Relations between velocity fields and faulting on the continents

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Synopsis

1. Velocity fields

The simple concepts of Plate Tectonics which were so successful in describing the deformation of the ocean basins are not easily applicable in continental tectonics, where the deformation is usually much more diffuse than in the oceans and not restricted to narrow plate boundaries. A different framework is needed within which to view continental deformation. The continental lithosphere consists of a thin (10–20 km) seismogenic ('brittle') layer above a much thicker (80–100 km) layer that probably deforms by distributed creep. The scale on which major topographic features, such as mountain belts, plateaus, and basins, occur suggests that at long wavelengths the deformation is best described by a **continuous velocity field**. An important problem is then to obtain this velocity field and understand its relation to the motions of the rigid plates that bound the deforming region. A major advance of the last decade has been in estimating such velocity fields, either directly from GPS measurements, or from spatial variations in strain rates estimated from seismicity.

But such velocity fields do not describe the detailed deformation of the upper 'brittle' crust, which deforms discontinuously by faulting. So an additional problem is to understand how this faulting in the upper crust is able to accommodate the velocity field that describes the deformation of the lithosphere as a whole. It is important to realize that a **scale** is imposed by this reasoning: the continuum approach will only be applicable at lengthscales comparable or greater than the thickness of the lithosphere (i.e. greater than ∼100 km), and certainly not at length scales similar to the thickness of the seismogenic upper crust (10–20 km).

2. Faulting and flow

What can we do when we have finally obtained a velocity field? The two fundamental questions in continental kinematics are : (1) 'what is the continuous velocity field that describes the average deformation at large length scales?' (2) 'How is that velocity field achieved by discontinuous slip on faults?' If we have some idea of the answer to these two questions, we can pose a third: (3) 'what is the relation between the two?' Since all our observations of faulting are restricted to the top 15–20 km of the lithosphere, and since the lower 100 km of the lithosphere is assumed to deform by a more distributed ductile flow, any attempt to address this question leads to another: (4) 'what controls the deformation of the continents — the strength of the upper crustal blocks and their interactions, or the flow in lower lithosphere?' This is a very tough question to address, and has not been sorted out. Since good GPS-based velocity fields are based on very short time scales, much of the deformation near faults is elastic. The rotation of crustal blocks may contain some clues to what's going on, but require yet another question: (5) 'what is the relation between the instantaneous (i.e. over short time) and the finite (i.e. long-term or cumulative) deformation?'

These are all problems in **kinematics** (to do with the geometry of the deformation), but start to merge with problems in **dynamics** (to do with the forces responsible), especially when we ask: (6) ‘why does the velocity field look like it does, anyway?’

3. Rotations in deforming zones

In several areas of distributed active deformation rapid rotations (of up to 90° in 10^7 years) of paleomagnetic declinations have been described in young rocks within the deforming zone, relative to declinations in stable regions outside the zone. Examples are known form California, Nevada, New Zealand, Greece, Turkey, Iran, Israel and Italy and central Asia.

These rotations reveal an important part of the deformation. In several places the rotation of fault-bounded blocks accommodates a velocity field in which the slip vectors on the faults are in a different direction from that of the motion between the bounding plates or rigid regions.

We would like to know how (or if) the rotation of these blocks is related to the velocity field that describes the ‘flow’ of the lithosphere at long wavelengths. Potentially, the rotation rate contains information on whether the motions of the blocks are primarily controlled by the flow beneath them, or by the motions of neighbouring blocks.

The simplest scheme to imagine is that of a rigid circular disc floating alone in a fluid that is sheared. If the velocity gradient across the deforming zone of width a is U/a, then a circular disc rotates at a rate of $-U/2a$ about a vertical axis, where U/a is the **vorticity** ($\dot{\omega}$) of the fluid. The rotation rates of blocks with a more general shape depend on their shape and on their orientation (e.g. a stick aligned parallel with the shearing flow will not rotate, whereas one oriented across the flow will rotate). To examine whether fault-bounded blocks behave as if they were equi-dimensional or elongated inclusions in a fluid, or whether their motions are dominated by their interaction with other blocks, we need to know their present-day rotation rates to better than a factor of two. This is rarely possible with paleomagnetism, as there are errors in the measurements of declination (typically ±10°), and the rotation could have occurred at any time since the rock was deposited. The best hope is that GPS may provide the measurements of instantaneous rotation rates that will help; but there are other problems with this, such as not knowing whether the deformation we see on short time scales is elastic or not.

4. No-length-change directions and rotations

If we know the velocity field, we know the distribution of strain rates ($\dot{\boldsymbol{\varepsilon}}$) everywhere. (If the velocities have been measured by GPS, there is an intermediate step, which is to fit a surface to the points where the velocities have been measured, to allow interpolation). We can then ask the question: ‘what orientation and type of faulting can produce this strain-rate tensor? If the faulting is uniform, in other words, if there is to be no variation in the magnitude of slip on the faults in the direction parallel to their strike, then *Holt and Haines* [1993] showed that there are two possible strike directions of faulting that can produce the horizontal components of the strain rate tensor. These are directions of zero length change in the velocity field, and they correspond to the strikes of the two nodal planes in a fault plane solution. In terms of the elements of the strain rate tensor, these strikes are:

$$\tan\theta_f = \frac{-\dot{\varepsilon}_{xy} \pm \sqrt{\dot{\varepsilon}_{xy}^2 - \dot{\varepsilon}_{xx}\dot{\varepsilon}_{yy}}}{\dot{\varepsilon}_{yy}} \qquad (1)$$

where θ_f is the strike of the fault. This result is correct only if

$$\dot{\varepsilon}_{xy}^2 \geq \dot{\varepsilon}_{xx}\dot{\varepsilon}_{yy}$$

Some fiddling about with algebra shows that this condition means that such faults can only exist if the principal horizontal strain rates have opposite signs, or if one is zero. Pure contraction and pure extension require two sets of faults, but other strain fields require only one set.

If faults of this orientation accommodate the deformation and are also elongated blocks 'floating' in the fluid (i.e. responding to forces on their base and not to interactions with each other), then it is fairly straightforward to calculate the sense and rate at which they would rotate, following *Lamb* [1987] — see *Haines and Holt* [1993] for another ghastly expression, if you're that keen.

5. Finite deformation

The problem is that the relation between the velocity field and the faults that can accommodate it is so tight (equation 1) that once the faults have rotated into a different orientation, they can no longer do the job: in that orientation they would accommodate a *different* velocity field. At that point something has to give: either new faults form or the velocity field changes. What actually happens?...

Outline

The problem	Why Plate Tectonics doesn't help much
A solution	Use a different description: a *continuous velocity field.* What does one look like? What assumptions are we making? When is it appropriate?
The velocity field	What is it? How do we obtain it? Use of: (a) earthquakes, (b) slip rates on faults, (c) geodesy
Questions	What can we do with the velocity field? Relations between the velocity field and the faulting? What controls the deformation of the crust: block strength and interactions or flow on the base?
Problems	How to deal with elastic effects in the velocity field? Can we distinguish elastic and permanent deformation when faults are close together?
Block rotations	Possible significance of block rotations. (a) vorticity and floating blocks (b) 'pinned' blocks (c) no-length-change directions
Finite deformation	Something must give, but what? Does faulting change with time?

Conclusions	Relative strength of blocks and faults. Anisotropy of structural fabric and reactivation. Relative strength of crust and mantle.

References

The bulleted references (•) will give a rapid overview of the main topics. Others are for more energetic enthusiasts.

1. • **Jackson, J.A. (1994)** Active tectonics of the Aegean region. *Ann. Rev. Earth Planet. Sci.*, **22**, 239–71.
   Clarke et al., (1998) Crustal strain in central Greece from repeated GPS measurements in the interval 1989–1997. Geophys. J. Int., **135**, 195–214.
   McClusky, S. et al., (1999) GPS constraints on plate motions and deformations in the eastern Mediterranean: implications for plate dynamics. *J. geophys. Res.*, in press. This updates **Reilinger et al., (1997)**, J. geophys. Res., **102**, 9983–9999.
   — The Aegean has spawned many of ideas discussed in this lecture. A light and easy-to-read overview of the Aegean and the topics covered here is in Jackson (1994), but the velocity field used in that paper is from earthquakes and is inferior to that now available from GPS: see Clarke et al. (1998) and McClusky et al. (1999).

2. **Holt, W.E. & Haines, A.J. (1993)** Velocity fields in deforming Asia from the inversion of earthquake-released strains. *Tectonics*, **12**, 1–20.
   Jackson, Haines & Holt (1992) Determination of the horizontal velocity field in the deforming Aegean Sea region from the moment tensors of earthquakes. *J. geophys. Res.*, **97**, 17,657–84.
   England, P. & Molnar, P. (1997) The field of crustal velocity in Asia calculated from Quaternary rates of slip on faults. *Geophys. J. Int.*, **130**, 551–582.
   — These all discuss no-length-change directions and rotations. Holt & Haines is the most important, but perhaps the toughest to understand. Pages 17,657–60 and the discussion of Jackson et al (1992) provides useful background: the rest of it doesn't matter.

3. • **Bourne, S., England, P. & Parsons, B. (1998)** The motion of crustal blocks driven by flow of the lower lithosphere and implications for slip rates of continental strike-slip faults. *Nature*, **391**, 655–659.
   Bourne et al., (1998) Crustal deformation of the Marlborough fault zone in the South Island of New Zealand: geodetic constraints over the interval 1982–1994. *J. geophys. Res.*, **103**, 30,147–30,165.
   — the Nature paper confidently asserts the answer: but is it right?

4. **McKenzie, D. & Jackson, J. (1983)** The relationship between strain rates, crustal thickening, paleomagnetism, finite strain and fault movements within a deforming zone. *Earth Planet. Sci. Lett.*, **65**, 182–202, and correction *ibid.*, **70**, 444, (1984).
   Lamb, S.H. (1987) A model for tectonic rotations about a vertical axis. *Earth Planet. Sci. Lett.*, **84**, 75.
   — two thoroughly nasty and complicated papers which no-one understood (look at them to see why). But they were early attempts to understand all this. For heroes and fanatics.

5. **McKenzie, D. & Jackson, J. (1986)** A block model of distributed deformation by faulting. *J. Geol. Soc. Lond.*, **143**, 349–353.

— short-'n-easy and simple, for beginners: written because no-one understood this part of McKenzie & Jackson 1983 (or any other part). The data have now improved, but the fundamental arguments haven't changed.

6. • **Molnar, P. & Gipson, J.M. (1994)** Very long baseline interferometry and active rotations of crustal blocks in the Western Transverse Ranges, California. *Bull. geol. Soc. Am.*, **106**, 594–606.
   England, P. & Wells, R. (1991) Neogene rotations and quasicontinuous deformation of the Pacific Northwest continental margin. *Geology*, **19**, 978–981.
   — both confidently assert that the upper crust responds passively to the flow beneath, on the basis of finite (large amplitude) block rotations. But are the arguments watertight?

7. • **Jackson, J.A. (1999)** Fault death: a perspective from actively deforming regions. *J. Struct. Geol.*, **21**, 1003–1010.
   — a discussion of the evidence that faulting changes with time and its significance, especially where rotations about a vertical axis are important.