Aspects of 'strike-slip' or wrench tectonics – an introductory discussion

A. G. MILNES

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Some basic principles of strain analysis are discussed in relation to the interpretation of structural patterns in map view. 'Strike-slip' or wrench tectonic regimes show more complex patterns than extensional or contractional regimes because of two effects. The 'rotation effect' is well known – the progressive development and rotation of structures due to rotational strain, as illustrated using the simple shear model in many reviews and textbooks. Extensional and contractional structural patterns develop mainly under irrotational strain conditions. The 'strain path effect' is less generally recognized – in contrast to extensional or contractional tectonics, wrench tectonic regimes imply an approximately constant-area strain path in map view, along which the Y (short) axis of the strain ellipse shortens at the same time as the X (long) axis increases in length. The effect can best be understood with reference to the Ramsay (1967) 2D strain field diagram. Since irrotational constant-area strain regimes and rotational regimes with increasing or decreasing area (transtension, transpression) also exist, the interpretation of map patterns in terms of tectonic regime requires a good knowledge of the basic rules of strain analysis.

A. G. Milnes, Geologisk Institutt, Universitetet i Bergen, Allégate 41, N-5007 Bergen, Norway.

Introduction

The theme of the 1993 meeting of the Tectonics and Structural Geology Study group of the Norwegian Geological Society was 'strike-slip tectonics'. Although the scope of this theme is immediately obvious to any structural geologist, I feel that there are certain fundamental aspects which are often overlooked, sometimes leading to an unnecessary lack of clarity. In this context, the title itself is the first problem. 'Strike-slip' is a term which was originally applied to a single structure, i.e. a fault plane on which slip was parallel to the strike (cf. Sylvester 1984). In contrast, 'tectonics' in common usage means the study or association of a whole spectrum of structures of many different types, orientations and scales, viewed as the expression of large-scale differential movement of parts of the Earth's crust. In the case of 'strike-slip tectonics', this differential movement on a regional scale is lateral as opposed to orthogonal (Fig. 1). Such movement produces arrays of strike-slip faults, often in various orientations, but also numerous dip-slip and oblique-slip faults, both normal and reverse, and many other structures (see below). Conversely, strike-slip faults are common features in both extensional and contractional tectonic regimes. Hence, I prefer to reserve 'strike-slip' for a specific kinematic description of a single structure and to use a different term for the overall tectonic regime. In this article, I will refer to the tectonic regime in question as *wrench tectonics* (cf. Hobbs et al. 1976; Sylvester 1984; Mount & Suppe 1987) and apply that term to characteristic associations of structures on a regional scale. These structural associations are very different from those found in extensional and contractional tectonic regimes, and, as we shall see, this difference is much more fundamental than the presence or absence of strike-slip faults.

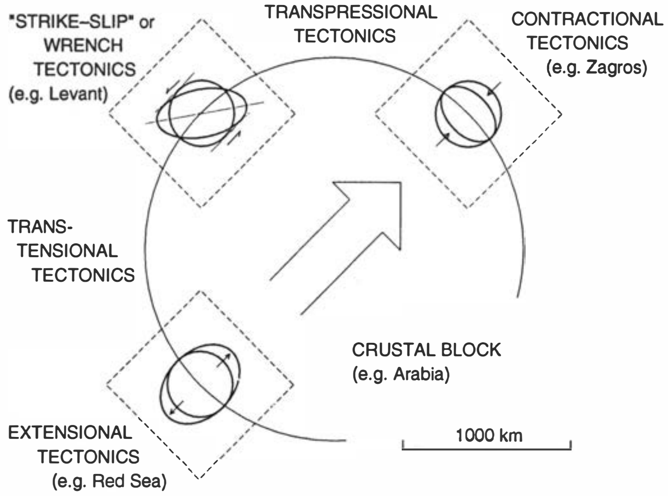

Fig. 1. Illustration of the strain conditions to be expected in the three 'end member' tectonic regimes around the borders of a circular crustal block, which is in movement relative to its surroundings. The strain ellipses show the size, shape and orientation of the regional 2D strain in a horizontal plane at the different positions (cf. Fig. 3). 'Strike-slip' or wrench tectonics develops in areas of mainly lateral movements between crustal blocks, whereas extensional and contractional tectonics reflects dominantly orthogonal movements. In Nature, of course, many intermediate regimes exist, as discussed in detail in Fossen et al. (this volume).

Wrench tectonics in map view

The following discussion is based on the structural patterns produced by wrench tectonics in map view. In this respect, the most immediately obvious difference between wrench and extensional/contractional tectonics (in map view, removing topographic effects) is the higher complexity of the former, with its irregular associations of folds and faults (normal, strike-slip and thrusts in different orientations and positions), uplifts and basins, duplexes and detachments (e.g. Sanderson & Marchini 1984; Christie-Blick & Biddle 1985; Woodcock & Fischer 1986; Sylvester 1988; Twiss & Moores 1992). This complexity is due to two effects which are best discussed in relation to the regional 2D strain of the crust in a horizontal plane at the Earth's surface (Fig. 1). The first of these effects is the *rotation effect*, since wrench tectonics develops in a regional rotational strain regime, in which the stress (infinitesimal strain) axes and the (finite) strain axes do not coincide. This is in contrast to extensional and contractional tectonics which, in map view, are often characterized by irrotational strain. The second effect can be called the *strain path effect*. Wrench tectonic regimes develop along a strain path which is characterized by simultaneous extension (parallel to the X or long axis of the strain ellipse) and contraction (parallel to the Y or short strain axis) in the horizontal plane. This is in contrast to extensional and contractional tectonics which develop along strain paths characterized by one strain axis (Y in extensional regimes, X in contractional regimes) remaining approximately constant throughout the deformation. Some general aspects of these two effects are discussed below.

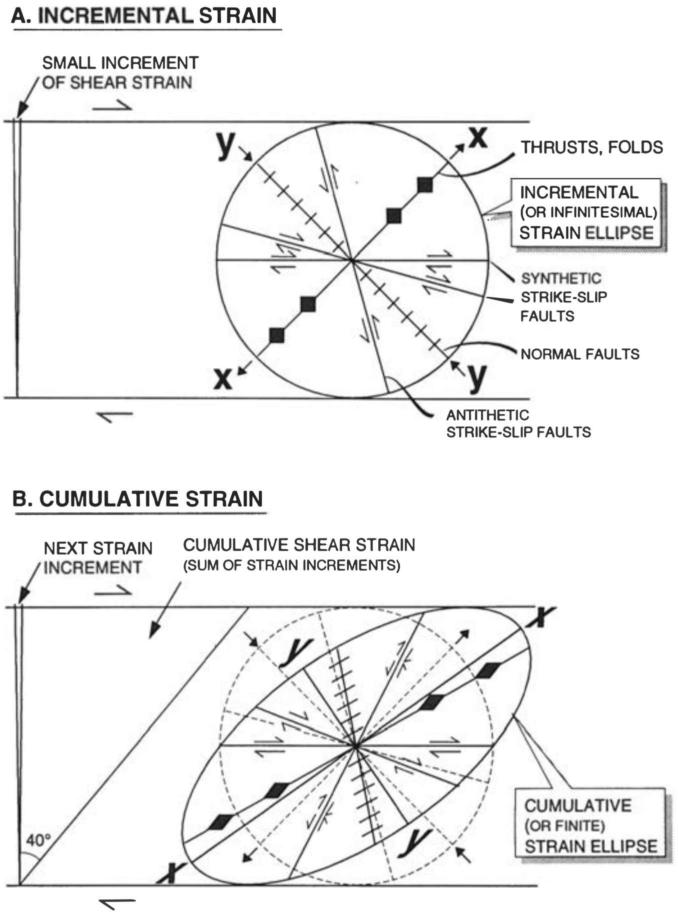

Fig. 2. Diagram to illustrate the complexities of rotational strain, showing (a) the large-scale structures expected to be initiated by a small increment of regional shear strain (equivalent to a shear angle of 1°), using a simple shear ('card deck') model, and (b) the same model after a large number of strain increments (equivalent to a shear angle to 40°). In (b), the complexities are compounded due to the rotation of earlier formed structures (for instance, from their original orientations in (a)), their locking or reactivaiton with different kinematics, and the formation of new structures related to the current incremental strain ellipse.

Rotation effect

The rotation effect is illustrated in many textbooks and review articles with reference to the classical simple shear strain model (e.g. Christie-Black & Biddle 1985, fig. 5; Sylvester 1988, fig. 12; Park 1989, fig. 9.13; Hatcher 1990, figs. 12–5). These show how strike-slip, thrust/reverse and normal faults, and folds would be expected to be arranged in map view in a regional simple shear regime, in relation to the strain ellipse. What is often left unstated, however, is that this diagram relates to a small strain increment. The ellipse drawn is not the true shape of the strain ellipse produced by that small increment of strain (which would be indistinguishable from the original circle – Fig. 2a) but merely a diagrammatic representation showing the orientation of the incremental strain axes (X and Y both at 45° to the shear direction). According to the well-known geometry of simple shear (e.g. Ramsay 1967), structures initiated during the first strain increment rotate during subsequent increments, and new structures with the initial orientation can develop at any time in the subsequent progressive deformation, whilst the cumulative (or finite) strain ellipse slowly increases in axial ratio and successively rotates. Already using the axial ratios of the ellipses shown in the classical diagrams would imply that the initially formed structures had rotated considerably from the orientations shown (Fig. 2b). In fact, maps of wrench tectonic regimes generally look less complicated than the geometry of progressive simple shear would imply. This is partly due to the physical constraints, which dictate that once a structure is generated, e.g. a synthetic strike-slip fault, it tends to continue as an active discontinuity as long as it has an orientation favourable for taking up subsequent strain increments. Only after it has rotated into an unfavourable orientation, and become locked, do conditions favour the development of a new fault in the initial orientation. Even this short summary suffices to illustrate the complexities which are to be expected in any rotational deformation, and the complicated map patterns which develop in any region of long-continued wrench tectonics (San Andreas, e.g. Twiss & Moores 1992; May et al. 1993; Dead Sea, e.g. Ron et al. 1990).

The fact that wrench tectonics results in complicated structural patterns which can be analysed in terms of progressive rotational strain using a well-established experimental, theoretical and observational basis, is hardly a new idea. The corollary of it – that the structural patterns in map view resulting from extensional or contractional tectonics (both examples of regional irrotational strain, see Fig. 1) are correspondingly simple – is, however, rarely pointed out. This can be demonstrated most clearly by considering the expected distribution of, for instance, strike-slip faults within the different tectonic regimes. In a wrench tectonic situation, strike-slip faults, both synthetic and antithetic with respect to the overall sense of shear (e.g. Riedel shears), are expected in different orientations, often interacting in complex ways in the course of long-continued movements (Fig. 2b). Many of these faults will not be parallel to the shear direction of the whole regime. In extensional and contractional situations, i.e. basically irrotational tectonic regimes, strike-slip faults mainly form parallel to the extension/contraction direction (as transform faults, lateral ramps, etc.). They do not suffer external rotation and they do not intersect each other in the course of even long-continued deformation. The classical example is the system of transform faults associated with oceanic spreading ridges, but the same principle applies to continental extension or foreland thrust-and-fold belts (e.g. 'tear faults' in the Canadian Rockies, Davis 1984, figs. 9.33 and 9.34). However, this effect is not only due to the mainly irrotational nature of the large-scale strain, but also to the typical strain path taken by these regimes. This is the topic of the next section.

Strain path effect

One of Ramsay's many significant contributions to structural geology in his classical textbook (Ramsay 1967) was to leave behind the limited 'pure shear/simple shear' way of discussing *2D* strain. He pointed out that discussing *3D* strain in terms of *constant volume* was in many geological situations meaningful and a good approximation to nature. However, he emphasized that discussing *2D* strain in terms of *constant area*, as had been done up until then, was not only an unnecessary strait-jacket but could be positively misleading. To remedy the situation, he introduced his 'strain field diagram (Ramsay 1967, figs. 3–34 and 3–54), on which the strain path of *any* homogeneous 2D deformation can be plotted. Ramsay applied it to the interpretation of complex fold and boudinage patterns in competent layers (see also Ramsay & Huber 1983, figs. 4.10 and 4.11), and it has later been applied to the interpretation of other types of structural association (e.g. Davis 1984, figs. 4.50, 9.25, 10.31), but in general its use has not caught on. I feel that this is unfortunate, because I suspect that a more general appreciation of its implications could clarify many a tectonic discussion. The question of tectonic regimes is a case in point.

Figure 3 shows the Ramsay strain field diagram as it may be applied to regional 2D strains at the Earth's surface. One must imagine a large circle inscribed on the Earth's crust at some position, and the possible ways that the circle can change in the course of subsequent crustal movements, assuming roughly homogeneous deformation at the scale chosen (cf. Fig. 1). On the Ramsay diagram, the initial circle plots at a point which has the coordinates (1,1), and as deformation proceeds the successive points move away from this position along a line representing a succession of ellipses with steadily

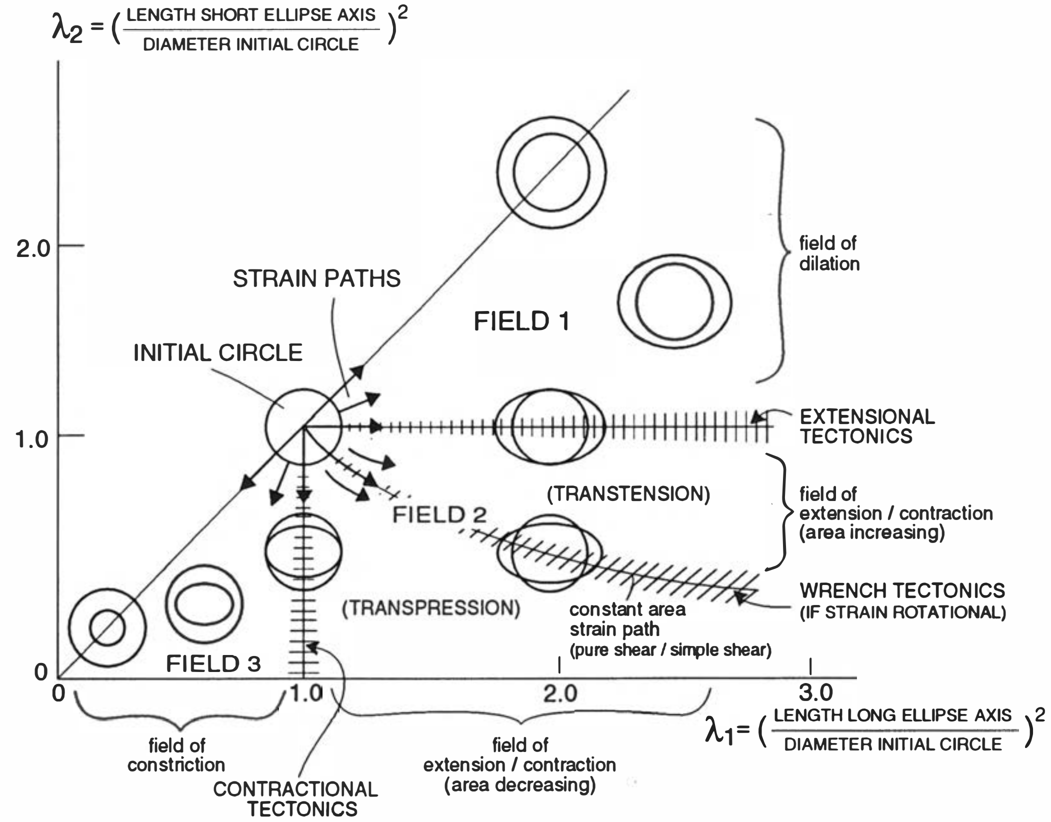

Fig. 3. Application of Ramsay's strain field diagram (Ramsay 1967) to the characterization of tectonic regimes.

increasing axial ratio, the *strain path*. If both the strain ellipse axes become progressively longer than the radius of the initial circle, the strain path moves into Ramsay's strain field 1 (dilational field, Fig. 3), if both become shorter, the strain path moves into Ramsay's strain field 3 (constrictional field, Fig. 3), and if one axis becomes shorter whilst the other becomes longer, the strain path moves into Ramsay's strain field 2 (combined extension/contraction field, Fig. 3). Amongst all these possible strain paths, only one line marks the path of constant area ellipses (pure shear/simple shear strain path, Fig. 3): all strain paths below this line show a progressively decreasing area of the strain ellipses in the course of deformation, all strain paths above show a progressively increasing area. Referring to Fig. 1, it is clear that 'strike-slip' or wrench tectonics, develops roughly along the constant area line in strain field 2. The strain paths of extensional tectonic regimes roughly follow the line separating fields 1 and 2 (Y axis retains the same length as the original circle), and those of contractional tectonic regimes the line separating fields 2 and 3 (X axis retains the same length as the original circle). The intermediate types of tectonic regime, labelled on Fig. 1 as transtensional and transpressional, lie in field 2 in the corresponding sub-fields (Fig. 3). These intermediate strain paths, which represent the general case in Nature, are treated mathematically in the definitive article by Fossen et al. (this volume).[1] Crustal movements which would follow a strain path in field 1 are well known (triple junctions) – and those following a strain path into field 3 must be assumed to have existed, although I would be hard put to give an example!

I feel that applying the Ramsay strain field diagram to large-scale tectonics in this way helps to clarify terminology and to avoid misinterpretation. With regard to wrench tectonics, it shows that rotation is only one of the factors contributing to the complexity of the structural patterns; the other is that the strain path lies in strain field 2, in which shortening takes place in one direction at the same time as lengthening takes place at right angles to it. In extensional and contractional tectonics, this is not the case. A structural map of, for instance, the Viking graben shows an interlacing network of normal and oblique–normal faults related to E–W extension (e.g. Speksnijder 1987); there was insignificant strain in a N–S direction. The area of the crust increased (and the crustal thickness correspondingly decreased). Similarly, and conversely, in the Rocky Mountains thrust-and-fold belt, for instance, the area in map view decreased during deformation (with corresponding crustal thickening), and there was negligible strain parallel to the fold belt (if this were not so, the reliability of balanced cross-sections could be seriously questioned).

The strain path of 'strike-slip' or wrench tectonics in map view, then, roughly follows the line of constant area in the strain field diagram (Fig. 3). Shortening in one direction is taking place at the same time as lengthening at right angles to it and the structural pattern is correspondingly complex. This would be true *also without rotation* – the Ramsay strain field diagram does *not* distinguish between rotational and irrotational strain paths. This means that the existence of a complex structural pattern in a region, including, for instance, conjugate strike-slip fault systems, folded, thrust and uplifted segments, and normal faults and pull-apart basins, does not *a priori* prove that it developed in a wrench regime. The strike-slip faults in the Jura fold-and-thrust belt (see Twiss & Moores 1992, fig. 7.11) are oblique to the movement direction and imply that lengthening parallel to the chain took place coeval with shortening at right angles to it. The regional strain path lies within field 2, but the strain was irrotational (due to progressive thrust-belt arcuation; see also Oldow et al. 1993). This is a 'pure shear' situation and is therefore *not* an example of wrench tectonics.

Conclusions

The main conclusion from the above discussion is that care must be taken when discussing and interpreting structural patterns in terms of wrench tectonics. Complex patterns of the types discussed are suggestive, and sufficient to render them distinguishable from those produced by extensional or contractional tectonics, but the rotational component needs detailed argumentation. To understand the pattern and to interpret it in terms of the geometry and kinematics of regional strain and crustal movement, requires a good knowledge of the basic rules of strain analysis. This means that if an ellipse is used to illustrate the interpretation, answers to the following questions should be clear: (1) Is the ellipse intended as a good representation of the shape of the cumulative (finite) strain ellipse, or only as a schematic ellipse to illustrate the orientation of the infinitesimal strain (or stress) axes? (2) If the ellipse represents the cumulative (finite) strain, where does its strain path lie on the Ramsay strain field diagram (in other words, what was the relative size of the initial circle)? (3) If the regional strain ellipse lies in strain field 2, close to the strain path of constant area, what evidence can be adduced that it was rotational (proving the existence of a 'strike-slip' or wrench regime), and how can the shear direction and sense of shear be deduced?

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[1] 'Wrench tectonics' as discussed in this article implies, strictly speaking, a simple shear strain path. However, I think the term could be extended to cover what Fossen et al. (this volume) define as 'wrench-dominated transpression' and 'wrench-dominated transtension', in a general way.

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