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Palaeostress and neotectonic analysis of sheared conglomerates: Southwest Alps and Southern Apennines

Jean-Claude Hippolyte*

Laboratoire de géodynamique des Chaînes Alpines (CNRS, UMR 5025), Université de Savoie, Campus Scientifique, 73376 Le Bourget du Lac Cedex, France

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Abstract

Geometrical and mechanical characteristics of the deformation of poorly cemented conglomerates are described. Using striated pebbles for analysis of palaeostresses, it is crucial to distinguish radial striation patterns, which result from deformation of the matrix around a rigid pebble, from unidirectional striation patterns that represent shear zones crossing the conglomeratic material. Examples of palaeostress determinations from striations of the latter type are given for extensional settings (Provence) and compressional settings (Southern Apennines, Southwest Alps). Their comparison with fault analyses in brittle rocks that underlie the conglomerates validates their usefulness for palaeostress analyses and suggests that some conglomerates behave as materials containing pre-existing surfaces of mechanical anisotropy that fail by sliding on some suitable oriented surfaces. These examples show that sheared conglomerates can be used for stratigraphic dating of the deformation, for studies of syndepositional deformation and for neotectonic analysis. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Brittle tectonic analysis of mesofractures and palaeostress determination permits the deciphering of the evolution of structures from outcrop to tectonic plate scale (cf. Hancock, 1985; Angelier, 1994; Dunne and Hancock, 1994). In particular, if one wants to precisely date the deformation by finding the most recent faulted rocks, or collect evidence of recent deformation, syntectonic deposits which are often clays, sands and conglomerates have to be studied. However, some difficulties may arise in carrying out fault analysis in these materials. The sandy material usually does not exhibit slip indicators along fault planes. The sense of slip on faults cutting clays and marls is often ambiguous if not indicated by stratigraphic offsets. In contrast, conglomerates often show well-preserved striations and sense indicators on pebble surfaces, and sometimes on fractures cutting the pebbles.

In deformed conglomerates, different structures will result from variations in the contrast between the mechanical properties of the pebbles with those of the matrix. Faults cutting pebbles and matrix indicate a brittle behaviour of the whole material and can clearly be used in palaeostress determination (e.g. Petit et al., 1985). In poorly cemented conglomerates, fractures cutting only the pebbles may result from intra-pebble amplification of the tectonic stresses (e.g. Eidelman and Reches, 1992). These tensile fractures are most common whenever the strain rate is high, the matrix is weak and the pebbles rigid (e.g. quartzitic) (McEwen, 1981). In compressional settings, these tensile fractures can form in pebbles at a depth of a few hundred metres or deeper and they indicate the trend of σ_1 (Eidelman and Reches, 1992). More frequently, the poorly cemented conglomerates are deformed by shear movements. In this case, the different value of the elastic moduli of the pebbles and of the matrix, together with the low strength of the pebble–matrix bond (McEwen, 1981), result in deformation which is mainly localized at the pebble–matrix boundary. The resulting striated outer surfaces of pebbles have often been used to determine palaeostress axes, considering them as similar to fault planes (e.g. Campredon et al., 1977; Petit et al., 1985; Combes, 1984; Fesce, 1986; Ritz, 1992). Furthermore, Schrader (1988) has shown that striation fields made by the sandy matrix around a rigid pebble can be used in deformation analysis. This paper presents examples showing that some striation patterns can be good tectonic and neotectonic indicators, and can be used in palaeostress determination.

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* Fax: +33-4-79-75-87-77.

E-mail address: jean-claude.hippolyte@univ-savoie.fr (J.-C. Hippolyte).

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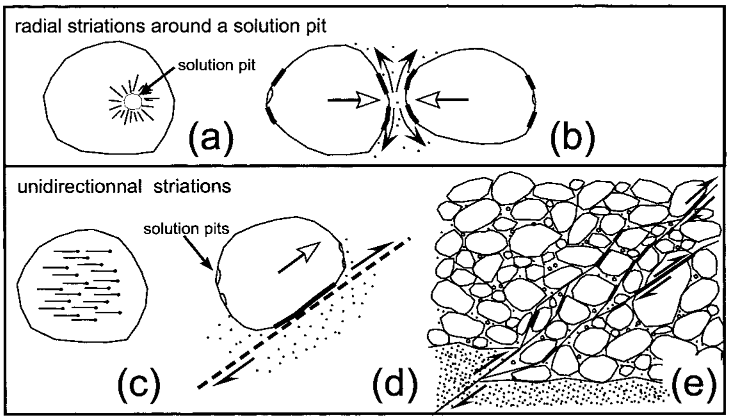


Fig. 1. Sketches of tectoglyphs observed on pebble surfaces and their origin. (a) Solution pits and short radial striations formed with pure shear to oblique strain symmetries (Schrader, 1988). (b) Movement in the sandy matrix is divergent around pebble indentations. (c) Parallel striations on a pebble surface formed during shearing of the conglomerate (also see Fig. 2a and f). (d) Discontinuity between a pebble and the matrix activated as a shear plane. (e) In the conglomerate, discontinuities are striated (dark), in particular along shear zones cutting the whole material.

2. Deformational features in conglomerates

Tectoglyphs on pebble surfaces have been noted and used as tectonic indicators by many geologists. The surfaces of carbonate pebbles can be marked by solution pits (Trurnit, 1963; McEwen, 1981; Schrader, 1988) or striated by the sand or gravels of the matrix (Petit et al., 1985; Schrader, 1988). Solution pits come from indentation of carbonate pebbles of less soluble pebbles and gravels. For limestone pebbles of similar composition, they come from penetration of the pebble with the larger radius of curvature at the contact by the pebble with the smaller radius of curvature (McEwen, 1981). Solution pits result from pressure-solution induced by tectonic forces (e.g. Behrens and Wurster, 1972; McEwen, 1981) but, as they can be either perpendicular or oblique to the shortening direction, they do not allow an accurate determination of the maximum compression direction.

Striations provide information on the relative displacement of the pebbles and their matrix (Figs. 1 and 2a–c). A method for strain analysis of striations was devised by Schrader (1988). He described lineation patterns, on highly striated pebbles of the Swiss Molasse Basin, which indicate strain ranging from pure shear to simple shear. Our observations in various conglomerate formations in Europe agree with this classification, but show that striations resulting from simple shear are more frequent than expected, in particular in faulted basins. We think that one must distinguish two types of striations, sometimes present in the same outcrop: radial striations (Fig. 1a, b) and unidirectional striations (Fig. 1c, d).

The radial striation patterns (Fig. 1a) generally originate from two opposite points on the pebble surface, and these points are sometimes marked by solution pits indicating indentation from other pebbles. This kind of striation corresponds to pure shear or oblique strain symmetries (Schrader, 1988). This feature is interpreted to result from a nearly coaxial deformation of the matrix around a rigid pebble, for example during compaction or shortening of the conglomeratic material (Fig. 1b). In the pure shear case, the stress and strain directions coincide (Schrader, 1988). Whereas in the Swiss Molasse Basin (Schrader, 1988) the pebble surfaces are almost entirely striated, in the basins studied here (see below), only rare and small (less than 5 cm) pebble surfaces with radial striations were observed. The scarcity of this kind of striation in examples of deformed conglomerates may be due to the low amount of sandy matrix. Effectively, in these examples a sandy matrix does not support the pebbles. The local development of the striation and its radial aspect suggest that it can result from a local stress field produced by the contact between pebbles (cf. McEwen, 1981).

The unidirectional striation pattern (Figs. 1c and 2) was most common in the sedimentary basins investigated here. In contrast with the radial striation pattern, these striation geometries do not spread from a solution pit but are present on one, or sometimes two, opposing, sub-planar facets of a pebble (Fig. 2a, e). The different distribution of these striations with respect to the solution pits (Fig. 1d) suggests a different origin. This feature corresponds to the simple shear case of the Schrader (1988) classification. In contrast with his description of isolated pebbles, this paper considers the deformation of the whole conglomeratic formation and interprets such features to result from the development of shear zones within the conglomeratic material (Figs. 1e and 2d, e). Within such zones, striation may appear along some well-oriented pebble facets (Fig. 1e). All orientations of pre-existing discontinuities being present in a conglomerate, this deformation can be compared with the deformation of a highly fractured rock. Shear zones cutting through the matrix and striating pebble surfaces are rarely visible in this heterogeneous material (e.g. Petit et al., 1985). However, the presence of a shear zone can be revealed by parallel striations on the side of different pebbles aligned

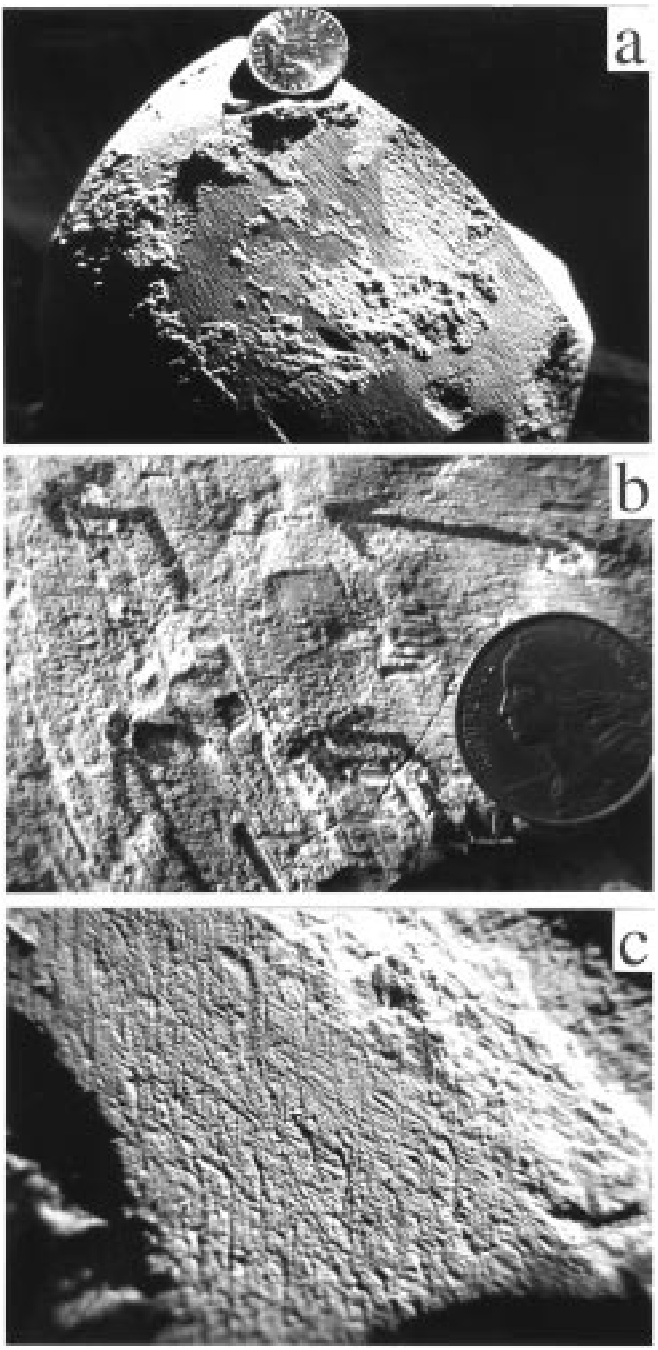


Fig. 2. Examples of shear surfaces in conglomerates. (a) Pebble with local and unidirectional striations. The sense of movement (reverse) is indicated by fibrous calcite and solution pits. (b, c) Chronologies of slickenside lineations on pebble surfaces of a Miocene conglomerate in the Valensole Basin (Fig. 6). Observation of striations that bend gives both the chronology and the sense of movements. In part b, the sense is indicated by ploughing at the tip of lineations, in part c the sense of the second movement is confirmed by fibrous calcite. (d, e) Fractured and striated boulders and pebbles in a Miocene conglomerate from Romania. Those striations on pebble surfaces (e; reverse sense of slip indicated by the Riedel criteria) are associated with consistent reverse movements in faulted pebbles (d; see the offsets of pebble surfaces). This association shows that the slip movements result from the development of shear zones in the conglomerate and therefore can be used for palaeostress analyses. (f) Two striated pebble surfaces in the same plane attest to the existence of a shear surface passing through the conglomerate matrix.

along it (Figs. 1e and 2f) or by the existence of fault planes in cemented areas of the matrix.

The unidirectional striations on pebbles created along shear zones in a conglomerate are probably the structures that have been used by most authors to determine palaeostress orientations (e.g. Campredon et al., 1977; Petit et al., 1985; Combes, 1984; Fesce, 1986; Ritz, 1992). To test the validity of such a palaeostress analysis, this study examines several examples, from both extensional and compressional settings, where palaeostresses can be determined using

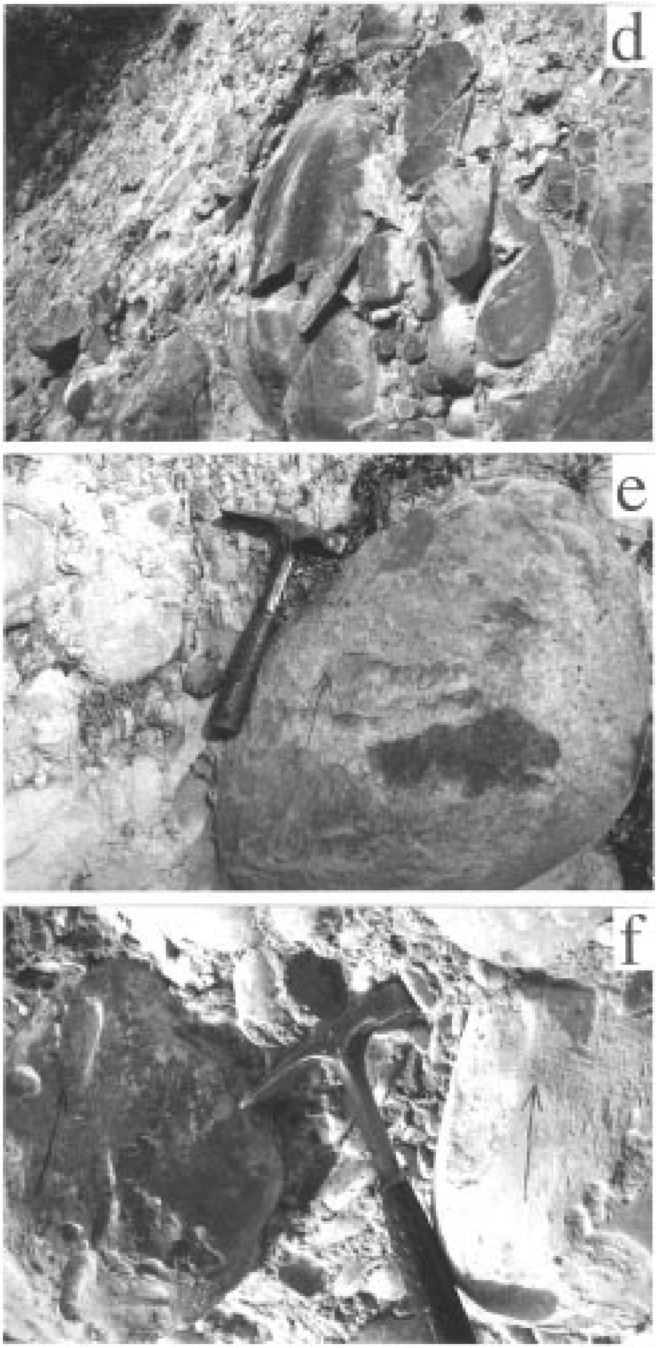


Fig. 2. (*continued*)

shear surfaces measured on pebbles, and in the brittle substratum of the conglomerates.

3. Comparison between faults and striated pebbles in palaeostress determination

3.1. Extensional setting

During the Late Eocene and the Oligocene, E–W extension developed in the European platform creating the West European rift system (Fig. 3a; e.g. Bergerat, 1985; Le Pichon et al., 1988). At the end of the Oligocene (Hippolyte et al., 1993; Mauffret and Gorini, 1996; Roca et al., 1999), the Liguro-Provençal Basin (Fig. 3a) began to rift, followed by drifting and counterclockwise rotation of the Corso-Sardinian block in Aquitanian-Burdigalian (Edel, 1980, Orsini et al., 1980; Rehault, 1981).

A Rupelian to Middle Chattian E–W extension that is assigned to the West European rifting was recorded by brittle deformation in the Oligocene grabens of Provence (Fig. 3c; Bergerat, 1985; Villeger and Andrieux, 1987;

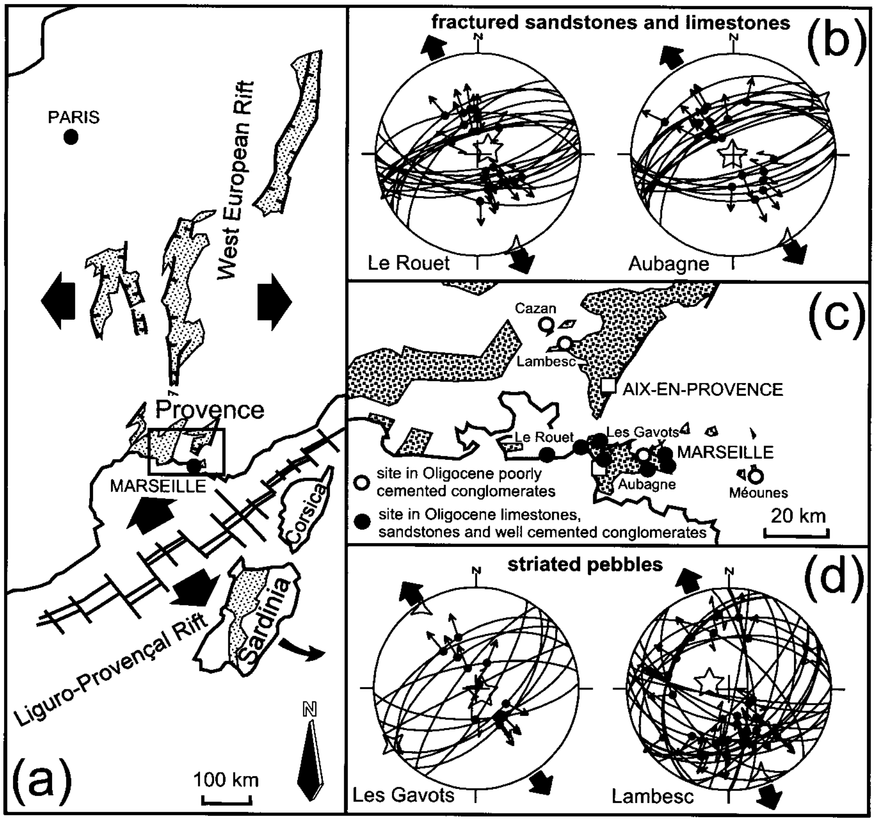


Fig. 3. Comparison between stress analyses using faults and striated pebbles in an extensional setting. (a) Location of the Oligocene basins of Provence in the West European rift. (b) Examples of Schmidt diagrams of fault planes with computed palaeostress axes: five-point star = σ_1, four-point star = σ_2 and three-point star = σ_3. (c) Location of sites where deformation occurred during the Liguro-Provençal SSE-trending extension. (d) Examples of Schmidt diagrams of pebble striations. Mean values of the trends of extension, of the Φ ratios [$\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$] and of the quality estimators ANG: N150°E, 0.43, 13° in poorly cemented conglomerates, N155°E, 0.42, 10° in brittle rocks (cf. Hippolyte et al., 1993).

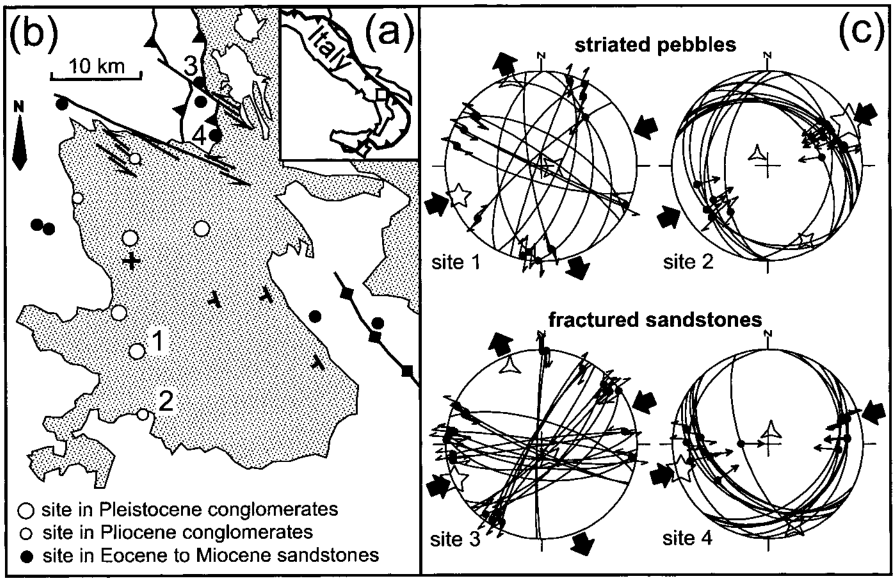
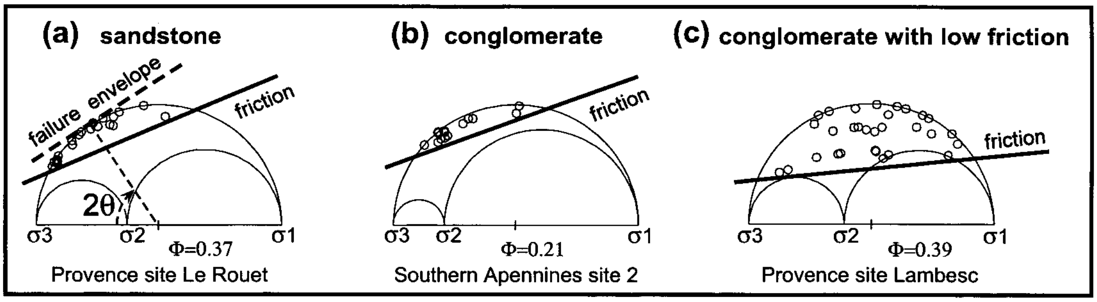


Fig. 4. Comparison between stress analyses using faults and striated pebbles in a compressional setting. (a) Location of the Sant'Arcangelo Quaternary piggyback basin in Italy. (b) Location of sites of palaeostress analysis (ENE–WSW-trending compression; Hippolyte et al., 1994) in poorly cemented conglomerates or in fractured sandstones. (c) Examples of Schmidt diagrams of pebble striations or of fault planes. Mean values of the azimuths of the maximum horizontal stress, of the Φ ratios [$\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$], and of the quality estimators ANG: N66E°, 0.28, 11° in the conglomerates, N64E°, 0.24, 11° in the faulted Tertiary sandstones (cf. Hippolyte et al., 1994).



(a) sandstone (b) conglomerate (c) conglomerate with low friction

Provence site Le Rouet Southern Apennines site 2 Provence site Lambesc

Fig. 5. Characteristic Mohr diagrams (τ versus σ_n, without scale) of sandstones and conglomerates. σ_1, σ_2 and σ_3 are principal stress magnitudes, $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. Little circles represent the resolved stress on the measured fault planes for the best-fit tensor. (a) In sandstones, conjugate faults form with resolved stresses at the intersection of the largest $(\sigma_1 - \sigma_3)$ Mohr circle with the perpendicular to the failure envelope showing the characteristic dihedral angle (2θ) of about 60°. Pre-existing fractures are reactivated depending on the friction of the material (reactivated fractures have resolved stresses located above the initial friction line). (b) The resolved stresses on striated pebble surfaces have similar positions as in sandstone (a). (c) In some conglomerates, the resolved stresses indicate low friction.

Hippolyte et al., 1993). The beginning of the Liguro-Provençal rifting during the Late Chattian is characterized in these grabens by a tectonic subsidence rate 14 times higher than in the Rupelian (Nury, 1984) and faulting under an NNW–SSE-trending extension (Fig. 3b; Hippolyte et al., 1993, Mauffret and Gorini, 1996). In contrast with the Rupelian to Middle Chattian formations, there is no limestone in the Late Chattian synrift sediments outcropping in Provence, only sands and conglomerates. Near Marseille, these Late Chattian conglomerates are well cemented and faults cutting these rocks, similar to faults measured in the underlying Rupelian to Middle Chattian limestones, allow the orientation of the principal axes of the Late Chattian stress field to be constrained over a 40-km-wide area (black circles in Fig. 3c) characterized by σ_3 trending NNW–SSE (Fig. 3b, c; Hippolyte et al., 1993). Within this area, and 30–40 km north and east of this area, Late Rupelian conglomerates (site Les Gavots) and Late Chattian synrift conglomerates (sites Cazan, Lambesc, Méounes) (Fig. 3c) are poorly cemented and their deformation mainly resulted in the striation of pebble surfaces. Striated pebbles at these sites were measured (a site is an outcrop a few tens of metres long) and palaeostress axes were computed following the method of Angelier (1990) (Fig. 3d). Despite a larger dispersion of the striated surface orientations, the mean values of the Late Chattian trends of extension, of the Φ ratios $[\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)]$, and of the quality estimators ANG (i.e. average angle between computed shear stress and observable slickensides for a given stress model) determined from the striated pebbles are comparable to those determined from fault planes in the Oligocene brittle rocks (Fig. 3).

3.2. Compressional setting

In Southern Italy (Fig. 4a), the Sant'Arcangelo Basin (Fig. 4b) is a piggyback basin filled by more than 3000 m of Pleistocene marls, sands and conglomerates deposited during the last Apenninic thrust activity (Casero et al., 1991; Roure et al., 1991; Hippolyte et al., 1994). This basin records a syndepositional tilt toward the west and is weakly faulted (Fig. 4b). Nevertheless, in the Pliocene and in the syntectonic Pleistocene conglomerates, striated pebbles are found that indicate reverse and strike-slip deformation (Fig. 4b, c). This deformation corresponds closely to that deduced from the following large structures: (1) ESE-trending sinistral strike-slip faults along the northern edge of the basin (Fig. 4b) above an oblique ramp of a deeply buried thrust recognized on seismic data and by drilling, and (2) reverse faults cutting the sediments of the basin and also recognizable on seismic profiles (Hippolyte et al., 1994). This deformation corresponds to an ENE–WSW compression (Fig. 4c) and all the striations measured in the four sites located within the syntectonic Pleistocene conglomerates (Fig. 4b) consistently correspond to this trend of compression (cf. Hippolyte et al., 1994). As for the extensional basins described above, the strike-slip and reverse slips measured on pebble surfaces (Fig. 4c, sites 1 and 2) are similar to those measured on fault planes in neighbouring brittle rocks (Fig. 4c, sites 3 and 4), but sometimes with a larger dispersion in orientation. Despite this dispersion, the palaeostress analysis gives very similar results in the conglomerates and in the substratum (Fig. 4c). In the Sant'Arcangelo Basin, the main objective in analysing striated pebbles is to show that the uppermost and horizontal stratigraphic levels are not post-tectonic deposits, but are deformed by the ENE-trending compression (site 1, Fig. 4b). It allows a precise stratigraphic dating of the Pleistocene compressional activity, which is in agreement with a syn-tectonic interpretation of this piggyback basin (Casero et al., 1991; Roure et al., 1991; Hippolyte et al., 1994).

3.3. Characteristics of shear deformation in conglomerates

A particular characteristic of deformation in conglomerates is that the surface of the pebbles, which have been smoothed by fluvial transport, may record small

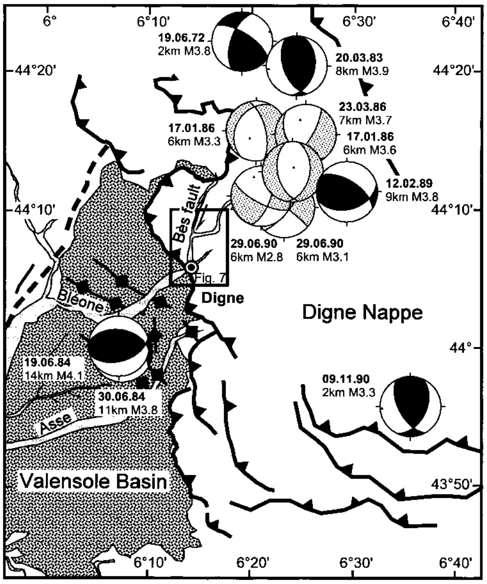


Fig. 6. Location of Fig. 7 in the Southeastern Alps. Focal plane mechanisms (Madeddu et al., 1996) are compressional, except a cluster of extensional to strike-slip focal mechanisms at about 5 km below the Digne Nappe (in grey), probably related to foreland flexuring decoupled from the thrust emplacements.

(millimetric) movements that are generally not recorded on rougher fault surfaces. Another feature, which was found at a few sites (e.g. site Lambesc in Fig. 3d and site 1 in Fig. 4c), is a large dispersion in attitudes of the striated surfaces. The Mohr diagram of Fig. 5c shows that the large dispersion of fault attitude in the site Lambesc (Fig. 3d) indicates a low coefficient of sliding friction compared to those of sandstones and other conglomerates (Fig. 5a, b). Note that the line drawn in Fig. 5c is a friction line. If it was a failure envelope that had a low gradient, it could have meant that failure occurred at high mean stress and at large depth. At Lambesc, the syn-tectonic conglomerates have never been deeply buried. This low coefficient of sliding friction is probably due to the low overburden (a few tens to hundreds of metres) of the conglomerate during deformation.

Two main types of computation method exist for palaeostress determinations. Classical methods (Carey and Brunier, 1974; Armijo and Cisternas, 1978; Etchecopar et al., 1981; Angelier, 1994) invoke the minimization of a function that depends only on the angle between the measured slip striation and a computed shear stress. A second approach is based on the introduction in the minimization procedure of a vector υ (Angelier, 1990; Villemin and Charlesworth, 1992) that depends not only on the shear-slip angle but also on the shear stress magnitude. As this method takes into account the relative magnitude of the shear stress on fault planes, it allows account to be taken of the possibility of the computed reduced stress tensor having induced slip on a fault plane despite rock cohesion and friction. It follows that this method allows a better location of the stress axes in cases where the angle between two antithetic families is large (Angelier, 1990), which is the case for a weakly cemented conglomerate deformed at low overburden (e.g. site Lambesc in Fig. 3d and site 1 in Fig. 4c).

4. Use of striated pebbles in neotectonics

The main interest in characterizing deformation from striated pebbles is that it can allow stratigraphic dating of a tectonic event. In the Southwest Alps, the Digne Nappe is the outermost thrust unit and is classically regarded as the most recent (Pliocene–Quaternary) thrust emplacement as constrained by the age of underlying Neogene sediments of the Valensole Basin (Fig. 6; e.g. Gigot et al., 1974; Clauzon, 1975). However, nowhere have clear Quaternary rocks been found underthrusted. Moreover, there is not even indirect evidence of a Quaternary thrust movement because the palaeostress field (NNE–SSW compression), supposed to be contemporaneous to the latest thrust movement (Combes, 1984; Ritz, 1992), is determined from fault planes mainly measured in Mesozoic to Miocene rocks, and its upper age is not precisely known. It should be noted that the paucity of seismic data available (Fig. 6) does not allow the conclusion that this nappe emplacement is still active.

In the following, it is shown that the analysis of striated pebbles near the front of the Digne Nappe (Fig. 7) clearly demonstrates its neotectonic Quaternary activity. In the Digne thrust sheet, immediately northeast of Digne (Fig. 6), Jorda et al. (1992) found striated pebbles in tilted alluvial deposits (Fig. 7) that they interpreted as Quaternary alluvial terraces. The striation type is unidirectional. Striated surfaces were measured at site 1 (Fig. 7). Most of them indicate reverse movements corresponding to an ENE–WSW compression (Fig. 7). At site 2, at the extremity of a mapped fault with 250 m of dextral offset (Fig. 7; Haccard et al., 1989) the deformation is strike-slip and also corresponds to an ENE–WSW compression, with NE–SW pebble surfaces exhibiting dextral movements. The presence of compressional deformation is in agreement with the hypothesis of a compressional tilting of these deposits (Jorda et al., 1992) in relation with the folding and ramp-flat geometry of the leading edge of the Digne Nappe (Fig. 7). The ENE–WSW trend of compression is in agreement with the 3.5 km dextral stratigraphic offset (Haccard et al., 1989) of the Bès thrust fault (Fig. 7).

The location of the Digne conglomerate, in a valley at lower elevation than the Late Miocene sediments of the Valensole Basin (Figs. 6 and 7), attests for a post Late Miocene age, but a Quaternary age of this deformed conglomerate is not certain. In fact, its thickness, which is presently more than 80 m at site 1 and which was probably more than 100 m between sites 1 and 2 (Fig. 7), suggests that it records the Pliocene filling of a Messinian canyon. To stratigraphically date the thrust activity, it was therefore important to find evidence of Recent deformation. The

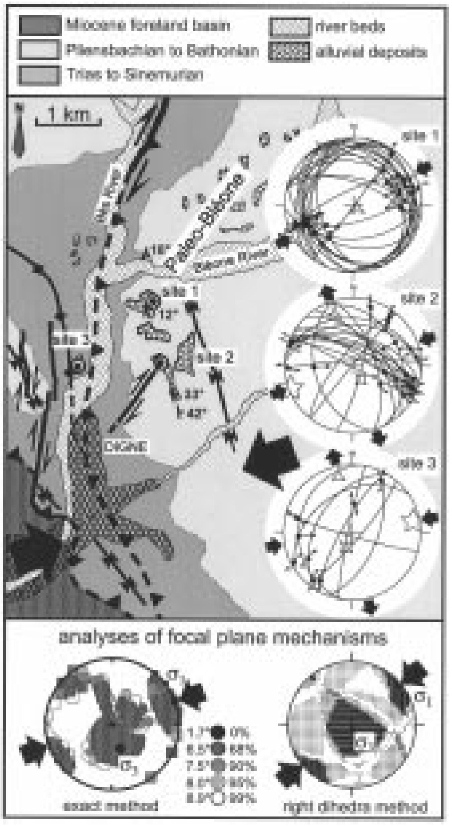


Fig. 7. Sites showing neotectonic deformation in Pliocene (sites 1 and 2) and Quaternary (site 3) alluvial deposits at the front of the Digne Nappe, and present synthetic stress tensor of the Digne area from the compressional focal plane mechanisms of Fig. 6. From focal plane mechanisms, the best-fitting stress model with the exact method (Gephart and Forsyth, 1984) is an N70E compression. The average misfit values associated with each of the confidence limits are indicated. The right dihedra method (Angelier and Mechler, 1977) indicates probability areas of 80–100% for σ_1 and σ_3 axes (in dark) with a center of the maximum area giving σ_1 at N48E.

movement of the Bès thrust has a dextral component and, at Digne, this fault splays in several strike-slip faults that offset dextrally older NW–SE folds of the Digne Nappe (Fig. 7). Within this fault splay, we found striated pebbles in an alluvial terrace whose late Quaternary age (Haccard et al., 1989) is attested to by its location below the Pliocene thalweg (site 3, Fig. 7). In this terrace, pebbles are weakly striated, possibly due to a lower overburden (about 20 m) than in the Pliocene canyon filling (100 m). However, the deformation also indicates an ENE–WSW compression (Fig. 7, site 3) and demonstrates the activity of the decollement of the Digne Nappe during the late Quaternary.

The ENE–WSW orientation of compression is compatible with the focal mechanisms of the southern outer Alps (Fig. 6). Despite a poorly constrained depth of hypocentres, the compilation made by Madeddu et al. (1996) shows that the two most superficial focal mechanisms have ENE-trending orientations of P-axes (N070 and N088). On the whole, focal mechanisms of this area are characterized by a cluster of extensional to strike-slip movements (grey in Fig. 6) at about 5 km beneath the Digne Nappe, interpreted to represent flexural deformation decoupled from the overthrusted units. Using the right dihedra method (Angelier and Mechler, 1977), the remaining, compressional, focal plane mechanisms allow determination of an ENE–WSW present trend of compression in the Digne area and a N70E best orientation of compression using the method of Gephart and Forsyth (1984). Neotectonic analysis of striated pebbles in Pliocene and Quaternary sediments of the Digne Nappe therefore reveals stress orientations compatible with the available seismic data, and the present compressional trend of the Digne area is interpreted to have been active since at least Pliocene time.

5. Conclusions

Shear surfaces in conglomerates can testify to the presence of tectonic deformation even at low overburden (20 m in the case of horizontal σ_1). Because the smooth surfaces of calcareous pebbles in conglomerates can record millimetric slips, this material can be a good indicator of neotectonic deformation in areas of low deformation rates.

Striation of pebbles can be used in palaeostress computations where it can be demonstrated that the slickensides result from the development of shear zones within the conglomeratic material, which was the case in the basins studied here. Faults cutting a conglomeratic material may splay in numerous shear surfaces and are comparable with faults propagating in a pre-fractured limestone. The use of mesoscale tectonic structures in conglomerates can allow precise stratigraphic dating of a stress field and, in particular, may permit deformation analysis in syntectonic deposits.

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