A standardized protocol to test oblique transpression models in heterogeneous high-strain zones (the Torcal de Antequera massif, southern Spain)

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1. Presentation
2. One of the main topics of studies on high-strain zones is defining theoretical models that approximate natural cases. As we have been obtaining a better knowledge of these zones, models have progressively complicated from the simple shear model of Ramsay and Graham, through monoclinic transpression models, to triclinic transpression or general deformation. Models can get even more complex if we consider non-isochoric deformation, non steady-state flow or heterogeneous distribution of the main components of the flow. And these are only kinematic models.
3. This Increasing complexity introduces several variables that make comparison with nature rather cumbersome. To facilitate this task, few protocols have been proposed. Most kinematic models have been tested with ductile, roughly homogenous, high-strain zones. However, general conditions leading to transpressive kinematics take place also in upper crust generating strongly partitioned high-strain zones showing heterogeneous brittle-ductile deformation. So we questioned to which extend these kinematic models would work with brittle-ductile deformation and, therefore, the main objectives of this study were: (1) to define a protocol applicable to these zones and, from this, (2) to obtain a better understanding of kinematics of upper crust transpressional zones.
4. To afford this, we selected our case study from a nearly E-W directed band at the external zones of the Betics, in the western Mediterranean area. A part of this band is the so-called Torcal de Antequera massif (TAM from now on).
5. Several features make the TAM very appropriate for this study, as it meets several of the conditions needed to make models applicable: (1) It is roughly tabular-shaped and its limits are well defined and constitute narrow high-strain zones where slip is likely. (2) It is rather small and shows a nearly continuous rock exposure, thus contributing to reduce bias in structures sampling. (3) It shows a quite well-known, simple rock sequence, with limestones overlaid by marly limestones, without major mechanical contrasts and no metamorphism, so structural differences within the zone can be attributed mainly to kinematics. Finally, (4) apart from some minor calcite veining, volume likely remained approximately constant during deformation. We know deformation is not steady-state but it is assumed as usual. In these shear zones, deformation is highly heterogeneous, so we discretize the zone into domains where we can assume, at least, the structures all together accommodate a unique bulk strain.
6. From a structural and kinematic point of view, two main domains have been defined within the TAM. The boundaries of the TAM are marked by narrow bands showing right-lateral strike-slip dominated transpression (Outer Domains, ODs). The Inner domain (ID) shows NE-SW striking, SE-vergent shortening structures (reverse faults and folds) and NW-SE oriented normal faults. Each domain type has been analyzed separately. As an example, we show the study on the inner domain.

7. The protocol we present here is inspired on those of Czeck & Hudleston (2003) and Fernández et al. (submitted to JSG), but adapted to brittle-ductile deformation. It is applied independently to each domain. The model used is controlled by three main parameters: angle ϕ, between the simple shear direction and the azimuth of the zone boundaries, known as transpression obliquity; angle υ, between the extrusion due to the coaxial component and the true dip of the zone; and the kinematic vorticity number (W_k) of the flow. To constrain these parameters, the protocol comprises up to five consecutive steps. Depending on the available information in each case, some steps may not be used. For example, in our case study we could only apply the first four.
8. In step one, transpression and extrusion obliquity (angles ϕ and υ) should be estimated based on geological observations. Slip on faults inform about the possible orientation of the simple shear direction. On its turn, extrusion would be assumed to be dip-parallel unless structures point to the opposite. Anyway, we can always get back to this step if results are unrealistic. In our case study, we have chosen a wide transpression angle range (≤ 60º) and extrusion angles smaller than 15º.
9. In steps two and three, the orientation and shape of the FSE estimated for the analyzed zone is compared to those obtained from the model. In the inner domain, the orientations of the main strain axes have been obtained from folds orientation and fault-slip data.
10. To obtain the shape of the FSE, cross-sections have been constructed subparallel to axes Z and Y. From the former, we have estimated the maximum extension and the shortening, both around 0.2-0.3.
11. The intermediate axis has been obtained measuring the extension accommodated by all the normal faults along a NE-SW section (subparallel to Y).
12. The result is one order of magnitude smaller than the other two axes.
13. Now, these results are compared to those arising from the model. The plots show the orientations of λ_1 and λ_2 for different W_k values from two examples with different combinations of υ and ϕ angles (0º, -10 on the left; 0º, -60º on the right). These axes are compared with X and Y axes estimated from the TAM. On the left, we can see good adjustments with X axes for low to medium finite strain and W_k values ranging from 0.6 to 0.78. Adjustment with Y axes is more restricted (W_k = 0.65 – 0.78). The obtained combination of υ, ϕ and W_k is one suitable result. In contrast, on the right, we observe some good adjustments for certain W_k values but no one when Y is considered.
14. In step 3 we follow a similar procedure now respecting to the shape of the ellipsoid. The examples are the same as before.
15. After the first three steps, we summarize the results obtained from comparison between the model and the natural case. On the left, we see there is a fair to poor adjustment with W_k = 0.6 – 0.65 whereas larger W_k values (0.68 – 0.75) have been disregarded after step 3. In contrast, the second example does not show a single combination of parameters that can account for the observed finite strain ellipsoid. Here is an example of a good combination. This third case is also a good example on how combination of different approaches can narrow the range of possible parameter combinations.

16. All results are summarized in one single table where all possible combinations of parameters that have shown any type of adjustment are presented and classified according to the quality of this adjustment. Arrows point to the four cases shown in the previous table. We can tell to which extent the three transpression parameters are constrained following this procedure.
17. We present the obtained results on a strain triangle, slightly modified from that of Jones et al. (2004). We have turned it counterclockwise and added contour lines for W_k and ϕ values. υ is not included in this diagram. The possible combinations of transpression parameters deduced for the Inner Domain of the TAM is ϕ = 10 - 20º, υ < 5º and W_k = 0.6 – 0.65, which would plot on the pure shear-dominated transpression field. Note that if we would have analyzed separately reverse faults on one side and folds and normal faults on the other, we would get something close to thrust tectonics and monoclinic transpression, respectively.
18. We can go a bit further with step 4, in which we use the geometrical relationship between the kinematic parameters ϕ and W_k and the angle of oblique convergence α, between the far field vector and the azimuth of the high-strain zone. We have applied the same procedure to the Outer Domains resulting in slightly smaller ϕ and υ values and larger W_k values, plotting on the strike-slip simple shear-dominated transpression field. If we assume both domains accommodated strain partitioning from a single bulk strain, the latter should plot somewhere between the loci of both domains. This would correspond to an overall oblique convergence angle (α) between 17 and 35 º. The last step would consist of an approach from GPS measurements. We haven't applied this step because we are getting now the first detailed GPS data from the area, which is very complex.
19. Conclusions and further perspectives.