Supplementary material for “Direct calibration of salt sheet kinematics during gravity-driven deformation”

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Seismic and well database

The data volume is post-stack time migrated, processed to a zero phase wavelet, and displayed with a polarity such that acoustically hard reflections (increase of acoustic impedance downwards) appear as positive amplitudes. The bin spacing is 12.5 m giving an effective lateral resolution of 25 m in the interval of interest. Dominant frequency is 50 and 30 Hz in the post-Messinian and Messinian intervals, respectively. The average P wave velocity for the post-Messinian interval is 2,000 m/s (based on nearby exploration wells Or-South-1, Nir-1 and Gaza-Marine-1; Fig. 1A; Fig. DR4) resulting in a vertical resolution of 10 m, based on the standard quarter wavelength criterion (Brown, 2011). The P wave velocity for the Messinian of 4,200 m/s is taken from exploration wells that drilled through the salt sheet to the southwest of the study area (Feng et al., 2016) giving a vertical resolution of 35 m within the salt. These velocities were used for depth conversion, along with an estimated 3,000 m/s for the pre-Messinian interval. Stratigraphic calibration of the key marker horizons in the 3D seismic survey were provided by long range correlations to exploration boreholes Or-South-1, Nir-1 and Gaza-Marine-1 (Fig. DR4).
**Interpretation criteria for identification of pockmarks and fluid escape pipes**

Pockmark craters were interpreted according to standard seismic interpretation criteria including a circular planform, crater-like morphology and incision at their base (Judd and Hovland, 2009). The absence of any seismically resolvable fill in the seafloor pockmark was used to infer a probable Holocene age (c.f. Reiche et al., 2014). Fluid escape pipes were interpreted based on diagnostic seismic features including loss of reflection coherency in a cylindrical zone, anomalous amplitude reflections within and immediately surrounding the pipe, and an upper termination in a pockmark crater (Moss and Cartwright, 2010; Cartwright and Santamarina, 2015)(Fig. 2; Figs. DR2 & DR3). Imaging challenges for interpreting fluid escape pipes within thick salt layers were taken into account (Kirkham et al., 2017) and contribute to positioning uncertainties for the calculation of flow velocity. This primarily affects the detailed measurement of pipe diameter, rather than the center points of pipes or pockmarks. Reflection X (Fig. 2) was interpreted by connecting the most frontal circular amplitude anomaly identified on closely spaced amplitude slices through the volume. Each circular anomaly was digitised for each slice, and an interpolation routine was used to connect the individual anomaly outlines into a volumetric body (Fig. DR1).

**Dating key seismic horizons**

Marker horizons were correlated to petroleum exploration wells further south in the basin using the 3D seismic data and a regional 2D seismic survey (Fig. DR4). The nearest boreholes that provide an age calibration for the important marker defining the
formation of the earliest pockmark are Nir-1, Or-South-1 and Gaza-Marine-1 offshore Gaza, some 240 km to the south (Fig. 1; Fig. DR4). The well ties indicate a Calabrian age for this onset marker horizon (c. 1.7 +/- 0.3 Ma), based on calibration of the Gelasian-Calabrian boundary. The boundary is dated at 1.806 My (Gradstein et al., 2012), and was identified in biostratigraphic well reports through the recognition of index taxa. The shallowest and last occurrence of *D. brouweri* is a regional marker for the top of Zone NN18 (1.95 Ma)(Catalano et al., 1998). The lowermost section of the Calabrian is defined by the downhole decrease in the recovery of *Gephyrocapsa spp.* (Rio et al., 1997) and the first occurrence of *G. tenellus, B. etnea* and *H. baltica* (Barbieri et al., 1998). These observations define the Gelasian-Calabrian boundary on seismic data within a range of error of approximately 150 ky (Fig. DR4). The uncertainty reflects the errors implicit in long range seismic correlation and in correctly picking the zonal fossils used to date the horizon. The top and base of the Messinian Evaporites are confidently identified by correlation to well ties in the area of the Tamar Field, some 60 km to the southwest (Feng et al., 2016)(Fig. 1a).

**Salt Flow Kinematics**

The average flow velocity for the upper boundary of the salt sheet was calculated from the biostratigraphic date for the horizon incised by the earliest pockmark, and the horizontal distance between the earliest and latest pockmark craters (3.4 km)(Fig. DR1). These values give an average flow velocity of 2 (+/- 0.3) mm/a over the past 1.7 myrs. The shear strain rate of $4.23 \times 10^{-14}$ was calculated from the average velocity divided by the salt sheet thickness (1500 m), making the important assumption that the sheet did not thin during this time interval. The dynamic viscosity was calculated
by dividing the shear stress by the shear strain rate (Barnes et al., 1989), assuming a Newtonian rheology and homogenous composition for the salt sheet. Both of these assumptions are questionable, although at low temperature, and slow strain rate the salt deformation could be expected to be dominated by solution-precipitation creep which would be consistent with a Newtonian rheology (Jackson and Hudec, 2017). Thin interbeds of claystones have been inferred within the salt from analysis of petrophysical logs acquired in exploration boreholes further south in the basin (Feng et al. 2016), and these would certainly influence the gross behaviour of the salt. We also assumed a constant temperature profile through the salt, which is a gross simplification, but have no data on temperature variations within, above or below the salt.

The salt was assumed to deform dominantly by shear traction at the upper boundary of the salt sheet, consistent with the idealised boundary conditions for Couette Flow (Weijermans and Jackson, 2014). Shear stress was calculated for a present day overburden tilt of 0.7° measured from a depth converted seismic profile (Fig. 1D) using a standard analytical approach for Couette Flow (Weijermans and Jackson, 2014) and assuming an overburden thickness of 400 m (present day), and a density averaging 2000 kg/m³. Earlier pipes may have formed with tilt angles different from that today, and we assumed a range of 0.1 to 2° based on analysis of the reflection configurations and isopach patterns in the Late Pliocene to Pleistocene interval. These values yielded viscosity values ranging from $3.22 \times 10^{17}$ to $6.6 \times 10^{18}$ Pa.s (present day value is $2.27 \times 10^{18}$ Pa.s) which is within the range quoted from theoretical and field studies of evaporites dominantly composed of halite (Jackson and Hudec, 2017).
Figure DR1: A three dimensional block model of the first and most recent fluid escape pipes (P1 and P21), emanating from the crest of the anticline Fold A. The pipes terminate at pockmarks located at individually specific stratigraphic levels, successively younging towards the ESE. The distance between the first and most recent pockmarks is 3.4 km. The trail of pipes produces a WNW-ESE oriented trail of reflection discontinuity as exhibited in the variance extraction map of the top surface of the evaporites (M) and highlighted by the red dotted outline. Three dimensional mapping of the pipes through the salt displays a columnar structure for the most recent pipe (P21) and a gently curvilinear geometry to the first pipe (P1) that closely approximates that which would be expected from Couette Flow through the salt. OU –
Oligocene Unconformity; BMM – Base Mid Miocene; N – Base salt; PM1 – Pockmark 1; PM21 – Pockmark 21.
Figure DR2: Seismic profiles 500 m either side of the pockmark trail and Reflection X, demonstrating that the geometry of intra-salt reflections is similar on both sides.
and contrasts with the geometry of Reflection X. Reflection X was hence superimposed over an already deformed evaporitic succession.

(A) An RMS amplitude slice (3363 ms (see black arrow on seismic profiles); Fig. DR2B-D for position of slice) through the pipe trail in the salt (highlighted by white dotted line) and numerous intra-Messinian stratal anomalies (highlighted by black dashed line). The lines of section for Fig. DR2B-D are displayed and the deformed intra-Messinian reflections (IMR1 and IMR2) that these seismic profiles intersect are highlighted. (B) A seismic profile 500 m to the northeast of the pipe trail exhibiting numerous reflective layers within the evaporitic succession. Fold A is present within the seismic profile; however no fluid escape pipes are visible within the evaporitic or Plio-Pleistocene sequences. The intra-Messinian reflections highlighted in Fig. DR2A (IMR1 and IMR2) are also highlighted here. Several amplitude anomalies (AA) that are acoustically soft are displayed within the Plio-Pleistocene. (C) A seismic profile through the pipe trail that shows an area of vertical discontinuities within the Plio-Pleistocene which is underlain by an acoustic fabric and the coherent reflection of Reflection X, which is discordant to the intra-Messinian reflections. The intra-Messinian reflections highlighted in Fig. DR2A are also highlighted here (IMR1 and IMR2). (D) A seismic profile 500 m to the southwest of the pipe trail that exhibits numerous intra-Messinian reflections (also highlighted in Fig. DR2A) that display similar geometries to the cross-section in Fig. DR2B and shows no evidence of the fluid escape pipes, acoustic fabric or Reflection X seen in Fig. DR2C. M – Top salt; N – Base salt.
Figure DR3: (A) A WNW-ESE oriented distribution of fluid escape pipes in the Pliocene to Recent, expressed in a horizontal slice of the coherence attribute volume (2912 ms) as a linear trail of circular to sub-circular discontinuities (highlighted by red dashed line). (B) An RMS amplitude horizontal slice (3364 ms) through the evaporitic unit at the exact same spatial location as in Fig. DR3A. The fluid escape pipes appear as a localised WNW-ESE oriented trail of amplification (highlighted by white dotted line). Intra-salt stratal anomalies (labelled 1-5 and highlighted by black dashed lines) exhibit contrasting geometrically irregular areas of high amplitude.
Figure DR4: Seismic to well tie. The well data aided the calibration of the top of the salt (M) and of the Gelasian/Calabrian boundary 1.806 Ma (G/C B). (A) A section of the stratigraphic column from the Or-South-1 well that extends from a depth of 1100 m within the Pleistocene to a total depth of 2095 m where it terminates in the evaporites. The well shows detailed lithological variation and the boundaries between the top of the salt (M) and the Plio-Pleistocene sequences, and the boundary between the Gelasian and Calabrian. (B) A composite seismic cross-section (see Fig. DR4C for location) that extends from the South Levant Basin to the 3D seismic survey area in the North Levant Basin and shows the long range calibration of key marker horizons from the Or-South-1 well. (C) Map of the Levant Basin that displays the location of the 3D seismic study area offshore Lebanon, and the location of the Gaza-Marine 1,
Nir-1 and Or-South-1 wells in the South Levant Basin used for the well to seismic tie. The position of the composite line used in Fig. DR4B to demonstrate the long range calibration of key marker horizons is shown. (D) A zoomed-in (close up) seismic profile from the South Levant Basin (see Fig. DR4B for location) showing our interpretation of key marker horizons. (E) A zoomed-in seismic profile from the North Levant Basin (see Fig. DR4B for location) showing our interpretation of key marker horizons.

REFERENCES


