ELSEVIER

Journal of Structural Geology 28 (2006) 1084–1092

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Calcite e-twins as markers of recent tectonics: insights from Quaternary karstic deposits from SE Spain

J.M. González-Casado [a,*], P. Gumiel [b], J.L. Giner-Robles [c], R. Campos [d], A. Moreno [a]

[a] *Dpto. de Geología y Geoquímica, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[b] *Instituto Geológico y Minero de España (IGME), Ríos Rosas 23, 28003 Madrid, Spain*
[c] *Dpto. de Geodinámica, Universidad Complutense de Madrid, 28040 Madrid, Spain*
[d] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Avenida Complutense 22, 28040 Madrid, Spain*

Abstract

Superficial Pleistocene karstic coatings found in the boundary region between the Iberian and Betic Chains (Spain) are often offset by normal faults. These travertines were sampled to investigate whether mechanical twins in calcite can develop at low paleodepths. Surprisingly, twinned grains are very abundant in sparry grains, which are found in the proximity of the fault planes (mean twin densities 28 twins/mm). Paleostress determinations based on the analysis of calcite e-twinning yielded the same principal stress orientations as the fault population analysis, i.e. a NW–SE extension tectonic regime. Therefore, calcite e-twin analysis is a useful method with which to establish the orientation of recent stress tensors. Calcite e-twins develop under conditions of minimum overburden (∼300 m) during fault slip. The low differential stresses during the fault slip event suggest that the critical resolved shear stress on the twin plane must be lower than the expected mean value of 10 MPa or that local stresses experienced by rock in and near the fault zone exceed ambient stress conditions during fault slip.

Keywords: Paleostress analysis; Calcite; e-twins; Neotectonics; Resolved shear stress; Differential stresses

1. Introduction

Calcite e-twins have been used to deduce the stress tensor responsible for the deformation of a calcite aggregate by assuming that the twin plane is a shear plane and that the twin direction is parallel to the maximum resolved shear stress (RSS). Twinning occurs only if the resolved shear stress equals or exceeds a stress yield value; usually a mean value of 10 MPa is accepted. Consequently, twinning movement can only take place in one direction and there are precise relationships amongst twin planes, c-axes, shear direction and principal stress orientations (compression 'σ_1' and tension 'σ_2' axes are located at 71.5 and 18.5° to the c-axis, respectively, and at 45° to the e-twin plane; Turner, 1953; Weiss, 1954). Several useful methods that establish principal stress orientations have been developed based on these facts (e.g. Turner, 1953, 1962; Weiss, 1954; Spang, 1972; Pfiffner and Burkhard, 1987). Later developments that also took into account the value of the resolved shear stress led to more refined methods that could establish the complete stress tensor, i.e. orientation and magnitude of principal stresses (e.g. Laurent et al., 1981, 1990; Laurent, 1984; Lacombe and Laurent, 1992; Rocher et al., 2004).

Twinning has also been used to infer differential stress magnitudes and paleotemperatures. Paleopiezometric determinations are based on twin intensity—number of twins per millimetre—(Rowe and Rutter, 1990), on the percentage of carbonate grains with one, two, or three twin sets (Jamison and Spang, 1976) or they have been established from the results of some twin inversion methods. On the other hand, temperatures can be inferred from calcite twin morphology and twin intensity (Ferrill et al., 2004).

Usually these methods have been applied to limestones from orogenic belts, where calcite grains are deformed under high differential stress conditions and in a compressive tectonic regime. In these cases, the use of calcite e-twins to deduce paleostress or strain tensors has been shown to yield robust data (e.g. Groshong et al., 1984; Ferrill, 1991; Lacombe et al., 1992; Rocher et al., 1996; González-Casado and García-Cuevas, 1999, 2002; Craddock et al., 2000). By contrast, there are not many studies that have researched the presence of twinned calcite grains in moderately strained carbonate rocks from intraplate areas or sedimentary basins (e.g. Lacombe et al., 1994). Nor has the presence been studied in detail of e-twins in

* Corresponding author. Tel.: +34 914973841; fax: +34 914974900.
E-mail address: g.casado@uam.es (J.M. González-Casado).

0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.03.019

limestones that have been strained at low depth (i.e. deformed at low lithostatic pressure) or in Quaternary limestones. These investigations have probably not been carried out a priori, because, in these tectonic environments, it is difficult to achieve the assumed value of 10 MPa for the critically resolved shear stress necessary to start twinning. Nevertheless, some recent papers show the presence of calcite twinned grains in karstic coatings from the Paris basin located at 20 m deep (Rocher et al., 2003) and in veins and amygdales hosted in recent igneous rocks of Iceland (Craddock et al., 2004). These data show the possibility that calcite e-twins can develop under low differential stresses and low lithostatic pressure, i.e. with a small overburden.

The aim of the present study is to test if e-twins can develop at low lithostatic pressure under low differential stresses and, consequently, to establish whether they can be useful in neotectonic studies to establish the orientation of the stress tensor and differential stress magnitudes. We chose the quaternary karstic deposits of the Mediterranean coast of Spain (Coastal Sierras of the Valencian region; Fig. 1) because: (a) karstic deposits in this region related to the Quaternary uplifting of the coast are very abundant; (b) this region shows a significant tectonic activity at present; and (c) recent and present stress tensors are well known from fault population analyses and seismic studies. Our results show the presence of abundant calcite e-twins where karstic deposits are offset by the Quaternary normal faults. Finally, and in order to test the validity of the results, we have compared the data obtained from the calcite e-twin analysis with that derived by using fault slip orientations.

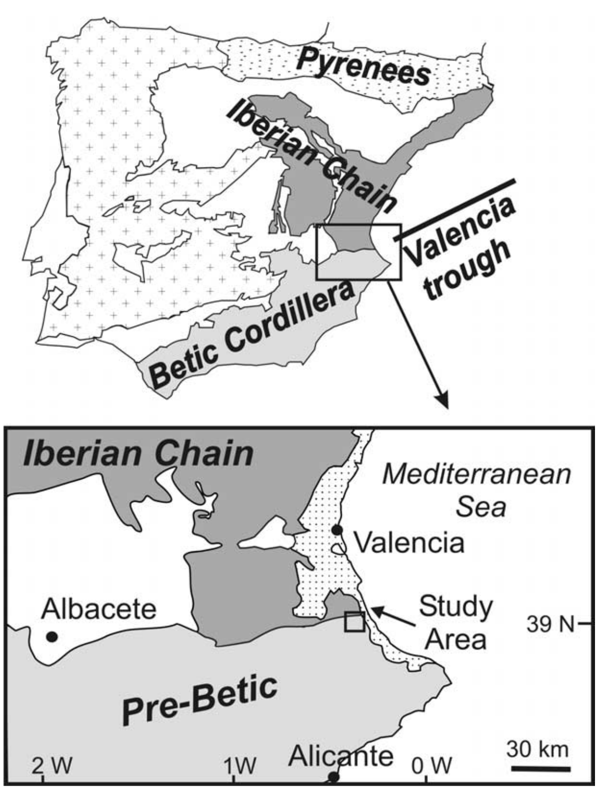

Fig. 1. Simplified geological map of the Iberian Peninsula and location of the area studied.

2. Geological setting

The samples were taken from the coastal mountains close to the Valencian Trough, where the boundary lies between the Iberian and the Betic chains (Eastern Spain; Fig. 1). This region is comprised of a thick, Mesozoic sedimentary cover, which is formed by three different stratigraphic units: Triassic rocks on Germanic facies and Jurassic and Cretaceous marine limestones. The Late Triassic lutite and gypsum beds from the Keuper are the regional detachment level of the Mesozoic sedimentary cover. The tectonic structure is mainly characterised by open folds and small thrusts in two directions: one of which is NW–SE, parallel to the longitudinal Iberian Chain trend and the other of which is NE–SW, parallel to the Betic Chain trend (Fig. 1). These structures were formed during successive Cenozoic (Alpine) tectonic episodes.

Recent normal faults with associated seismicity are common in this region (e.g. Herraiz et al., 2000; Rueda and Mezcua, 2003). These faults show two main trends: the most important one has a ENE–WSW orientation, probably related to the Valencian Trough formation; the other set has a NW–SE orientation, parallel to the coastline (Figs. 1 and 2). Both sets of faults are presently active and condition the development of the present landscape and coastal uplifting. The ENE–WSW and NW–SE fault trends coincide in orientation with the nodal planes of earthquake focal mechanisms, which confirms their recent activity (Fig. 2).

The study area is located in a 10 km wavelength open dome (Xeraco Dome), which is elongated in an ENE–WSW direction and truncated by the shoreline in its east limb. This fold has developed in Cretaceous and Jurassic limestones and is probably related to the interference between the Betic and Iberian structures and to the upward migration of gypsum beds from the Keuper. This fold is offset by several normal faults with ENE–WSW and NNW–SSE trends (Fig. 3).

These faults have a complex tectonic history; many of these faults are reactivations of old joints and fissures that developed during the crustal stretching associated with the opening of the Valencian Trough during the Cenozoic and coastal uplifting. Karstic coatings (travertines) filled the fissures and were offset by faults that had formed by shear reactivation of old fissures. These faults have spectacular striations and chatter marks on their surface (Fig. 4). Travertine deposits filled the fissures from the Late Pleistocene to the Holocene period during the Quaternary uplifting of the coast and subsidence of the coastal zone (Gutierrez-Elorza et al., 2002) and have been dated (U/Th) at 207 ± 14 ka.

3. Paleostress orientation analysis

3.1. Method

The paleostress tensors were calculated by using the method of Laurent et al. (1981, 1990) and Laurent (1984), which is a

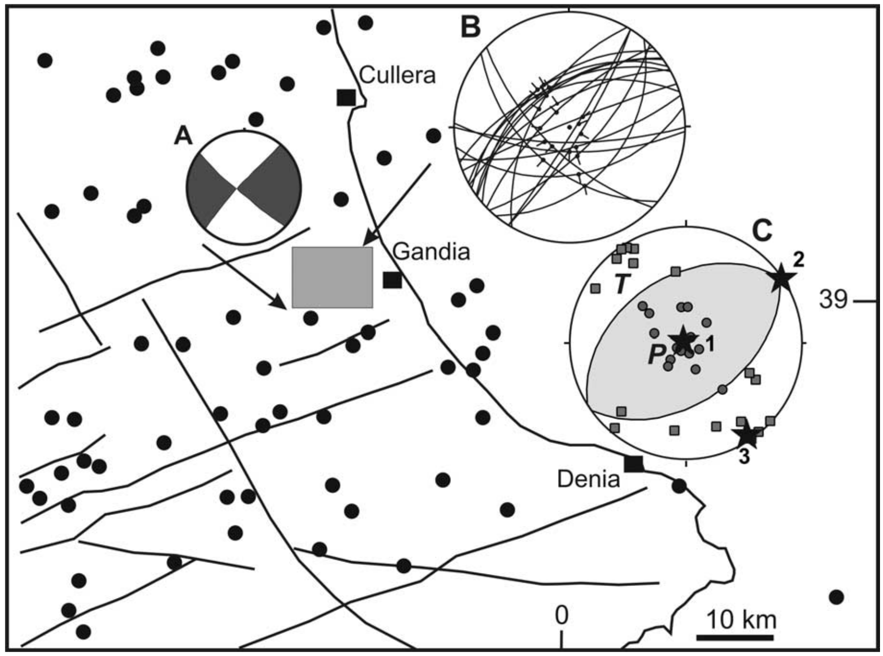

Fig. 2. Fracture and lineation map of the studied region. The instrumental earthquake epicentres have been plotted on this map (modified from Rueda and Mezcua, 2003). (A) Earthquake focal mechanism from the study area. Note that the two nodal planes are parallel to the fault direction. (B) Stereographic plot with the faults and striations measured in the studied outcrop. (C) P/T diagram for the previous faults. The NW–SE extension direction deduced from this diagram agrees with the opening direction of the Valencian Trough. The square gives the position from Fig. 3 map.

computer-based inversion process, similar to the 'Numerical Inverse Method' developed by Etchecopar (1984) for fault analysis. Several authors have found this technique (e.g. Lacombe et al., 1990, 1992; Laurent et al., 1990; Tourneret and Laurent, 1990; Rocher et al., 1996, 2004) to yield good estimates of the magnitude and orientation of principal stresses in slightly to moderately deformed limestones. In the case studied here, the orientation of the three e-planes for each measured calcite grain is established by means of the procedure developed by Tourneret and Laurent (1991), after which the presence or absence of twinning in these orientations is then verified. Therefore, twins represent e-planes where the resolved shear stress equalled or exceeded the stress yield value (10 MPa) and consequently twin gliding takes place within them, while untwinned e-planes represent orientations for which resolved shear stress is lower than the stress yield value. Consequently, when calculating the paleostress tensor, both the twinned and non-twinned e-planes are taken into account. In the twinned e-planes, the calculated resolved shear stress must be equal to or higher than the considered stress yield and, simultaneously, it must be smaller than the stress yield in the untwinned e-planes. The working procedure consists of data inversion following a computer-based numerical inverse method (Etchecopar, 1984). This process yields the orientation of the principal stress axes (σ_1, σ_2, σ_3), the ratio between the principal stresses $\phi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ and the maximum differential stresses ($\sigma_1-\sigma_3$). A basic assumption of this technique is that e-twins are produced under a single, homogeneous, average tensor, i.e. that there is a homogeneous stress distribution in the sample, thus the separation of different stress tensors using this technique is problematical (Burkhard, 1993). Consequently, we discarded incompatible twins and we only calculated one stress tensor.

In order to complement and validate determinations carried out with the former method, the location of the principal stresses was also established by means of the 'Dynamical Numerical Analysis' of Spang (1972) and, finally, the principal strains were also calculated using the 'Strain Gauge Technique' developed by Groshong (1972, 1974). This method establishes the principal strain axis orientation and relative magnitudes. Data-scatter was reduced by eliminating 20% of the twin sets, which had the highest deviations from calculated expected values (Groshong et al., 1984).

In order to compare the results obtained from the calcite analysis with other independent methods of estimating the orientation of principal stresses, fault data were analysed at the same sites where the calcite samples were taken from. The stress tensor orientation was established by means of a 'Right Dihedra Diagram' (Angelier and Mechler, 1977), which shows areas of compression (P) and tension (T) common to all the faults considered. The principal stress tensor axes are located within these areas. The three dimensional orientation of these zones (right dihedra stereographic diagrams) enables the deduction of the tectonic regime.

3.2. Results

Five orientated samples were collected on the Xeraco Dome along two fault belts that had developed over old fissures filled with karstic deposits (Figs. 3 and 4). For each sample, measurements were made on two thin, orthogonal sections; one that was perpendicular to the fault plane and yet parallel to the slickenside and the other was perpendicular to both the fault plane and the slickenside.

Travertines are formed by an aggregate of sparry calcite grains, ranging in size from 1 mm to 10 μm (Fig. 5), with a slight preferred orientation of the optical axes. The calcite grains studied here have a chemical composition of almost pure calcite (>38% Ca). Mechanical twins are very abundant in calcite grains close to faults, which cut through the karstic deposits; the mean twin intensity of ~30 twins/mm suggest small strains (Table 1 and Fig. 5). Twinning of calcite grains gradually diminishes away from the fault plane. Their aspect determines their classification as thin twins (straight twins; cf. Weiss, 1954; Ferrill, 1991, or twins of type I; Burkhard, 1993). Ferrill et al. (2004) state that these kinds of twins develop at temperatures below 170 °C, but here, the twins must have been formed at very low temperatures (<30 °C) due to the shallowness (<300 m) of their location where their formation took place and due to the lack of evidence of hydrothermal fluid flows. Despite the small strains, grains with two e-twin systems are relatively abundant. Measurements were made only in grains that had at least one twin set using a petrographic microscope with a U-stage (grain size range 90–2000 μm). The following was measured for each calcite grain: c-axis orientation, the three theoretical e-twin orientations, the

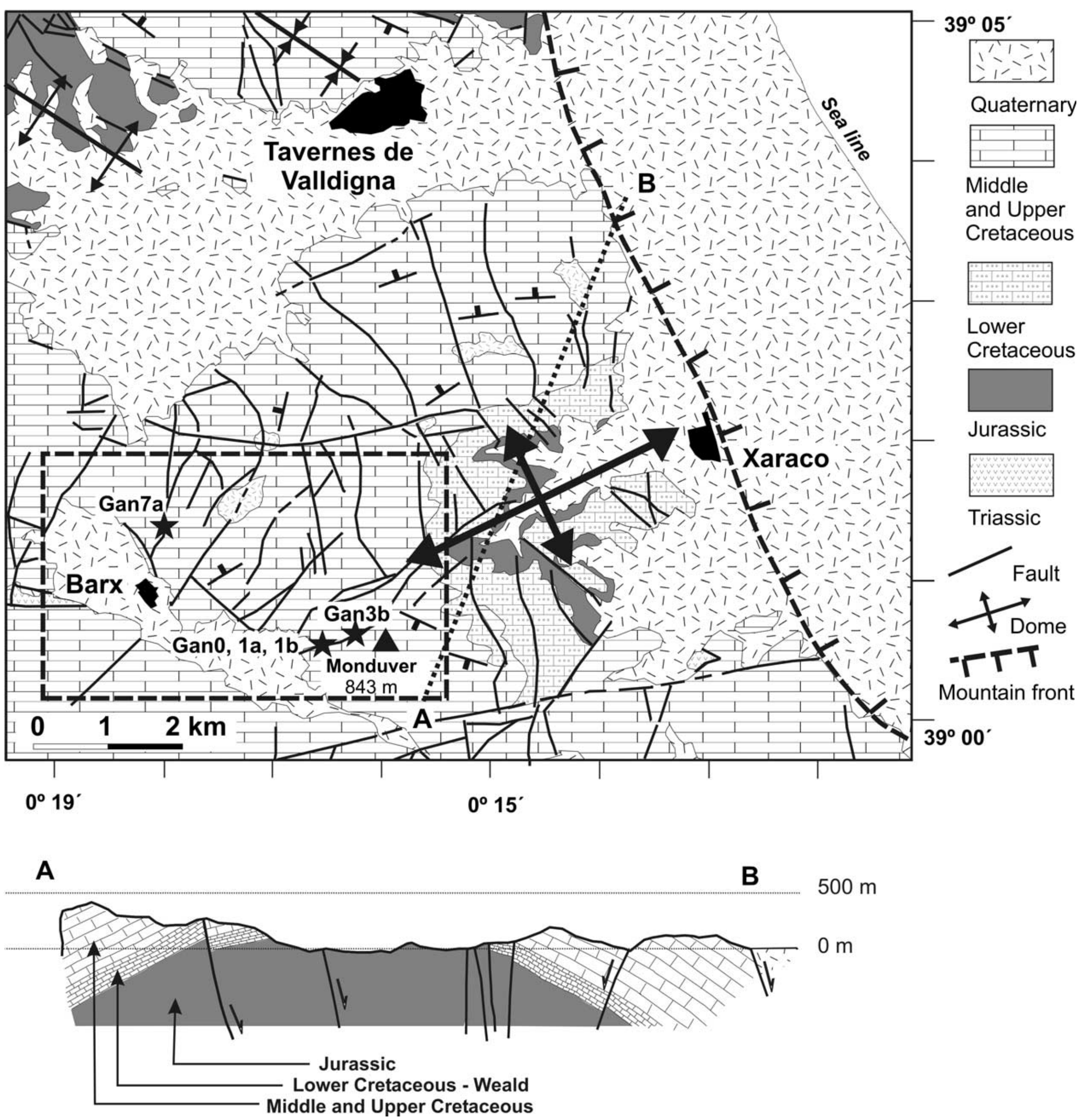

Fig. 3. Simplified geological sketch of the Xeraco Dome (southern Valencian Gulf) and cross-section. Modified from Ríos-Aragües et al. (1982). The square gives the position of Fig. 6.

Fig. 4. Travertines offset by a small, normal fault. Scale 14 cm.

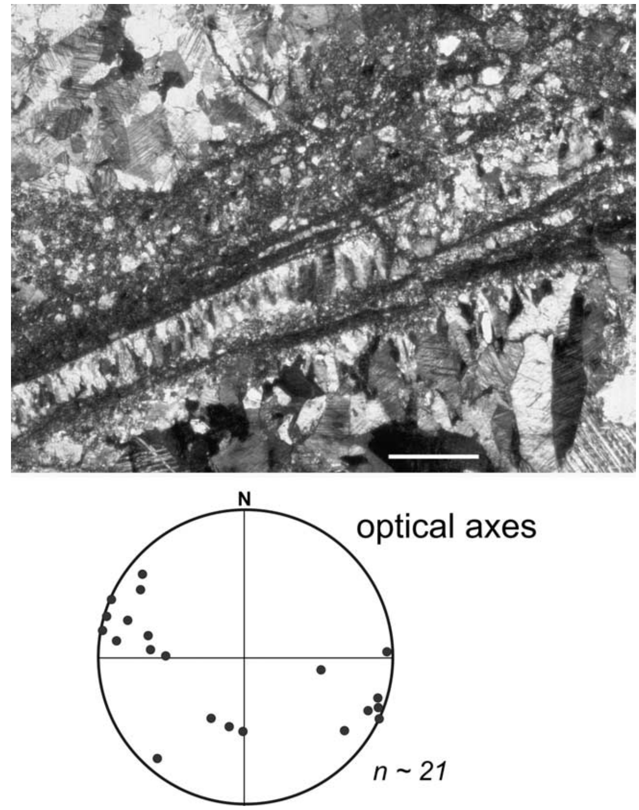

Fig. 5. Microphotograph of a fault band developed in the travertines. The fault microphotograph corresponds to that shown in Fig. 4. Note the high number of grains with two twin sets (twins are type I ~0.5 μm). Scale bar 25 μm. The stereonet (Schmidt projection, lower hemisphere) shows calcite optical axes distribution for the microphotograph sample.

orientation of the twinned planes, number of twins and grain width. With the Groshong method, we considered the default value of 0.5 for the thin twin width: thick twin ratio, to get the best match for the experimental results (Evans and Groshong, 1994).

The results of the calcite e-twin analyses are shown in Table 1 and Fig. 6. The orientation of the principal stress axis σ_3 (extension direction) deduced from the 'Numerical Inverse Method' is for the five studied samples that are congruent with the fault movements and regional tectonics, i.e. a subhorizontal extension direction ranging from NW–SE to E–W. However, axis σ_1 is located around a vertical position, being subvertical only in three samples; in the other two, permutations are given with σ_2 or both axes showing intermediate plunges. This fact might be explained by the small differences of stress magnitudes between σ_1 and σ_2, which allow stress axes permutations. There is a preponderance of ϕ values ($\phi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$; Table 1) that are higher than 0.5, i.e. that the tensors close to the axial extension are more abundant and there are even some values close to axial tension. The 'Dynamical Numerical Analysis' method yields the same orientations for the stress axes; however, the positions of the main stress axes are reversed and σ_1 is located subhorizontally and σ_3 subvertically in some samples.

In turn, the orientation of the principal strain axes e_1 (maximum elongation) and e_3 (minimum elongation) calculated using the 'Strain Gauge Technique' gives a perfect correlation with the regional tectonic frame. The orientation of the principal strain axes e_3 (minimum elongation) is subvertical in all five samples and the orientation of e_1 (maximum elongation) is subhorizontal and has a NW–SE or WNW–ESE trend (Fig. 6). As the average of distortion by twinning is very low, 0.36% (percent elongation), we can assume coaxial deformation. Therefore, principal strain orientations suggest that twinning reflects NW–SE extensional episodes related to the movement of normal faults. The strain analyses results also show that the percentage of negative expected values (NEV, i.e. twins that are not adjusted to the tensor solution) are usually $<20\%$, which indicate that the strain by twinning took place in a single event; here, non-coaxial or superposed deformation was deduced.

The stress field has also been calculated by analysing faults that are located in the same outcrops where the travertines were sampled. In all faults, the slip direction was established by using observed features on the fault surface. The results show one main fault set of normal faults that have small offsets and a NE–SW orientation (Fig. 2). These faults give right dihedra diagrams with a NW–SE subhorizontal extension direction and a vertical maximum compression direction (Fig. 2), i.e. the same orientations deduced from calcite e-twin analysis. Therefore, it can be deduced from this that e-twins and faults are cogenetic and according to the method described in Lacombe et al. (1991) and Lacombe and Laurent (1992), the maximum differential stresses sustained in the rock can be recorded by calcite twinning.

The recent character of these faults is established by their relation to seismic epicentres (Fig. 2), and because these faults are spatially associated with recent geomorphic structures and they also control the sedimentation of Quaternary deposits. In the Valencian Trough, the bathymetric data also reveal faults with these orientations, which control the opening of this submarine trough. So all NW–SE faults, which have a regional character, have had recent movement.

Table 1

Results of calcite e-twin analysis. 'Numerical Inverse Method' (Etchecopar), 'Numeric Dynamic Method' (Spang) and 'Strain Gauge Technique' (Groshong) are shown. In these three cases the orientations (plunge and plunge azimuth) of the principal strains/stresses are shown. The following are also shown in the strain: the elongation percentage of the principal strain axes, the negative expected values (Nev's, percentage of the total number data), the number of twins analysed (M) after discarding data that had the highest and largest deviations (m is the number of data considered) and the square root of the second invariant of the strain tensor, J2 (percentage strain). The following is indicated in the stress results: total number of twinned planes measured (TNT), total number of untwinned planes measured (TNU), number of twinned planes compatible (TPC) with the tensor solution and the ratio between principal stresses $(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)=\phi$

		Gan0	Gan1a	Gan1b	Gan3b	Gan7a
Strain Gauge Technique	e_1	176/16*.60	112/17*.43	157/12*.22	297/01*.26	077/33*.13
	e_2	268/07*.32	017/13*−.11	254/29*−.03	027/04*.07	344/04*−.03
	e_3	022/73*−.92	253/66*−.32	047/59*−.19	192/86*−.33	246/55*−.10
Twins/mm		53.6	33.4	22.5	18.2	12.6
	J2	.81	.38	.20	.30	.12
	M/m	18/22	23/28	25/31	16/20	28/34
	Nev's	18.1%	17.8%	19.3%	2%	17.6%
Numerical Inverse Method	S_1	203/02	199/29	289/43	202/42	268/77
	S_2	299/60	041/59	035/14	006/47	356/01
	S_3	109/39	294/10	137/44	105/08	087/13
	TNT	36	27	31	20	34
	TNU	30	33	32	28	26
	TPC	15	12	12	10	14
	R	0.3	0.8	0.9	0.7	0.9
Numeric Dynamic Method	a_1	267/63*.04	120/03*.54	141/18*.59	284/07*.33	086/20*.64
	a_2	012/08*−.01	022/06*−.21	236/12*−.23	179/64*−.13	203/51*−.28
	a_3	106/25*−.39	234/83*−.32	354/68*−.41	017/25*−.20	343/33*−.35
Grains with one e-twin set		64%	55%	53%	81%	39%
Grains with two e-twin sets		36%	45%	47%	19%	61%

4. Paleostress magnitudes analysis

4.1. Method

Estimates of paleodifferential stress magnitudes (paleopiezometry) using twins have various restrictions: temperature, strain hardening, grain size, grain size distributions and porosity condition paleopiezometric estimates (Newman, 1994; Ferrill, 1998). Usually, two paleopiezometric methods have been used; one is based on twin density (Rowe and Rutter, 1990) and the other on the percentage of carbonate grains with one, two, or three twin sets (Jamison and Spang, 1976). Usually the Rowe and Rutter method tends to overestimate the differential stresses. Ferrill (1998) has stated that for limestones that have been deformed at low temperatures, the technique of Jamison and Spang (1976) gives the best estimations, despite this approach having a severe limitation in the selected value for the critical resolved shear stress. Even though the resolved shear stress value of 10 MPa has been controversial, several authors agree that a value of 10 ± 5 MPa is reasonable (e.g. Lacombe, 2001). As we discussed earlier, the 'Numerical Inverse Method' also gives a value for the maximum differential stress (σ_1–σ_3). In this method, a critical point is the relative percentage of untwinned planes used during the stress inversion (Lacombe and Laurent, 1996), grain size distribution and the spatial distribution of c-axes. In the samples studied, the number of untwinned planes measured is relatively high, which might have conditioned the differential stress magnitudes obtained in this case using the Etchecopar inverse method. Nevertheless, the results of each different paleopiezometric method described above can differ by a factor of 4–20 (Ferrill, 1998). In this paper we used a different approximation; we tried to determine the differential stress magnitudes by combining deformation paleodepth and rock mechanics data.

4.2. Results

The results from applying the aforementioned techniques give overestimated differential stress magnitudes. The Rowe and Rutter technique gave magnitudes around 200 MPa, clearly over-estimated, making this method inapplicable to these conditions. The estimations made using the 'Numerical Inverse Method' gave a mean value of 37 MPa; such high values might be conditioned due to the high number of untwinned planes accounted for in the tensors solution. As we stated in point 3, during the twin formation episode, σ_1 was located subvertically, thus its magnitude must be equal to the lithostatic pressure. The paleodepth during twin formation was less than 300 m, because most of the samples are located at altitudes of 700 m and the topographical surface during the deformation event must be around 1000 m (at present, the highest point in this region is Cerro Mondúver, 843 m; Fig. 3). Therefore, the lithostatic pressure must be in the order of 7.35 MPa (dry conditions), depending on the rock density considered. On the other hand, the σ_3 value can be inferred

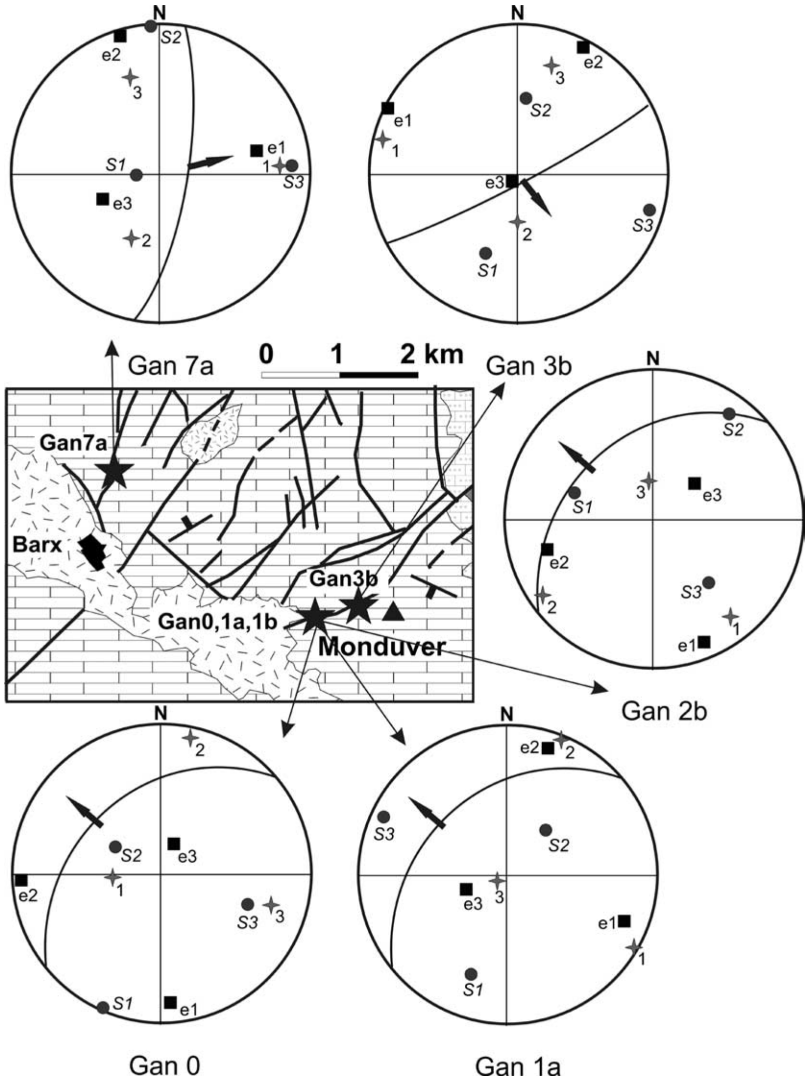

Fig. 6. Stereonets (Schmidt projection, lower hemisphere) showing principal stress orientations deduced from e-twin analyses (circles represent the results of the 'Numerical Inverse Method' and stars represent data from the Spang 'Numeric Dynamic Method'). The orientation of the principal strains has also been plotted; the squares represent the results from the strain gauge technique. The orientation of the fault plane and its striation has also been represented. The situation of the study area is shown in the map from Fig. 3.

from: (a) the Byerlee friction curve (Byerlee, 1978) if we considered that the twins are coeval with the fault slip or (b) with the failure envelope for limestones if twins are coeval with the rock failure.

The estimations were made using the Byerlee friction curve and the failure envelope proposed by Lacombe and Laurent (1992) and Rocher et al. (2004), which is based on the Coulomb failure criterion for intact rocks deduced from experimental deformations of limestones (Hoek and Brown, 1980). The estimated differential stresses ranged between 3.96 and 15.6 MPa depending on the friction or failure criterion considered (Fig. 7). As the twinned grains are only found close to the fault planes or in the fault gouge areas (Fig. 7), they probably formed during the fault slip event, in which case the friction curves give the best result. Furthermore, it is difficult to justify the formation of twins before the fault slip event during the tensional stage when fissures opened and were filled with travertines. Consequently, the paleodifferential stress values must be in the 3.96 and 5.89 MPa interval, depending on whether we considered maximum or minimum friction curves. These estimations imply resolved shear stress between 8 and 11 MPa, which are consistent with the previously proposed values (e.g. Lacombe, 2001). In all cases, these results were lower than those estimated with classical paleopiezometric techniques. This shows that they yield highly overestimated values for some cases by an order of magnitude.

5. Discussion and conclusions

The analysis of calcite e-twinning data reveals that the region studied here has undergone extensional tectonic deformation with a maximum NE–SW shortening. Similar results were obtained from fault population analyses or earthquake focal mechanisms (Herraiz et al., 2000). However, the best agreement with the regional tectonic frame was obtained by means of the strain analysis method,

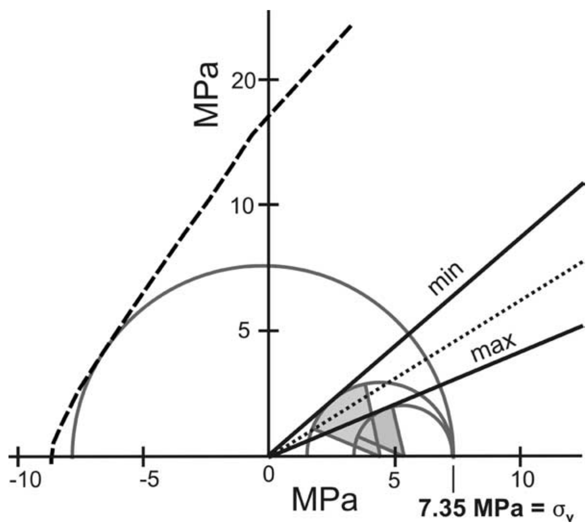

Fig. 7. Estimation of differential stress from the Mohr Plot. The Byerlee curves for maximum and minimum friction are shown. The fresh failure envelope for limestones is based on data from experimental deformation in limestones (Hoek and Brown, 1980). The orientation of fault planes with dips between 50 and 80° are also shown. Lithostatic pressure during e-twin formation represents σ_1 magnitude (extensional deformation).

assuming coaxial deformation. This is because in the strain analysis method, resolved shear stress values are not necessary in the calculation, whereas in the stress analysis method it is necessary to choose a resolved shear stress value and this value varies according to the environment where the twins were formed. In short, calcite grains represent little strain gauges with diverse orientations distributed throughout the rock; stress is obtained from the strain via the stress–strain relationship for the material, or from boundary conditions deduced from laboratory experiments. Clearly, the analysis of calcite e-twins is a useful tool with which to establish the characteristics of the stress tensor and with which to provide useful information on the recent stress field in this region.

The palaeo-differential stress magnitudes deduced here, which take into account lithostatic pressure and rock mechanics data, show that classical paleopiezometric techniques give overestimated values. On the other hand, these new data point out that e-twins can be formed with minimum differential stress during a fault slip event. These data also suggest that at low temperatures and confining pressures, the critical resolved shear stress during twinning can be lower than 10 MPa. Also an analysis of the Mohr diagram (Fig. 7) suggests that e-twins do not form during rock failure, but rather during fault slip, which explains the formation of e-twins under extensional regimes. Nevertheless, we must add a note of caution, as the calcite grains studied here might record local stress deviations and local stress concentrations rather than those from the regional stress field. This could explain the disagreement of results from the various stress methods used here and the high differential stress values. Finally, as these determinations can be made with small samples, this method can also be useful in places that are difficult to access.

Acknowledgements

We wish to thank R.H. Groshong, M. Burkhard and O. Lacombe for their constructive reviews of this paper. Software programmes by M.A. Evans (Evans and Groshong, 1994) have been used in this study as well as those by Etchecopar, modified by M. Rocher (Rocher et al., 2004). The authors are grateful for the kind permission to use this software. Financial support for this paper was provided by Project BTE(2002)-01742 (MCyT). We also thank to T.G. Blenkinsop for his useful suggestions and comments.

References

Angelier, J., Mechler, P., 1977. Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en sísmologie: le méthode des dièdres droits. Bulletin de la Société Géologique de France 7, 1309–1318.

Burkhard, M., 1993. Calcite twins, their geometry, appearance and significance as stress–strain markers and indicators of tectonic regime: a review. Journal of Structural Geology 15, 351–368.

Byerlee, J., 1978. Friction of rocks. Pure and Applied Geophysics 116, 615–626.

Craddock, J.P., Nielson, K.J., Malone, D.H., 2000. Calcite twinning strain constraints on the emplacement rate and kinematic pattern of the upper plate of the Heart Mountain Detachment. Journal of Structural Geology 22, 983–991.

Craddock, J.P., Farris, D.W., Roberson, A., 2004. Calcite-twinning constrains on stress-strain fields along the Mid-Atlantic Ridge, Iceland. Geology 32, 49–52.

Etchecopar, A., 1984. Etude des états de contraintes en tectonique cassante et simulation de déformations plastiques (approche mathématique). Ph.D. thesis, Université des Sciences et Techniques du Languedoc, Montpellier.

Evans, M.A., Groshong Jr., R.H., 1994. A computer program for the calcite strain-gauge technique. Journal of Structural Geology 16, 277–281.

Ferrill, D.A., 1991. Calcite twin width and intensities as metamorphic indicators in natural low-temperature deformation of limestone. Journal Structural Geology 13, 667–675.

Ferrill, D.A., 1998. Critical re-evaluation of differential stress estimates from calcite twins in coarse-grained limestones. Tectonophysics 285, 77–86.

Ferrill, D.A., Morris, A.P., Evans, M.A., Burkhard, M., Groshong Jr., R.H., Onasch, C.M., 2004. Calcite twin morphology: a low-temperature deformation geothermometer. Journal of Structural Geology 26, 1521–1529.

González-Casado, J.M., García-Cuevas, C., 1999. Calcite twins from microveins as indicators of deformation history. Journal of Structural Geology 21, 875–889.

González-Casado, J.M., García-Cuevas, C., 2002. Strain analysis from calcite e-twins in the Cameros basin, NW Iberian Chain, Spain. Journal of Structural Geology 24, 1777–1788.

Groshong Jr., R.H., 1972. Strain calculated from twinning in calcite. Geological Society of America Bulletin 83, 2025–2048.

Groshong Jr., R.H., 1974. Experimental test of the least-squares strain gauge calculation using twinned calcite. Geological Society of America Bulletin 85, 1855–1864.

Groshong Jr., R.H., Teufel, L.W., Gasteiger, C., 1984. Precision and accuracy of the calcite strain-gauge technique. Geological Society of America Bulletin 95, 357–363.

Gutierrez-Elorza, M., García-Ruiz, J.M., Goy, J.L., Gracia, F.J., Gutiérrez-Santaolalla, F., Martí, C., Martín-Serrano, A., Pérez-González, A., Zazo, C., 2002. Quaternary. In: Gibbons, W., Moreno, T. (Eds.), The Geology of Spain. Geological Society, London, pp. 325–358.

Herraiz, M., De Vicente, G., Lindo, R., Giner-Robles, J., Simón, J.L., González-Casado, J.M., Vadillo, O., Rodríguez-Pascua, M.A., Cicuéndez, J.I., Casas, A., Cabañas, L., Rincón, P., Cortés, A.L., Ramírez, M., Lucini, M., 2000. The Recent (upper Miocene to Quaternary) and present tectonic stress distributions in the Iberian Peninsula. Tectonics 19, 762–786.

Hoek, E., Brown, E.T., 1980. Underground Excavations in Rock. The Institution of Mining and Metallurgy, London.

Jamison, W.R., Spang, J.H., 1976. Use of calcite twin lamellae to infer differential stress. Geological Society of America Bulletin 87, 868–872.

Lacombe, O., 2001. Paleostress magnitudes associated with development of mountain belts: insights from tectonic analyses of calcite twins in the Taiwan Foothills. Tectonics 20, 834–849.

Lacombe, O., Laurent, P., 1992. Determination of principal stress magnitudes using calcite twins and rock mechanics data. Tectonophysics 202, 83–93.

Lacombe, O., Laurent, P., 1996. Determination of deviatoric stress tensors based on inversion of calcite twin data from experimentally deformed monophase samples: Preliminary results. Tectonophysics 255 (3–4), 189–202.

Lacombe, O., Angelier, J., Laurent, Ph., Bergerat, F., Tourneret, Ch., 1990. Joint analysis of calcite twins and faults slips as a key for deciphering polyphase tectonics: Burgundy as a case study. Tectonophysics 182, 279–300.

Lacombe, O., Bergues, J., Angelier, J., Laurent, Ph., 1991. Quantification des paléo contraintes à l'aide des macles de la calcite: l'exemple de la compression pyrénéo provençale au front de la Montagne Sainte-Victoire (Provence). Comptes Rendus de l'Académie des Sciences Paris 313, 1187–1194.

Lacombe, O., Angelier, J., Laurent, P., 1992. Determining paleostress orientations from faults and calcite twins: a case study near the Sainte-Victoire Range (southern France). Tectonophysics 201, 141–156.

Lacombe, O., Laurent, P., Angelier, J., 1994. Calcite twins as a key to paleostresses in sedimentary basins: preliminary results from drill cores of the Paris basin. In: Roure, F. (Ed.), Peri-Tethyan Platforms. Revue Institut Français du Pétrole, Technip, pp. 197–210.

Laurent, Ph., 1984. Les macles de la calcite en tectonique. Ph.D. thesis, Université des Sciences et Techniques du Languedoc, Montpellier.

Laurent, Ph., Bernard, Ph., Vasseur, G., Etchechopar, A., 1981. Stress tensor determination from the study of e-twins in calcite: a linear programming method. Tectonophysics 78, 651–660.

Laurent, P., Tourneret, Ch., Laborde, O., 2000. Determining deviatoric stress tensors from calcite twins: application to monophased synthetic and naturally polycrystals. Tectonics 9, 379–389.

Newman, J., 1994. The influence of grain size and grain size distribution on methods for estimating paleostresses from twinning in carbonates. Journal of Structural Geology 16, 1589–1601.

Pfiffner, O.A., Burkhard, M., 1987. Determination of paleostress axes orientations from fault, twin and earthquake data. Annales Tectonicae 1, 48–57.

Ríos-Aragües, L.M., Zapatero, M.A., Beltrán, F.J., Goy, J.L., Zazo, C., 1982. Geological map of Alcira. Instituto Geológico y Minero de España geological map 770, scale 1:50,000.

Rocher, M., Lacombe, O., Angelier, J., 1996. Mechanical twin sets in calcite as markers of recent collisional events in a fold-and-thrust belt: evidence from reefal limestones of south-western Taiwan. Tectonics 15, 984–996.

Rocher, M., Baize, S., Jaillet, S., Cushing, M., Lozac'h, Y., Lemeille, F., 2003. Quaternary stresses revealed by calcite twinning inversion: insights from observations in the Savonnieres underground quarry (eastern France). Comptes Rendus Geoscience 335/8, 701–708.

Rocher, M., Cushing, M., Lemeille, F., Lozac'h, Y., Angelier, J., 2004. Intraplate paleostresses reconstructed with calcite twinning and faulting: improved method and application to the eastern Paris Basin (Lorraine, France). Tectonophysics 387, 1–21.

Rowe, K.J., Rutter, E.H., 1990. Paleoestress estimation using calcite twinning: experimental calibration and application to nature. Journal of Structural Geology 12, 1–17.

Rueda, J., Mezcua, J., 2003. Estudio del terremoto del 23 de septiembre de 2001 en Pego (Alicante). Obtención de una relación m_bLg–M_w para la Península Ibérica. Revista de la Sociedad Geológica de España 15, 159–173.

Spang, J.H., 1972. Numerical method for dynamic analysis of calcite twin lamellae. Geological Society of America Bulletin 83, 467–472.

Tourneret, C., Laurent, P., 1990. Paleostress orientations from calcite twins in the north Pyrenean foreland, determined by the Etchecopar inverse method. Tectonophysics 180, 287–302.

Tourneret, C., Laurent, P., 1991. A new computer method for rapid and precise determination of calcite crystallographic orientation from u-stage measurements. Computers and Geoscience 17, 251–269.

Turner, F.J., 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. American Journal of Science 251, 276–298.

Turner, F.J., 1962. 'Compression' and 'tension' axes determined from [0112] twinning in calcite. Journal of Geophysical Research 67, 1660.

Weiss, L.E., 1954. A study of tectonic style: structural investigation of a marble quartzite complex in southern California. University of California Publications in Geological Science 30, 1–102.