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Tectonic significance of fault-slip data

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Abstract

The statistical analysis of populations of minor faults is commonly used by structural geologists working in areas of brittle rock. It is based on measurements of fault attitude, direction and sense of slip. At individual sampling localities, results are classically interpreted as indicators of stress or strain rate fields, assuming a homogeneous stress or strain rate tensor, respectively. However, fault patterns are expected to vary with time because of displacements, rigid rotations, and internal strains, which generally occur along boundaries of fault-bounded blocks as deformation proceeds. Thus, in the general situation where early faults accumulate displacements and rigid rotations, and where new faults develop during progressive deformation, fault-slip data can be rather complex and variable in space, and reflect neither local stress or strain rate tensors, nor finite strains and finite rotations in a simple way.

We use two examples of faulted regions to illustrate the spatial variability of fault-slip data. This can be due to local complications at the edges of fault blocks, or to complex kinematic conditions at regional boundaries. Such complications may make it difficult to deduce a consistent and simple pattern of either stresses or strain rates. Instead, our results suggest that information contained in fault-slip data can be pertinent to finite deformation. In particular, the principal axes that we have deduced from the analysis of fault-slip data are consistent with the finite displacements at block boundaries that we have calculated by numerical restoration. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Over the last years there has been an ongoing debate, as to whether fault patterns and fault-slip data should be interpreted in terms of mechanics or kinematics (Gephart and Forsyth, 1984; Michael, 1984; Reches, 1987; Marrett and Allmendinger, 1990, 1991; Twiss et al., 1991; Cladouhos and Allmendinger, 1993; Pollard et al., 1993; Taboada, 1993; Angelier, 1994). Following an exhaustive and critical analysis, Twiss and Unruh (1998) have recently argued that kinematic interpretations are in general more reliable than mechanical ones.

In this paper, we take a similar view, and further discuss to what extent fault-slip data can record finite rotations and strains, and reflect regional strain fields. First, we discuss the various ways of interpreting fault-slip data. Then, we consider two deformed regions, where we have acquired (1) fault-slip data, by measurements on minor faults, (2) rotations about vertical axes, by paleomagnetic methods, and (3) displacement fields, by numerical restoration of offsets on major faults. We find that the fault-slip data are not accounted for by a uniform tensor field. Instead, they form a spatially heterogeneous pattern, which is strongly influenced by relative rotations between fault blocks. Principal axes, as deduced from the analysis of fault-slip data, are consistent with finite displacements at block boundaries, as calculated from the restoration. This conclusion may have considerable implications for fault-slip analyses in other deformed areas.

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2. Methods of analysis

It is generally accepted that the attitudes of newly created faults are determined by the local stress field, and are reasonably well predicted by the Mohr–Coulomb criterion (see Jaeger and Cook, 1979). For a population of existing faults, only those with favourable orientations can be reactivated by an applied stress field. On this basis, various works have developed methods for inferring principal stresses, by statistical analysis of fault attitudes and their associated directions and senses of slip (Carey and Brunier, 1974; Angelier and Mechler, 1979; Etchecopar et al., 1981; Angelier et al., 1982; Armijo et al., 1982; Gephart and Forsyth, 1984; Michael, 1984; Reches, 1987; Taboada, 1993; Angelier, 1994). Central to these methods are two assumptions: (1) the bulk state of stress is uniform, and (2) the slip direction is parallel to the maximum resolved shear stress on each fault plane.

A second set of methods has been developed, which is based on equivalent, but kinematic assumptions: (1) the bulk strain rate tensor is homogeneous, and (2) the slip direction is parallel to the maximum resolved shear rate on each fault plane (Marrett and Allmendinger, 1990, 1991; Twiss et al., 1991). These methods yield principal directions of strain rate.

Recently, Twiss and Unruh (1998) have reviewed the various methods and assumptions emphasizing an obvious point: by definition, fault-slip data provide direct information on kinematics, slickenlines being direct indicators of displacement directions on fault planes. For stresses to be obtained from fault-slip data, additional assumptions and inferences are therefore necessary. Of major importance is the relationship between stress and strain rate, expressed via the coaxiality and the relative shapes of their respective ellipsoids (see also Taboada, 1993). Twiss and Unruh (1998) have concluded that natural fault-slip data are more readily used as strain rate indicators than as stress indicators.

The strain rate hypothesis requires that displacements on individual faults are small enough so that their integration at the scale of the sampled population can represent an increment in the global deformation (Twiss and Unruh, 1998). On the other hand, whether the method of analysis is mechanical or kinematic, it will be reliable only if faults are numerous and if the directions and senses of slip are unambiguous. In practice, this often restricts the acquisition of data to substantially deformed zones.

3. Fault-slip data and finite deformations

During deformation, faults must accommodate displacements imposed via the external boundaries of the system. Consequently, they accumulate slip and may rotate, together with the intervening blocks. The rotations may alter the initial relationship between fault attitudes and the regional stress field or strain rate field (see Kissel and Laj, 1989 and references therein).

Another problem is that the direction and sense of slip on a fault are measurable, only if the displacement is finite. Crystal fibres on slip planes record successive infinitesimal displacements, and their overall lengths and orientations are direct indicators of finite displacements (Ramsay and Huber, 1983). Their use to infer principal strain rates is thus questionable.

In fact, the relationship between the size of sampled faults and that of the sampling site appears critical in determining the significance of fault-slip data. For a given fault pattern, to distinguish contributions of stress or strain rate controlled features from strain induced geometries may not be easy.

Even at small bulk strains, natural and experimental fault patterns are not controlled by the stress field alone. For example, fault patterns created during simple shearing, including Riedel faults (Riedel, 1929), are strongly asymmetric (Tchalenko, 1970); whereas patterns predicted by a single state of stress must be symmetric, irrespective of imposed boundary conditions. In plane-strain experiments, conjugate fault sets are present in different proportions, depending on the degree of non-coaxiality. The sets are equally represented for pure shear; unequally, for combinations of pure shear and simple shear (Hoeppener et al. 1969; Gapais et al. 1991). That the degree of symmetry of fault patterns often differs from orthorhombic is an argument for a kinematic control, rather than a mechanical one (Gapais et al., 1991; Twiss and Unruh, 1998). For triaxial strain fields, kinematic analyses have further shown that more than two independent fault sets are required to accommodate strains (Oertel, 1965; Reches, 1978, 1983), and this is generally found in natural and experimental fault arrays (Aydin and Reches, 1982; Reches and Dieterich, 1983).

Reorientation of faults with bulk strain has been much studied, especially where faults form domains of bookshelf or domino type (McKenzie and Jackson, 1983; Garfunkel and Ron, 1985; Nur et al., 1986; Mandl, 1987; Gapais et al., 1991). More complex fault patterns may be envisaged as combinations of several slip systems. If there are contiguous bookshelf domains, each containing a single set of faults, then these are expected to track the surfaces of no finite extension of the strain ellipsoid (Cobbold and Gapais, 1986; Gapais and Cobbold, 1987). For sandpacks, deformed in plane strain with a component of bulk simple shear, faults do show this tendency (Gapais et al., 1991).

There are other lines of evidence for a close relationship between fault-slip data and bulk strain. When

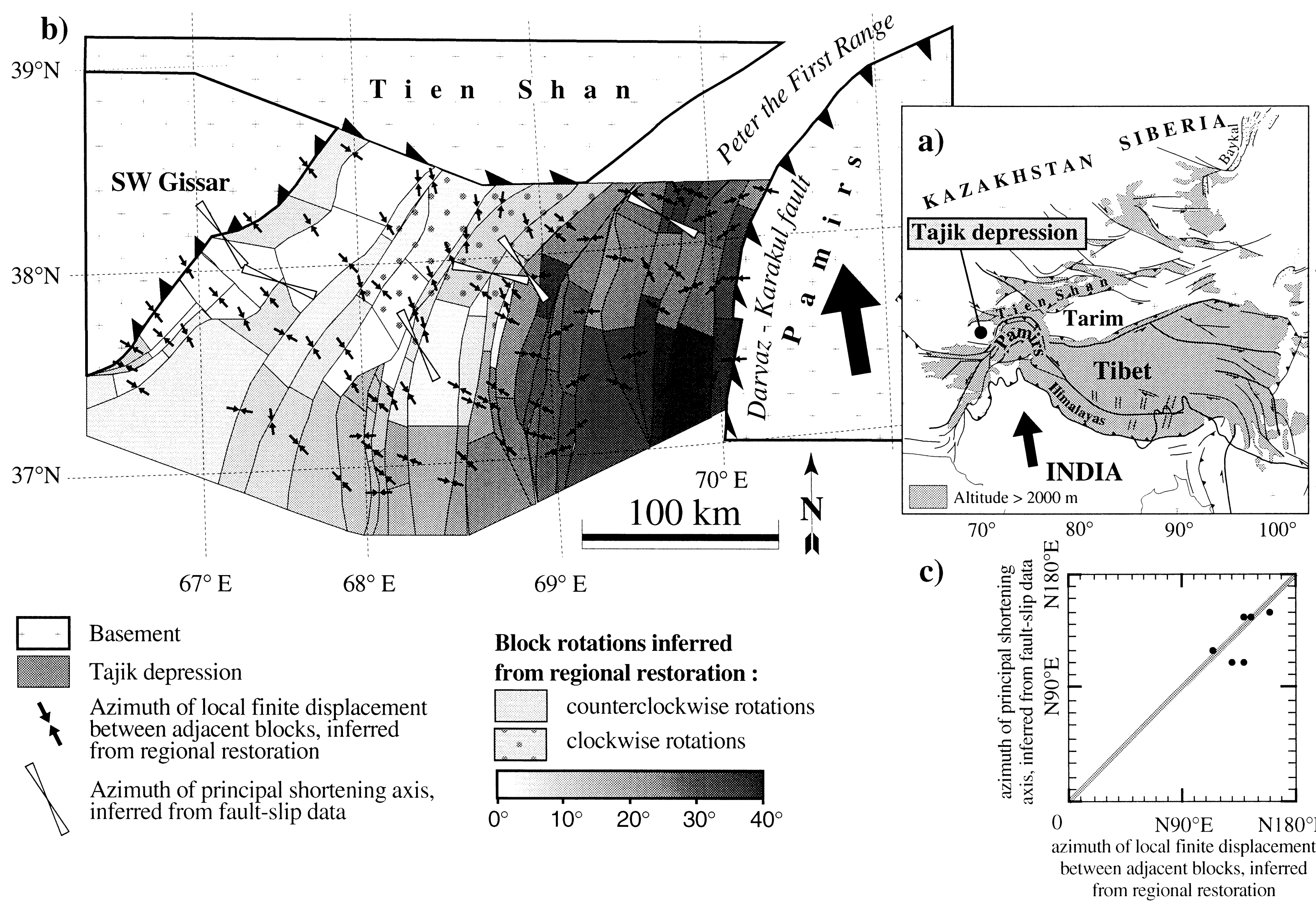

Fig. 1. Tectonics of the Tadjik depression (central Asia) (after Thomas et al., 1994, and Bourgeois et al., 1997, modified). (a) Location of the Tadjik depression with respect to the India–Asia collision. (b) Kinematic data and results from numerical restoration; the depression is filled by synkinematic tertiary sediments, and is bounded to the east, north and west by major thrust–wrench zones uplifting basement blocks. Within the depression, the mosaic of individual fault-bounded blocks used for restoration was determined according to structural data. (c) Relationships between local principal shortening directions deduced from fault-slip data and principal shortening directions calculated from restoration at neighbouring sites. The straight line with a slope of 1 drawn on the diagram underlines that some consistency exists between the two data sets. Complete information on fault-slip data sets and kinematic analysis can be found in Thomas (1994) and Thomas et al. (1996b).

natural fault-slip data are processed by graphical methods, like that of right-dihedra, the fields of shortening and extension are separated by surfaces which bear a simple relationship to the strain ellipsoid. These surfaces are (1) cones centred about the shortening direction for pancake-shaped ellipsoids, due to flattening, (2) cones centred about the stretching direction for cigar-shaped ellipsoids, due to constriction, or (3) two conjugate planes, intersecting about the intermediate strain axis, for plane strain (Pfiffner and Burkhard, 1987). Similar relationships have been observed for preferred orientations of other kinds of slip systems, such as intracrystalline ones (Pfiffner and Burkhard, 1987; Gapais and Cobbold, 1987) or semi-brittle faults and shear zones (Gapais et al. 1987; Cobbold et al., 1991). Sandpacks deformed in simple shear (Gapais et al., 1991) further confirm that fault-slip data can be used to infer principal strain directions.

Quantitative estimates of strains from fault-slip data would require knowing the amounts of slip and weighting the faults accordingly (Krantz, 1988; Marrett and Allmendinger, 1990, 1991; Cladouhos and Allmendinger, 1993). In practice, the amounts of slip are seldom available. Accordingly, available graphical methods used to analyse fault-slip data involve superposition of separate right dihedra, one for each fault (Angelier and Mechler, 1979). The methods therefore have two main weaknesses. First, all faults have the same weight. Second, the dihedra represent fields of infinitesimal shortening and stretching. Thus, the most that can be inferred are the principal directions and perhaps the shape of the strain ellipsoid (e.g. Cobbold et al., 1991).

Even more important limitations on the interpretation of fault-slip data result from the successive appearance of faults throughout a deformation history. Pre-existing faults suffer the entire deformation history, whereas syntectonic faults may appear at any time during progressive deformation. In practice, measured fault populations are therefore generally heterogeneous.

Despite these strong constraints, the graphical methods can provide information which is consistent with strain and rotation patterns at regional scale, as illustrated below.

4. Fault patterns in the Tadjik depression, Central Asia

In Central Asia, Tertiary basins of compressional style have been attributed to collision of India with Asia. One of them is the Tadjik depression, between the Pamir mountains to the east, the West-Gissar Range to the west and the Tien Shan–Gissar Range to the north (Fig. 1). A structural and paleomagnetic study within the Tadjik depression yielded the following results (Thomas et al., 1994, 1996a).

1. The basin contains continental clastic sediments, which were deposited coevally with Tertiary deformation.
2. The basin is lozenge-shaped, because it is bounded by major zones of thrusting and wrenching.
3. Within the basin is a series of foldbelts, containing thrust faults and wrench faults. These structures strike approximately N–S and they have resulted from overriding of the Pamirs toward the north.
4. Thrust sheets have undergone substantial counterclockwise rotations about vertical axes. Magnitudes range from 25° in the west, to 50° in the east.

Fault-slip data have been collected along major fault zones within the depression (Thomas et al. 1996b). From these, principal axes have been computed using the right-dihedra method at six sampling sites (program FaultKin of Allmendinger et al., 1994). A complete description of data can be found in Thomas (1994) and Thomas et al. (1996b). At each sampling site, the ratio between the number of kinematically compatible faults and the total number of faults measured is never less than 80%, and the principal shortening direction is subhorizontal or gently plunging (less than 25°) (Thomas et al. 1996b) (Fig. 1b).

Offsets on major faults, as reconstructed from subsurface data, were used to restore the area numerically in map view (Bourgeois et al., 1997). The method, which is purely geometric, is described in detail by Rouby et al. (1993) and Bourgeois et al. (1997). The deformed area was first represented as a mosaic of rigid blocks, bounded by major faults. Then, the overlaps between the blocks, representing fault heaves, were minimized by successive iterations, involving translations and rotations of the blocks. This leads to an undeformed mosaic of fault blocks, which can be compared with the original deformed mosaic, yielding fields of finite displacement and rotation. For the Tadjik depression, restoration has yielded large amounts of bulk contraction, ranging from 35% in the central part to 85% in the northeastern part (Bourgeois et al., 1997). The block rotations inferred from the restoration are consistent with those determined paleomagnetically (Thomas et al., 1994). Because there is little strike-slip between neighbouring blocks and because we assume that the blocks were rigid, the azimuths of finite displacements between adjacent blocks (Fig. 1b) provide estimates of principal shortening directions in fault zones.

For the few sampling sites that we have, there is good consistency between the shortening directions obtained from sampling sites and those obtained from restoration at neighbouring sites (Fig. 1c).

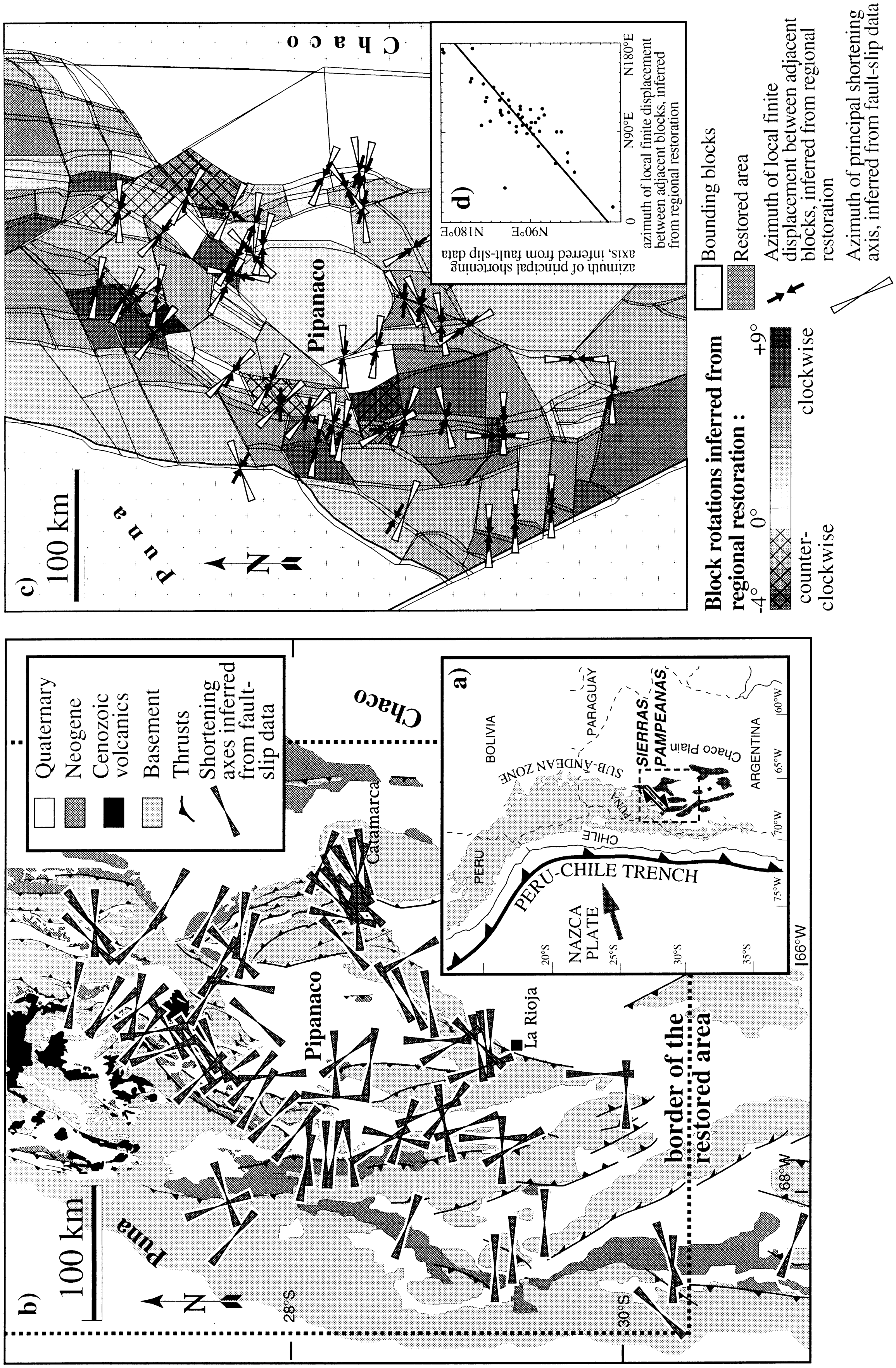

Fig. 2. Tectonics of the Sierras Pampeanas (NW Argentina) (after Urreiztieta, 1996 and Urreiztieta et al. 1996, modified). (a) General tectonic context of the area; light grey area is the Altiplano–Puna (average altitudes above 3000 m); dark grey zones are basement ranges in the Sierras Pampeanas. (b) Schematic geological setting and structural data in the Sierras Pampeanas. (c) Results of numerical restoration of the region; the mosaic of individual fault-bounded blocks used for restoration was determined according to structural data. (d) Relationships between local principal shortening directions deduced from fault-slip data and principal shortening directions calculated from restoration at neighbouring sites; the straight line shown on diagram is calculated from linear regression. It has an ordinate at origin of 11.99°, a slope of 0.86, and a correlation coefficient of 0.78. Complete information on fault-slip data sets and kinematic analysis can be found in Urreiztieta (1996).

5. Fault patterns in the Sierras Pampeanas, northwestern Argentina

The Central Andes culminate in a high plateau, the Altiplano–Puna. The altitudes are due to crustal thickening and magmatism, following convergence between South America and the oceanic Nazca plate. In northwestern Argentina, at the southern end of the high plateau, structures are complex (Fig. 2a, b). They appear to be due to three interfering processes (Urreiztieta, 1996; Urreiztieta et al., 1996): (1) regional shortening, due to plate convergence in a direction E–W to WSW–ENE; (2) dextral strike-slip along a zone striking NE–SW, which accommodates a jump in crustal thickening between the Puna and the adjacent Sierras Pampeanas; and (3) shortening in a NW–SE direction, attributed to lateral spreading of the Altiplano–Puna (Assumpção and Araujo, 1993). In the Sierras Pampeanas (Fig. 2a), this tectonic context has lasted since at least early Pliocene times. Resulting basement ranges alternate with compressional basins, which contain synkinematic continental sediments (Allmendinger, 1986; Urreiztieta et al., 1996) (Fig. 2b). To the east of the Sierras Pampeanas is the Chaco Plain, the undeformed foreland of the Andes (Fig. 2a, b).

Fault-slip data have been collected by various authors at numerous sites throughout the Sierras Pampeanas (Allmendinger, 1986; Marrett et al., 1994; Urreiztieta, 1996; Urreiztieta et al., 1996). Results shown here (Fig. 2b) are from Urreiztieta (1996). For most sites studied, principal shortening directions are subhorizontal or moderately dipping, but with a substantial scatter in strike, between E–W and NW–SE (Fig. 2b). At some sampling sites, paleomagnetic analysis has revealed significant clockwise rotations about vertical axes (Aubry et al., 1996). These rotations are due to Tertiary tectonics. The scattering of shortening directions has been interpreted by Urreiztieta et al. (1996) as resulting from the complex kinematic setting, whereas Marrett et al. (1994) attributed it to successive deformations during the Tertiary.

Restoration in plan view of the offsets across major faults (Urreiztieta, 1996) has yielded (1) large variations in principal shortening directions, required to optimize the fit, and (2) block rotations which are dominantly clockwise, as recorded by paleomagnetic data (Aubry et al., 1996). As for the Tadjik depression, there is little strike-slip between fault blocks, which we assume to be rigid. The azimuths of finite displacements between adjacent blocks (Fig. 2c) can thus be taken as estimates of principal shortening directions in fault zones. Forty-nine sites of measurement of fault-slip data have been selected and compared with results of restoration (Fig. 2c). Sites selected are those where (1) the plunge of the principal shortening direction is less than 20°, and (2) all faults measured are kinematically compatible (Urreiztieta, 1996). Principal directions deduced from fault-slip data compare well with those calculated by restoration at neighbouring sites (Fig. 2c, d). Linear regression between the two sets of data yields an ordinate at the origin of 11.99, a slope of 0.86, and a correlation coefficient of 0.78 (Fig. 2d). Furthermore, when the intercept at the origin is fixed to 0, the slope of the best-fit line becomes 0.97, with a correlation coefficient of 0.77.

6. Concluding remarks

In general, the restoration method used here provides estimates of strains and displacements at various scales, from that of adjacent blocks, to that of an entire region (Bourgeois et al., 1997). In the Tadjik depression, the fault network is of domino-type. The overall block rotations and associated strains are large, and results of restoration are consistent with measured fault-slip data. In the Sierras Pampeanas, the restored strain field and the fault-slip data are also internally consistent, despite the rather complex boundary conditions and the moderate amount of bulk strain.

From the consistency between the fault-slip data and the restoration, we infer that the fault patterns reflect local deformations. Indeed, the regional variations of principal directions calculated from the restoration result directly from jumps in finite rigid rotations between neighbouring blocks.

Fault-slip data should, to some extent, reflect local stress fields; but to be convincing, dynamic interpretations should verify that stresses are in equilibrium. Methods developed to analyse fault-slip data have extensively discussed internal compatibility and consistency of fault sets, especially at the scale of sampling sites (Carey-Gaillardis and Vergely, 1992; Dupin et al., 1993; Pollard et al., 1993; Yin and Ranalli, 1993; Twiss and Unruh, 1998); but, to our knowledge, no quantitative attempts have been made in a natural example to verify stress equilibrium at regional scale, so as to constrain the results of fault-slip analysis and better estimate the forces acting on the external boundaries.

Our results lead us to question the philosophy behind the collection and the statistical processing of fault-slip data. In particular, we wonder how variable may be the fields of stress or strain and how much this variation reflects local problems of block interference, rather than far-field stresses. Perhaps there is more advantage to be gained, from analysing fault-slip data at a limited number of well-chosen localities so as to constrain a restoration procedure, rather than from collecting extensive data sets at a maximum number of localities without checking compatibilities between sampling sites.

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