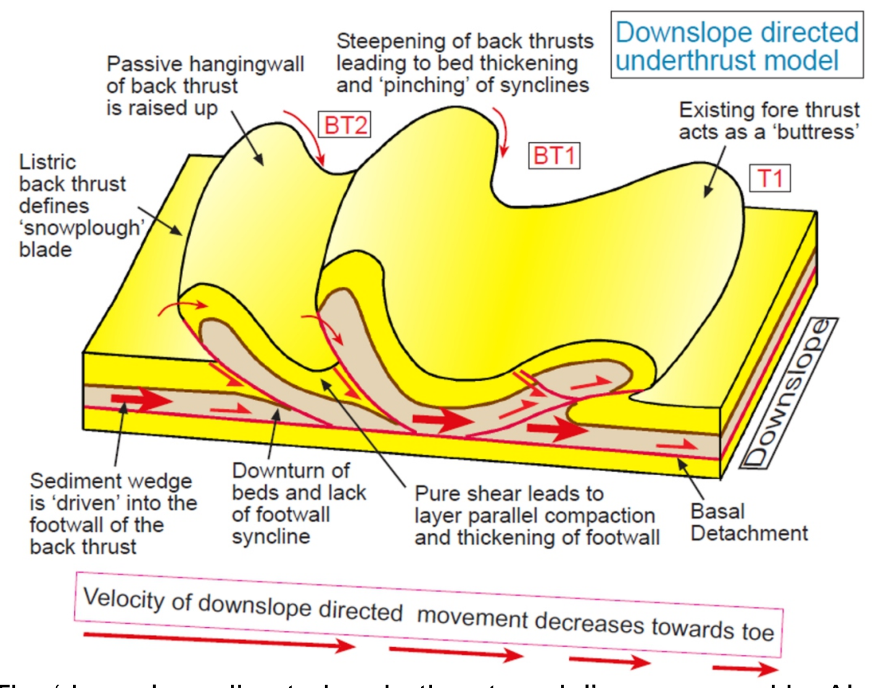


Figure 8: The 'downslope directed underthrust model' as proposed by Alsop et al. 2017b

3.4. DRIVING MECHANISMS

We propose that the initial, N-S trending W verging deformation was initiated by uplift of the Levant margin in the Messinian (Steinberg et al. 2010). This was followed by a later phase of NW-SE oriented NE verging deformation after the deposition of the MC2 package, likely driven by basin subsidence towards the Cyprus Arc.

4. CONCLUSIONS

- We propose a polyphase deformation model for the intrasalt stringers in the Levant Basin.
- Two distinct syn-Messinian sets of contractional faulting affects the salt sequence. The N-S oriented thrust faults exhibit a westwards transport direction, while the NE-SW oriented deformation structures supports a NE transportation.
- The observed thrusting in the Levant Basin show significant similarities to outcrop studies in the Dead Sea Basin. This further supports the report of polyphase deformation of the intra-Messinian layers.

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