SUPPLEMENTARY MATERIAL

Localised and distributed deformation in the lithosphere: modelling the Dead Sea region in 3 dimensions.

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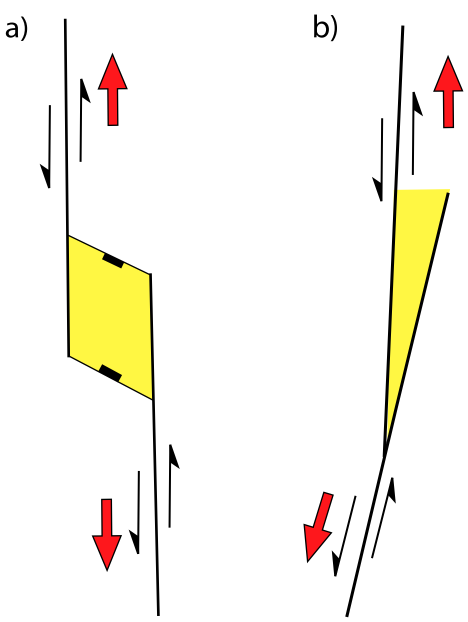
Tectonic Background

Most studies of the valleys that extend the length of Israel accept that they are tectonic in origin and the mechanism of formation is thought to be in some way associated with the strike-slip motion. The relation between the two has been subject to varying interpretations. Following the seminal paper of Garfunkel (1981) it became accepted that a major change occurred at about 5 Ma. It has been proposed that a transition from pure strike-slip to strike-slip and opening occurred at this time. However, Garfunkel has revised this view: “The basin formed at about 15 Ma or earlier, close to the beginning of the transform motion, and it reached about half its present length before the end of the Miocene” (Garfunkel and Ben-Avraham, 1996, Abstract). Garfunkel and Ben Avraham (1996) further admit that the “history of the transform motion is not well constrained”. More recent work of ten Brink et al. (1999) who analyzed the gravity field across the transform provides possible evidence for a continuous change in the pole of rotation. In a yet more recent paper, Garfunkel and Ben-Avraham (2001) conclude that “The pull-apart basins grew primarily by becoming longer as a result of the transform motion”, implying a very early initiation for the ~100 km long Dead Sea basin, a length that compares with the total offset on the transform. Recent articles such as Smit et al. (2010) accept the Garfunkel (1981) without considering more recent interpretations. However the mechanical arguments in this paper could be modified to suit most interpretations for the timing. Many interpretations of the kinematics of the Dead Sea system assume block motion that can be characterised using poles of rotation. On this basis a range of widely scattered pole have been proposed. However, a block description need not be correct as pointed out by Flerit et al., 2003, 2004 for western Turkey and the Aegean and for Tibet by Loveless and Meade (2011).

Figure S1



Most interpretations consider the Dead Sea valley system to have been created by superimposing a series of pull-apart basins with the implication that the basins occur where offset parallel faults extend to depth. The Dead Sea Basin is considered to be the most prominent. However like other large-scale and long-lived pull-aparts such as the Erzincan basin, the Sea of Marmara and others documented in Mann 2007, the associated faults are associated with a substantial change of strike. In the case of the Dead Sea the

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strike change is 11.5°. Figure S1a shows the common assumption for offset parallel driving faults at depth (following Wu et al., 2009). An alternative resulting from a bend is shown in Figure S1b. A change of strike in a strike-slip fault can also create significant opening and this is likely to result in similar surface faulting. In the paper, we show that although the overall shape of the Dead Sea valleys is linked to regional opening (east-west), the Dead Sea itself has become much deeper then the surrounding areas because of the influence of the change of strike on the vertical component of the deformation.

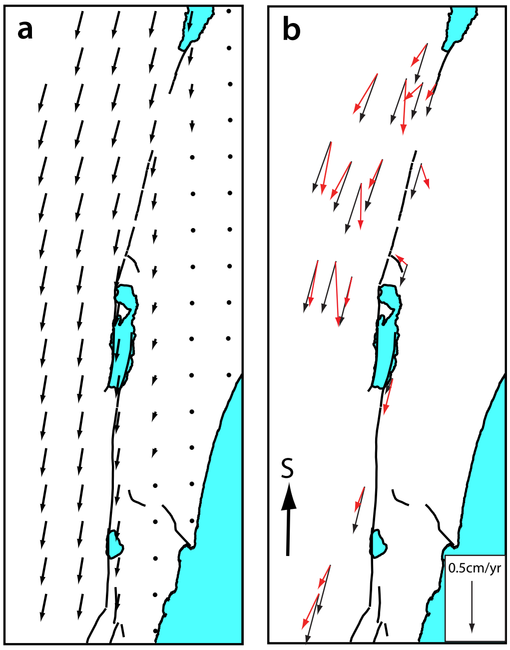
Model Parameters

The modelling is kinematic with the input and output in kilometers (and strain). Only Poisson's ratio must be specified. The results are insensitive to any reasonable choice of Poisson's ratio. We assume that the material is almost incompressible with a Poisson's ratio of 0.49.

Elements

element #	X-start	Y-start	X-finish	Y-finish	X-slip	Y-slip	Z-slip
1	808.847	4849.352	803.139	3830.825	0.001	0.00002	0.00003
2	803.139	3830.825	746.056	3688.117	0.001	-0.0002	-0.00003
3	746.056	3688.117	733.416	3419.826	0.001	0.0002	-0.00003
4	733.416	3419.826	693.865	3279.564	0.001	0.0002	-0.00003
5	693.865	3279.564	530.164	2305.073	0.001	0.0002	-0.00003

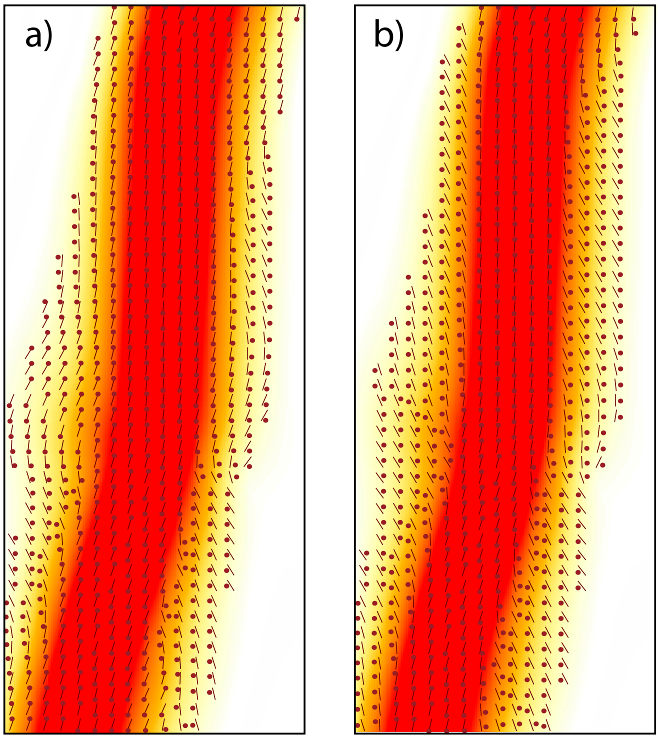
Figure S3



The surface displacement field and GPS measurements

FigureS3a shows the displacement vectors corresponding to the models in Figures 5c and 7a. The modelled vectors (black) are compared to the observed GPS data (red) (Le Béon et al., 2008). Errors in the GPS data can be 2-3 millimetres. Locally there are large differences between the two. This may be due to un-appreciated errors in the GPS due to tropospheric effects or instability of GPS measurement sites. Many of the sites are located within the region described in this paper as a zone of incoherent faulting (process zone) and may indicate true motion. Whatever the cause of the differences they do not suggest that the model we have used is incorrect.

Figure S4

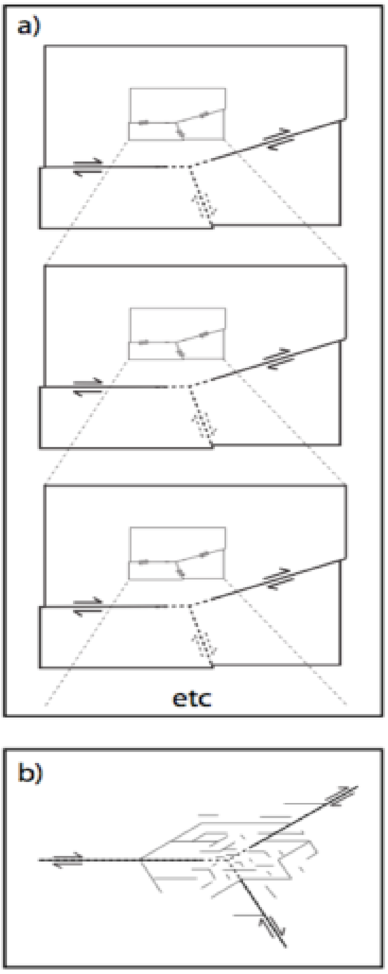


The effects of regional strain

The calculation to create Figure 7 adopts a regional extensional strain of $3.2.10^{-6}$ at 50°E and a vertical contraction of $1.6.10^{-6}$. This ensures that most of the predicted mechanisms are consistent with the direction of the horizontal principal axis determined by Le Béon et al., 2008. In FigureS4 we show two alternative regional strain conditions. For a no vertical strain is assumed and for b a vertical contraction of $4.0.10^{6}$ is assumed.

For the regions of high strain the predicted style of faulting is almost identical to Figure 7. Outside the region the mechanisms can be different but with minor exceptions no valley parallel normal faulting is predicted.

Figure S5



Fractal faulting at triple junctions illustrated for two dimensions.

Figure S5a shows slip on the main faults reducing to zero at the triple junction with the remaining shear strain components accommodated by smaller faults around the junction. The introduction of these faults re-creates the same geometry at a smaller scale resulting in fractal hierarchy of faults. Figure S4b shows a system of faulting at a junction adapted from a simplified 2D plane strain topological model (King, 1983). In general bends and junctions associated with faults in the Earth are 3D systems with geometrically more complex faulting. However the same hierarchical faulting must occur (King and Nabelek, 1985).

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