SUPPLEMENTARY MATERIAL: PALAEOSTRESS INVERSION METHODS

Following extensive fieldwork collecting fracture data, a fault slip analysis and palaoestress inversion was carried out to approximate the most likely stress conditions at the time of the fracture formation. This inverse problem which attempts to approximate the stress tensor given the direction and sense of slip of fault data, was first solved by Carey and Brunier [1] [original article in French, mentioned in 2, 3] and was developed with new improvements introduced in several studies thereafter [e.g. 3, 4, 5 to name but a few, 6]. Palaeostress inversion is mainly built around the Wallace-Bott hypothesis which assumes that on a plane of weakness affected by a normal stress, σ_n, and a shear stress, τ, if slip occurs, the direction of the slip will be parallel to that of the shear stress [2, 3, 7]. There are weaknesses in this main assumption, particularly when various faults are geometrically linked which can result in deviations of the stress and that it is impossible that the stress distribution is uniform in a rock mass. Succeeding theoretical and empirical analyses, however, have shown that the variations of the results are only minimal, thus, validating the key assumption [2]. Consequently, in a regional scale study utilising a large fault population, it is likewise assumed that: (1) the rocks are all homogenous and isotropic; (2) stress is uniform in a rock mass; (3) fault slips are independent of each other; (4) all faults in the population are caused by the same stress tensor/ stress field; (5) the strain is non-rotational; and (6) the finite strains are low [1, 2, 7, 8].

A stress tensor has six independent variables, but as discussed in Angelier (1984) and Angelier (1994), only four of these parameters can be determined from the fault direction and sense of slip dataset, so that the resulting tensor is termed a reduced stress tensor. These four degrees of freedom constrain the orientations of the three principal stresses and the shape ratio, Φ, which is defined as [2]:

$$\Phi = (\sigma_2 - \sigma_3) \;/\; (\sigma_1 - \sigma_3) \quad \text{Equation 1}$$

A misfit criterion is often used to evaluate the quality of the calculated stress tensor with one of the commonly applied criteria being the angle between the observed slip and the calculated resolved shear stress, termed the misfit angle. This can be a value between 0 to 180°, where a value of 0 suggests that the calculated shear stress lies perfectly parallel to the slip direction.

For this research, stress inversion was carried out using MyFault v.1.05 fault analysis software. It is able to carry out stress inversion analysis using five different published work flows: simple shear tensor average [9], minimised shear stress variation [4, 10]; minimised principal stress variation [11]; minimised non-slip shear stress [3]; and Fry's hyperplane average [12, 13]. Of these five, results using the minimised shear stress variation method are reported in this thesis given that it generally yields the smallest misfit angles on the SNGF fault datasets, hence, proved to be most suited for our dataset (Figure 1). Its key assumption is that the magnitudes of the tangential tractions of the stress tensor of the various fault planes at the time of rupture is similar, utilising a least squares criterion, where the difference between the slip direction and the calculated tangential traction is minimised [4].

For each set of fault data, MyFault calls for a RHR[1] strike or dip direction, dip angle, rake of the slickenlines, and a quality factor. Rake angles in MyFault are reported as the angle between the striae and the strike line measured in a clockwise direction, read on the footwall block. Sense of motion was based on these values wherein a pure sinistral fault has a rake of 0 or 360°, a normal fault has 90°, a dextral fault has 180°, and a reverse fault has a rake value of 270°. This is slightly different to how the rake angles were actually measured in the field, being that acute angle between the strike line and the fault striae, measured down from the horizontal (i.e. a pitch). Hence, there was some conversion to do.

[1] RHR refers to right-hand-rule convention where the thumb of your right hand aligns the strike line whilst the four other fingers point to the dip direction of the fault plane.

Striae data were weighted from 1 to 4 according to the quality of the rake measurements (Table 1). This numerical factor aims to ensure that the confidence of the data quality is reflected in the analysis by giving high quality data the most importance and low quality data less importance.

Table 1. Striae data were ranked from 1 to 4 depending on the quality of the field measurement and the kinematic indicators, hence, the confidence of the interpreted sense of motion. This is a modification from Sperner *et al.* [14]. Conversion refers to the transformation of the field data into the format required by MyFault. Doubtful conversion refers to those rare cases where the field rake measurements do not agree with the expected sense of motion (e.g. an E-W trending, south-dipping fault is reported to have a rake angle of 30° from the east and has an interpreted normal-dextral sense of motion; following the rake geometry on the fault and MyFault's conversion after Threet [15], this fracture could only be either a reverse-dextral or a normal-sinistral).

Quality and Weight Factor	Remarks
4	Good field measurement, clear sense of motion; confident conversion
3	Good field measurement but doubtful sense of motion due to weak kinematic indicators; doubtful conversion
2	Good field measurement but no evidence of sense of motion; OR poor lines but has clear sense of movement
1	No pitch reading

The MyFault calculations yield orientations of the three principal directions, the shape ratio, mean misfit angle, a World Stress Map (WSM) quality rank, and the principal shortening or extension direction, amongst others. A normalised Mohr circle diagram is also generated where the minimum principal stress is zero and that the maximum is one. It then follows that the calculated shape ratio is equivalent to the normalised intermediate principal stress. The changes in the directions of the three principal stresses across the three fracturing events and the varying magnitude of the shape ratio has implications for the dominant tectonic regime at the time of the fracturing (Figure 2).

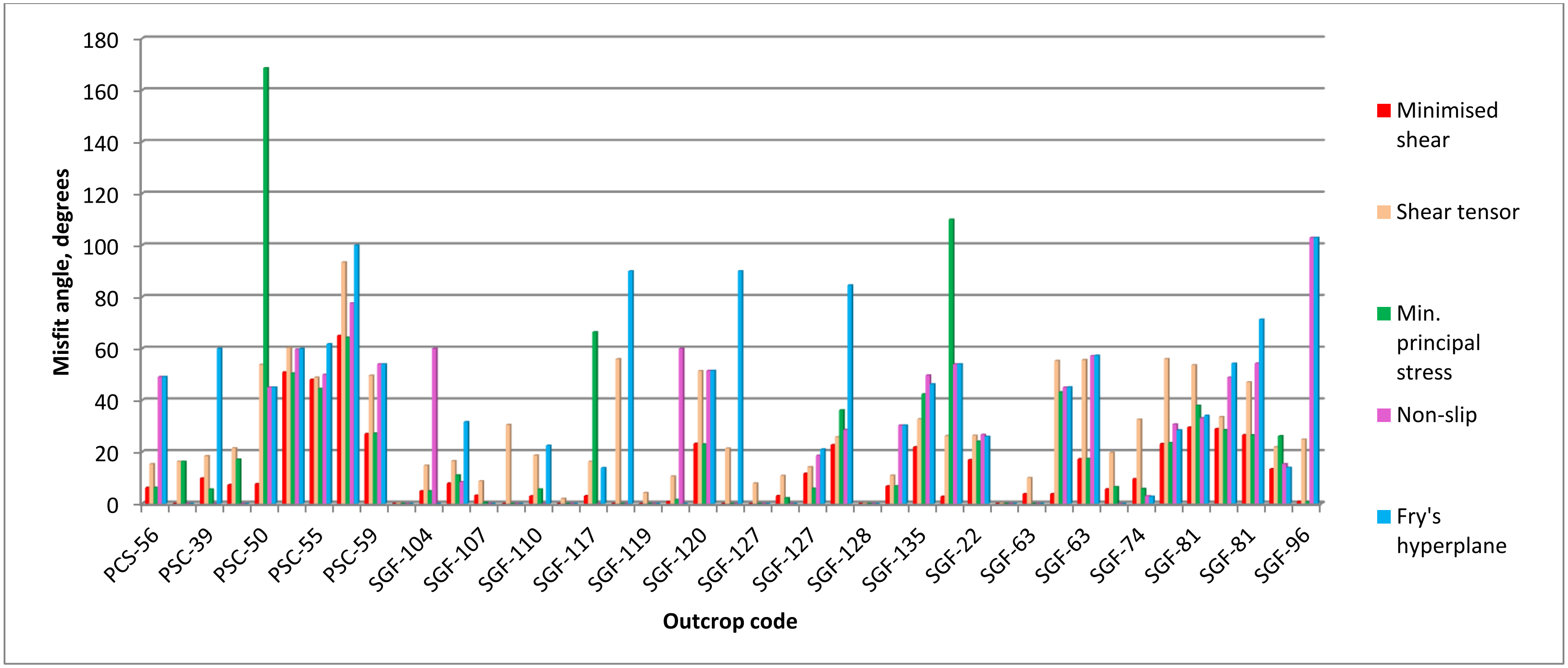

Figure 1. Summary of all misfit angles for each outcrop using the five stress inversion methods – minimised shear stress variation (red), simple shear tensor average (peach), minimised principal stress variation (green), minimised non-slip shear stress (pink), and Fry's hyperplane average (cyan).

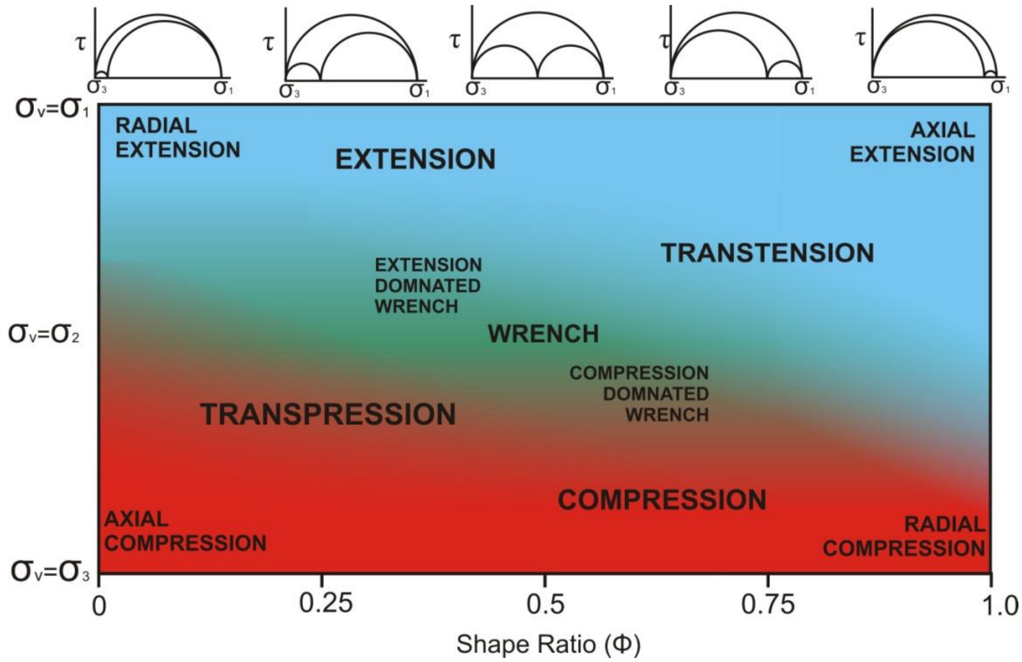

Figure 2. Likely tectonic regimes based on the values of the ellipsoidal shape ratio, Φ, compiled from Buchmann [16], Fossen and Tikoff [17], Hancock [18], Sassi *et al.* [19]. The vertical axis indicates which of the three principal axes is vertical whilst the horizontal axis defines the Φ value and the corresponding Mohr circle diagram. A progressive colour change suggests the boundaries are not really strongly defined.

1. Carey, E. and B. Brunier, *Analyse theorique et numerique d'un modele mecanique elementaire applique a l'etude d'une population de faille.* C.R. Acad.Sci Paris, 1974. **279**: p. 891-894.
2. Angelier, J., *Fault slip analysis and palaeostress reconstruction*, in *Continental deformation*, P. Hancock, Editor 1994, Pergamon Press: Oxford, UK. p. 53-99.
3. Angelier, J., *Tectonic analysis of fault slip data sets.* Journal of Geophysical Research: Solid Earth, 1984. **89**(B7): p. 5835-5848.
4. Michael, A.J., *Determination of stress from slip data: Faults and folds.* Journal of Geophysical Research: Solid Earth, 1984. **89**(B13): p. 11517-11526.
5. Angelier, J., *Inversion of field data in fault tectonics to obtain the regional stress—III. A new rapid direct inversion method by analytical means.* Geophysical Journal International, 1990. **103**(2): p. 363-376.
6. Etchecopar, A., G. Vasseur, and M. Daignieres, *An inverse problem in microtectonics for the determination of stress tensors from fault striation analysis.* Journal of Structural Geology, 1981. **3**(1): p. 51-65.
7. Bott, M.H.P., *The mechanics of oblique slip faulting.* Geological Magazine, 1959. **96**(2): p. 109-117.
8. Twiss, R.J. and J.R. Unruh, *Analysis of fault slip inversions: Do they constrain stress or strain rate?* Journal of Geophysical Research: Solid Earth, 1998. **103**(B6): p. 12205-12222.
9. Sperner, B., L. Ratschbacher, and R. Ott, *Fault-striae analysis: a Turbo Pascal program package for graphical presentation and reduced stress tensor calculation.* Comput. Geosci., 1993. **19**(9): p. 1361-1388.

10. Michael, A.J., *Use of focal mechanisms to determine stress: A control study.* Journal of Geophysical Research: Solid Earth, 1987. **92**(B1): p. 357-368.
11. Reches, Z., *Determination of the tectonic stress tensor from slip along faults that obey the Coulomb yield condition.* Tectonics, 1987. **6**(6): p. 849-861.
12. Fry, N., *Stress space: striated faults, deformation twins, and their constraints on paleostress.* Journal of Structural Geology, 2001. **23**(1): p. 1-9.
13. Fry, N., *Striated faults: visual appreciation of their constraint on possible paleostress tensors.* Journal of Structural Geology, 1999. **21**(1): p. 7-21.
14. Sperner, B., et al., *Tectonic stress in the Earth's crust: advances in the World Stress Map project*, in *New Insigths into Structural Interpretation and Modelling*, D.A. Nieuwland, Editor. 2003, Geological Society: London. p. 101-116.
15. Threet, R.L., *Down-Structure Method of Viewing Geologic Maps to Obtain Sense of Fault Separation.* Geological Society of America Bulletin, 1973. **84**(12): p. 4001-4004.
16. Buchmann, T.J., *3D multi-scale finite element analysis of the present-day crustal state of stress and the recent kinematic behaviour of the northern and central Upper Rhine Graben*. 2008, Berlin: Logos.
17. Fossen, H. and B. Tikoff, *Extended models of transpression and transtension, and application to tectonic settings.* Geological Society, London, Special Publications, 1998. **135**(1): p. 15-33.
18. Hancock, P., ed. *Continental Deformation*. 1994, Pergamon Press: Oxford. 421.
19. Sassi, W., et al., *Modelling of structural complexity in sedimentary basins: The role of pre-existing faults in thrust tectonics.* Tectonophysics, 1993. **226**(1–4): p. 97-112.