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Calcite twin widths and intensities as metamorphic indicators in natural low-temperature deformation of limestone

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Abstract—Twins in naturally deformed coarse-grained limestones of the northern Subalpine Chain (France) show a direct relationship of twin width and intensity (number of twins per mm) to the peak metamorphism under diagenetic and anchimetamorphic conditions. The transition from dominant thin twinning to dominant thick twinning occurs between a mean vitrinite reflectance (*Ro*) of 1.60 and 2.60, or temperatures of between 150 and 200°C. Below the transition temperature, increasing strain is apparently accommodated by adding new twins, and above the transition temperature, increasing strain is accommodated by twin widening. Similar transitions from thin to thick twinning with increasing metamorphism are also present in the Helvetic Alps, the Prealps, and the Central Appalachian Valley and Ridge Province. These data for naturally deformed limestones support the interpretation from experimental studies of a temperature effect on twin width and intensity and indicate that the twinning in the northern Subalpine Chain occurred at or near peak metamorphism.

INTRODUCTION

MECHANICAL *e*-twinning of calcite is one of the principal deformational mechanisms in coarse-grained limestones deformed experimentally and naturally at low temperatures and pressures (Handin & Griggs 1951, Turner 1953, Carter & Raleigh 1969, Groshong 1988). Experimental studies suggest that twin widths could be a function of the temperature of deformation. Twins in calcite deformed at low temperature are thin, generally less than 5 μm wide (Groshong 1974, Friedman *et al.* 1976, Groshong *et al.* 1984a). In experiments performed at room temperature (about 25°C), increasing strain develops new thin twins, therefore the twin intensity increases (Turner & Ch'ih 1951, Groshong 1974). Experimental deformation of calcite at temperatures of 300°C and above produces thick twins, commonly more than 5 μm in width and commonly lensoid in shape, tapering towards the grain boundaries (Heard 1963, Schmid *et al.* 1980). Heard (1963) suggested that the development of thick twins in the higher temperature studies may result from increasing ease of migration of crystal lattice defects out of the crystals at higher temperatures, which reduces strain hardening adjacent to the twins. In this interpretation, higher temperature deformation allows twin widening to accommodate increasing strain, and at low temperatures, defects cause strain hardening, which means that new thin twins form with increasing strain (Heard 1963). The purpose of this paper is to compare calcite twins in naturally deformed limestones from the northern Subalpine Chain to the results of previous studies of twins produced in experimentally deformed limestones, and to use the experimental data as a key to understanding the natural deformational conditions.

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SUBALPINE CHAIN SAMPLES

The northern Subalpine Chain of eastern France is a fold dominated fold–thrust belt of Mesozoic sedimentary rocks that formed beneath the allochthonous cover of the Prealps (Fig. 1) (Collet 1927, Charollais *et al.* 1977). One of the principal stiff lithotectonic units and the best exposed unit of the northern Subalpine Chain is the Cretaceous Urgonian Limestone (approximately 200 m thick) which is generally massive, coarse-grained and fossiliferous, and it is therefore useful for regional analysis of limestone deformation mechanisms and calcite twin-strain analysis.

Metamorphism

Published vitrinite reflectance (Kübler *et al.* 1979), illite crystallinity (Kübler *et al.* 1979, Aprahamian & Pairis 1981) and metamorphic mineral assemblage data (Kübler *et al.* 1979) illustrate an increase in metamorphism across strike from low-temperature diagenesis in the foreland part to anchimetamorphism in the internal part of the Urgonian Limestone exposure belt. To allow for the direct comparison of the illite crystallinity data (Kübler index) of Aprahamian & Pairis (1981) to the vitrinite reflectance data, the data were converted to equivalent mean vitrinite reflectance (*Ro*) values using the equation from Guthrie *et al.* (1986). Kübler *et al.* (1979) divided diagenesis into diagenesis zones DZ-1–DZ-4. Anchimetamorphism is zone 5 (AZ-5). The diagenesis zone 1–2 boundary corresponds to a mean vitrinite reflectance value of 0.30, the zone 2–3 boundary is at 0.60, the zone 3–4 boundary at 1.60 and the zone 4–5 (anchizone) boundary at 2.60 (Fig. 1) (Kübler *et al.* 1979). Mean vitrinite reflectance values are thought to principally record maximum metamorphic temperatures (Teichmüller 1987). Temperature ranges for the Sub-

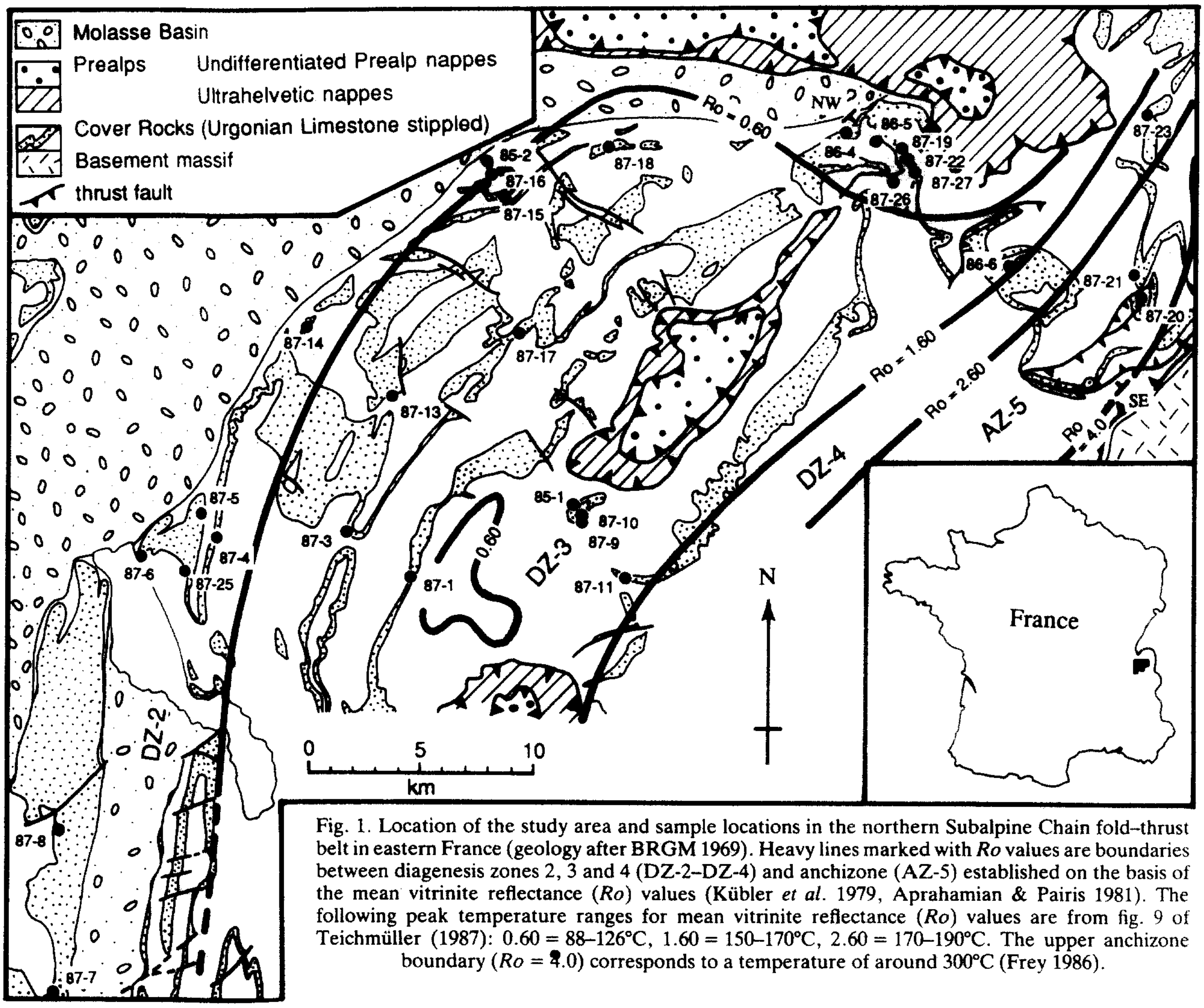

Fig. 1. Location of the study area and sample locations in the northern Subalpine Chain fold–thrust belt in eastern France (geology after BRGM 1969). Heavy lines marked with *Ro* values are boundaries between diagenesis zones 2, 3 and 4 (DZ-2–DZ-4) and anchizone (AZ-5) established on the basis of the mean vitrinite reflectance (*Ro*) values (Kübler *et al.* 1979, Aprahamian & Pairis 1981). The following peak temperature ranges for mean vitrinite reflectance (*Ro*) values are from fig. 9 of Teichmüller (1987): 0.60 = 88–126°C, 1.60 = 150–170°C, 2.60 = 170–190°C. The upper anchizone boundary (*Ro* = 4.0) corresponds to a temperature of around 300°C (Frey 1986).

alpine Chain metamorphic zone boundaries were determined using empirical temperature and mean vitrinite reflectance data (fig. 9 in Teichmüller 1987). Peak metamorphic temperatures increased from around 80°C in the foreland to around 300°C at the anchizone–epizone boundary (Frey 1986).

Sampling

Twenty-nine oriented samples of coarse-grained limestone (grainstone and packstone; 26 from the Urgonian Limestone, one from the underlying Cretaceous Hauterivian Limestone and two samples of Eocene limestone) were collected in the northern Subalpine Chain of eastern France (Fig. 1). Sampling was performed across the width (as much as 19 km) of the Urgonian Limestone outcrop belt and for a distance of 70 km along strike, from the Giffre River valley in the north, to south of Lac de Annecy. Samples were chosen to reflect regional strain patterns, avoiding local deformation near faults, and to represent the broadest range of metamorphism. For precision and accuracy of the measured twin strain magnitudes (Groshong *et al.* 1984b), two perpendicular thin sections (both normal to bedding) were cut from each sample, one parallel to strike and the other parallel to dip.

CALCITE TWINNING

Twin strain

Twinning strain was calculated for the samples using the strain gauge technique of Groshong (1972, 1974). Sixty twin sets (30 per thin section) were measured from each sample using a universal-stage. All twin sets were used in calculation of the strain, not just the dominant set for each grain. Calculations were made using the inner width for thick twins (measured within $\pm 0.5\,\mu$m), and a twinned material ratio of 0.5 for thin twins (after Groshong 1974). Two cleaning procedures were used to improve the results. In the first procedure (LDR), the 20% of the twin sets with the largest deviations were discarded to eliminate grains with the largest measurement errors and minimize problems due to inhomogeneous deformation (Groshong 1974, Groshong *et al.* 1984b). This is the standard cleaning procedure (Groshong *et al.* 1984b). The second procedure was used in addition to the LDR procedure, for the samples with one third or more twin sets having negative expected values (NEV), after the LDR cleaning procedure. Twin sets with negative expected values should not be twinned given the computed strain tensor. In the second cleaning procedure, the sets having the expected sense of shear

Table 1. Calcite twin data. Sample locations are shown in Fig. 1. e_1, e_2 and e_3 are percent elongations for the maximum, intermediate and minimum elongation directions, respectively. CP refers to the cleaning procedure: LDR = 20% largest deviations removed, PEV = positive expected values, NEV = negative expected values. Twin sets rem. = the number of sets removed in the cleaning process. Twin sets = the final number of sets used in the calculations. nev = the negative expected values (%) after cleaning. Error = the nominal error of strain values. Width and intensity refer to mean twin width and mean twin intensity, measured in μm and twins mm^{-1}, respectively. Zone refers to metamorphic zones within the diagenesis range (DZ-2–DZ-4) and anchizone (AZ-5), $\sqrt{J_2}$ is the square root of the second invariant of strain, used here as a measure of the total distortion by twinning (after Groshong *et al.* 1984a), measured in percent strain

Sample	CP	Twin sets rem.	Twin sets	Principal strains e_1	e_2	e_3	NEV	Error	Width	Intensity	Zone	$\sqrt{J_2}$
85-1	LDR	12	48	1.47	−0.14	−1.33	2.08	0.13	0.25	86.80	DZ-3	1.41
85-2	LDR	12	48	0.14	−0.01	−0.12	39.58	0.08	0.27	21.80	DZ-2	0.13
	PEV	1	29	0.80	−0.04	−0.77	3.45	0.10	0.27	34.34	DZ-2	0.79
	NEV	1	29	0.42	0.04	−0.46	6.90	0.06	0.26	21.59	DZ-2	0.44
86-4	LDR	12	48	1.57	−0.01	−1.57	27.08	0.27	0.50	40.54	DZ-2	1.31
86-5	LDR	12	48	3.49	−0.64	−2.84	14.58	0.38	0.81	39.00	DZ-2	3.21
86-6	LDR	12	48	1.20	0.20	−1.40	15.58	0.20	0.41	60.67	DZ-3	1.31
87-1	LDR	12	48	0.37	−0.09	−0.28	27.08	0.08	0.25	29.88	DZ-3	0.33
87-3	LDR	12	48	0.89	0.16	−1.04	20.83	0.17	0.26	50.68	DZ-3	0.97
87-4	LDR	12	48	0.68	0.09	−0.76	33.33	0.26	0.31	59.04	DZ-2	0.73
	PEV	2	32	4.31	1.39	−5.69	9.38	0.93	0.52	78.56	DZ-2	5.14
	NEV	1	25	1.10	−0.21	−0.89	8.00	0.27	0.26	52.00	DZ-2	1.01
87-5	LDR	12	48	2.55	0.36	−2.91	12.50	0.44	0.47	79.38	DZ-2	2.75
87-6	LDR	12	48	0.98	−0.25	−0.73	27.08	0.14	0.29	46.56	DZ-2	0.88
87-7	LDR	12	48	1.32	−0.59	−1.27	4.17	0.10	0.25	59.79	DZ-2	1.31
87-8	LDR	12	48	1.10	0.61	−1.71	4.17	0.15	0.29	74.67	DZ-2	1.50
87-9	LDR	12	48	0.83	0.47	−1.31	20.83	0.13	0.34	43.88	DZ-3	1.15
87-10	LDR	12	48	0.70	0.15	−0.85	16.67	0.13	0.25	41.50	DZ-3	0.78
87-11	LDR	12	48	0.23	0.02	−0.25	14.58	0.05	0.25	17.63	DZ-3	0.24
87-13	LDR	12	48	0.83	0.08	−0.91	10.42	0.08	0.28	38.50	DZ-3	0.87
87-14	LDR	12	48	1.60	−0.44	−1.16	14.58	0.22	0.29	65.21	DZ-2	1.43
87-15	LDR	12	48	1.53	−0.32	−1.21	12.50	0.31	0.27	86.63	DZ-3	1.40
87-16	LDR	12	48	2.55	0.25	−2.80	25.00	0.30	0.36	84.26	DZ-2	2.68
87-17	LDR	12	48	2.32	0.60	−2.92	12.50	0.22	0.40	64.13	DZ-3	2.67
87-18	LDR	12	48	0.41	0.15	−0.56	25.00	0.12	0.28	36.79	DZ-3	0.50
87-19	LDR	12	48	0.64	0.00	−0.64	16.67	0.07	0.30	26.04	DZ-2	0.64
87-20	LDR	12	48	4.99	−0.08	−4.91	33.33	1.77	4.39	35.83	AZ-5	4.95
	PEV	1	34	12.22	0.49	−12.71	0.00	2.01	5.78	40.88	AZ-5	12.47
	NEV	1	24	11.99	−2.48	−9.51	8.33	2.68	4.49	33.00	AZ-5	10.96
87-21	LDR	12	48	14.29	−5.53	−8.76	37.50	2.00	4.11	44.72	AZ-5	12.48
	PEV	2	36	19.56	−6.53	−13.03	8.33	2.01	5.39	44.33	AZ-5	17.25
	NEV	1	21	13.10	6.07	−19.17	9.52	3.11	3.02	50.95	AZ-5	16.97
87-22	LDR	12	48	2.72	−0.66	−2.06	16.67	0.22	0.32	79.54	DZ-2	2.46
87-23	LDR	12	48	4.99	−1.64	−3.35	37.50	0.66	1.57	37.46	DZ-4	4.41
	PEV	1	40	8.38	−2.24	−6.15	7.50	1.14	2.43	42.00	DZ-4	7.52
	NEV	1	19	3.78	1.44	−5.21	5.26	1.46	1.18	31.05	DZ-4	4.66
87-25	LDR	12	48	0.27	0.01	−0.28	8.33	0.04	0.27	16.33	DZ-2	0.28
87-26	LDR	12	48	0.77	0.45	−1.22	35.42	0.34	0.51	80.67	DZ-2	1.07
	PEV	2	27	7.16	−1.35	−5.81	7.41	1.32	0.48	94.15	DZ-2	6.59
	NEV	2	29	1.23	−0.32	−0.91	10.34	0.25	0.51	83.59	DZ-2	1.11
87-27	LDR	12	48	5.86	0.27	−6.13	14.58	0.73	0.99	75.96	DZ-2	6.00

for the calculated strain tensor (positive expected values; PEV) in the original data set of 60 twin sets, were separated from the NEV twin sets (Teufel 1980). Strains were then calculated for the PEV and NEV data sets separately, and each data set was cleaned by removing the 1–3 twin sets (less than 7% of the sets) with the largest deviations. The square root of the second invariant of strain (Jaeger & Cook 1979) is used in the following discussion as a measure of the total distortion (after Groshong *et al.* 1984a) (Table 1). Twin strains calculated using the LDR procedure for the samples range from 0.13 to 12.48%, however strains calculated for the PEV and NEV data are as large as 17.25 and 16.97%, respectively. The PEV and NEV strains may indicate two non-coaxial strains (Teufel 1980).

Twin width and intensity

Mean twin widths and twin intensities (twins mm^{-1}; Figs. 2 and 3) were calculated based on the averages for each of the twin sets used for calculating the strain magnitudes in each sample (Table 1). Average twin width (log scale) plotted vs twin strain (linear scale) illustrates that twin widths increase with twin strain (Fig. 4). The DZ-3 and DZ-2 samples plot together, indicating similar twinning behaviour in the two zones. The DZ-4 sample has a smaller twin strain (LDR) than one of the DZ-2 samples (4.41% vs 6.00%), yet the mean twin width for the DZ-4 sample (1.56 μm) is 57% larger than the mean twin width for the DZ-2 sample (0.99 μm). Including the PEV strains, the DZ-4 sample has a similar twin strain to two of the DZ-2 samples (7.52% vs 6.00% and 6.59%), but the DZ-4 samples has more than 2 and 5 times, respectively, the mean twin widths (2.43 vs 0.99 and 0.48 μm). The two AZ-5 samples have relatively large strains (4.95 and 12.48%, LDR; 10.96–17.25%, PEV and NEV) and dramatically larger mean twin widths (4.11 and 4.39 μm, LDR; 3.02–5.78 μm, PEV and NEV) than the samples from DZ-2 and DZ-3.

Plotting twin intensities vs strain (Fig. 5) shows that the AZ-5 and DZ-4 samples have relatively low intensities (<51 twins mm^{-1}; LDR, PEV and NEV). As a group, the twin intensities for the DZ-2 and DZ-3 samples generally increase with twin strain. Comparison of Figs. 4 and 5 illustrates that the DZ-4 and AZ-5 samples strained by twin widening rather than intensification. In contrast, the DZ-2 and DZ-3 samples strained by twin intensification and minor twin widening.

The two samples with the greatest twin widths (87-20 and 87-21, Fig. 3) have individual twin sets in which the thick twins average as much as 30 and 12.5 μm wide, respectively, and 68% and 63% of their twin sets have mean thick twin widths greater than 5 μm. Based on the metamorphic data, these two samples reached peak metamorphism in anchimetamorphic conditions (above 170–190°C, and below 300°C; Frey 1986, Teichmüller 1987, Burkhard & Kalkreuth 1989). The sample with the next highest mean twin width (87-23) has sets with thick twins that average as much as 7.5 μm in width, and 22% of the twin sets have mean thick twin widths of 5 μm or more. This sample reached DZ-4 conditions (between 150 and 190–200°C; Teichmüller 1987, Burkhard & Kalkreuth 1989). A nearby vitrinite reflectance value (Ro = 2.23; Kübler *et al.* 1979) suggests a temperature of 165–180°C for the sample (Teichmüller 1987). The other 26 samples reached peak metamorphism in DZ-2 and DZ-3 conditions, at approximate temperatures below between 150 and 170°C which corresponds to Ro = 1.6, and above between 55 and 105°C which corresponds to Ro = 0.43, the lowest Ro value in the study area (Kübler *et al.* 1979). Only three of these samples (86-4, 86-5, 87-27) have any twin sets measured with mean thick twin widths of 5 μm or more (2, 12 and 2% of twin sets, respectively).

By projecting all of the samples onto a restored metamorphic profile (fold and thrust shortening removed) along the Arve River (Fig. 6), it is seen that the mean twin widths mimic the metamorphism and corresponding peak temperature, increasing to the southeast from 0.25 to 0.99 μm in DZ-2 and DZ-3 (LDR, PEV and NEV) to 1.57 μm (LDR; 2.43 and 1.18 μm, PEV and NEV) in DZ-4, and 4.11–4.39 μm (LDR; 3.02–5.78 μm, PEV and NEV) in AZ-5. However, the twin intensities show no such correlation. They range from 17.63 to 86.80 twins mm^{-1} (LDR, PEV and NEV) in DZ-2 and DZ-3, and from 35.83 to 44.72 twins mm^{-1} (LDR; 31.05 to 50.95 twins mm^{-1}, PEV and NEV) in DZ-4 and AZ-5.

DISCUSSION

The transition from dominant thin twinning to dominant thick twinning in the northern Subalpine Chain occurs between Ro = 1.6 and 2.6 which corresponds to temperatures between 150 and 190°C (Teichmüller 1987) or 200°C (Burkhard & Kalkreuth 1989). The observations of twin widths and intensities for the naturally deformed limestones in this study compare well with the qualitative results of experimental studies of calcite deformation (Turner & Ch'ih 1951, Heard 1963, Groshong 1974, Friedman *et al.* 1976, Schmid *et al.* 1980). The correspondence of the twin width data to the peak metamorphic conditions experienced by the samples, and experimental data illustrating the onset of thick twin development at around 300°C, suggest that the twinning occurred during the metamorphism, and that differences reflect the effects of the across-strike metamorphic gradient.

A transition from thin to thick twinning corresponding to increasing metamorphism was first qualitatively observed in naturally deformed limestones by Groshong *et al.* (1984a) in the Helvetic Alps of eastern Switzerland. Similar relationships between twin width and peak metamorphism are also present in the Prealps of Switzerland, and the Central Appalachian Valley and Ridge Province in the eastern United States. Groshong *et al.* (1984a) observed, based on 13 samples, that twin lamellae in the frontal part of the Helvetic Alps (northern edge of Upper Glarus nappe complex) are thin and straight, in the intermediate parts (Lower Glarus nappe complex) the twins are thicker, and in the internal parts (Infrahelvetic complex) they are thick and often bent. Metamorphism in the internal parts reached $Ro > 3.5$ and in the front and intermediate parts $Ro < 3.5$ (fig. 9 in Groshong *et al.* 1984a), which corresponds to a temperature of around 270°C (Groshong *et al.* 1984a).

In the Prealps (Switzerland), Mosar (1989) identified a transition, based on 38 samples, from straight and thin twins in limestones that reached peak metamorphism in diagenetic conditions, to thick twins in limestones that reached peak metamorphism in anchizone conditions (Mosar 1988). The transition corresponds to the lower anchizone boundary (Mosar 1989) or a temperature of around 170–190°C (from fig. 9 in Teichmüller 1987) or 200°C (Burkhard & Kalkreuth 1989).

In the internal part of the Central Appalachian Valley and Ridge Province (North Mountain thrust sheet, Virginia), measured calcite twin shortening strains range from −1.1% to −8.1% (19 samples; Evans & Dunne 1991). Each of the samples has thick twins, regardless of the strain magnitude (Evans personal communication 1990). Evans & Dunne (1991) used conodont color alteration indices and deformation mechanism maps to demonstrate that the microstructural deformation occurred at temperatures between 250 and 350°C. In contrast, limestone samples from more forelandward positions in the Central Appalachian Valley and Ridge Province (Maryland and Pennsylvania) have principal

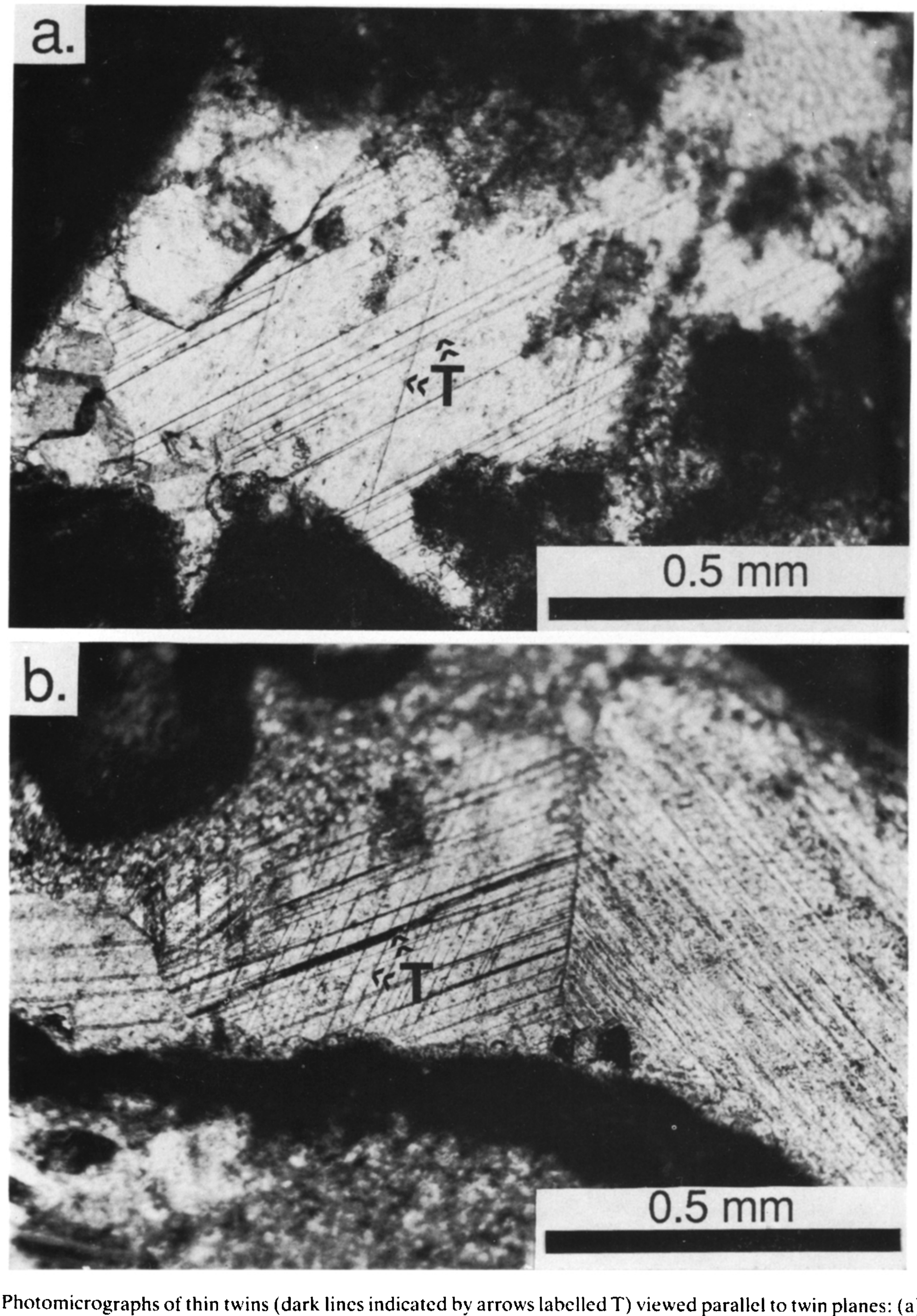

Fig. 2. Photomicrographs of thin twins (dark lines indicated by arrows labelled T) viewed parallel to twin planes: (a) sample 87-19 has 0.64% twin strain (square root of the second strain invariant), mean twin width = 0.30 μm and twin intensity = 26.04 twins mm^{-1}; and (b) sample 87-27 has 6.00% twin strain, mean twin width = 0.99 μm and twin intensity = 75.96 twins mm^{-1}.

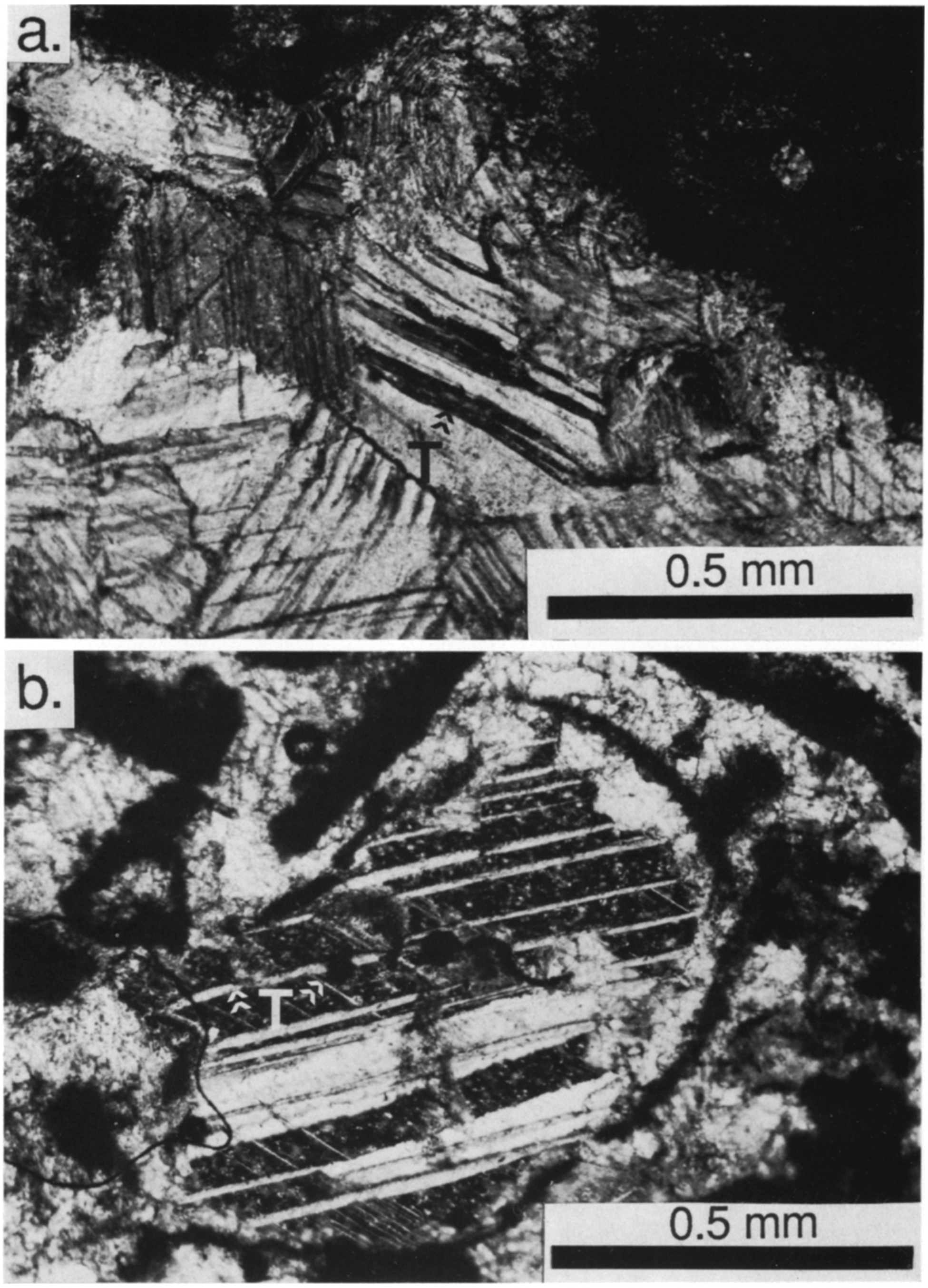

Fig. 3. Photomicrographs of thick twins (indicated by arrows labelled T). (a) Sample 87-20 has 4.95% twin strain (LDR; 12.47%, PEV; 10.96%, NEV), mean twin width = 4.39 μm (LDR; 5.78 μm, PEV; 4.49 μm, NEV), and twin intensity = 35.83 twins mm^{-1} (LDR; 40.88 twins mm^{-1}, PEV; 33.00 twins mm^{-1}, NEV). Twin strain is given as the square root of the second strain invariant, a measure of the total distortion by twinning (Jaeger & Cook 1979, Groshong *et al.* 1984a). LDR refers to data cleaned by removing the 20% of the twin sets with the largest deviations. PEV refers to positive expected values and NEV refers to negative expected values in the original data set, that were separated and cleaned for samples having one-third or more negative expected values after the LDR procedure. Twins in central grain appear as dark bands. (b) Sample 87-21 has 12.48% twin strain (LDR; 17.25%, PEV; 16.97%, NEV), mean twin width = 4.11 μm (LDR; 5.39 μm, PEV; 3.02 μm, NEV) and twin intensity = 44.72 twins mm^{-1} (LDR; 44.33 twins mm^{-1}, PEV; 50.95 twins mm^{-1}, NEV). Twins in the central grain appear as light bands.

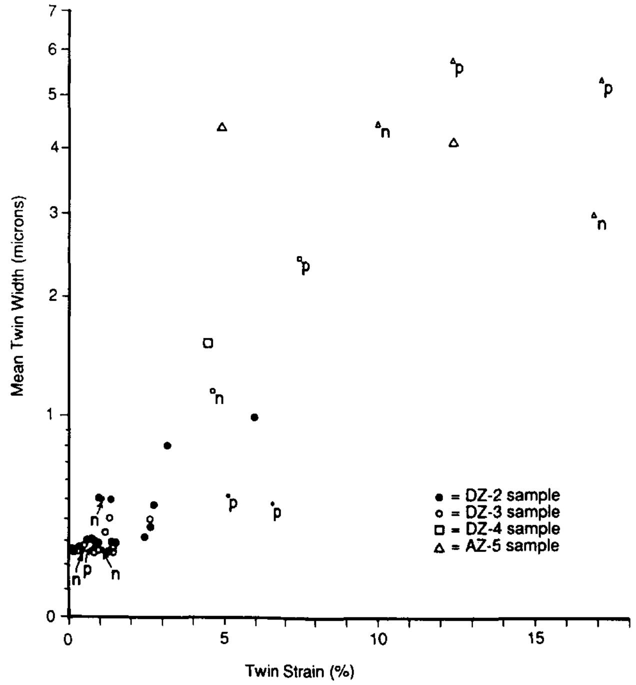

Fig. 4. Average twin width on a logarithmic scale vs twin strain (square root of second invariant of strain). The graph shows that the twin widths are quite similar for samples from DZ-2 and DZ-3, and that widths increase dramatically with strain for the samples from DZ-4 and AZ-5. LDR data for all samples are shown using large unlabelled symbols. Small symbols labelled p and n represent PEV and NEV data, respectively.

twin shortening strains that range from −0.5% to −12.7%, yet the twins are thin (27 samples; Groshong 1972, 1975, Spang & Groshong 1981). Burial temperatures were estimated, based on burial depth and conodont color alteration indices, to be less than 170–190°C for these samples (Groshong 1975, Spang & Groshong 1981).

The twin data for the northern Subalpine Chain, the Helvetic Alps, the Prealps, and the Central Appalachian Valley and Ridge Province all indicate that a transition from thin to thick twinning corresponds to increasing temperature, independent of strain. The transition appears to occur around the lower boundary of anchizone metamorphism, with the exception being the Helvetic Alps of eastern Switzerland. In the northern Subalpine Chain, the transition is within DZ-4 or temperatures around 150–200°C. In the Prealps, the transition has been placed at the lower anchizone boundary (approximately 170–200°C), and in the Central Appalachians in the general range of 190–250°C. In contrast, the transition in the Helvetic Alps corresponds to a mean vitrinite reflectance of 3.5 or a temperature around 270°C (Groshong *et al.* 1984a). However, Groshong *et al.* (1984a) reported that the twinning did not occur at peak metamorphism (because the twins recrystallized), but preceded the metamorphic peak. The transition, therefore, actually developed at a mean vitrinite reflectance less than 3.5 and a lower temperature.

The transition from thin to thick twinning in naturally deformed limestones apparently occurs at or below the lower anchizone boundary at temperatures in the range of 150–200°C which is significantly lower than the inferred transition at around 300°C in experimental studies (Heard 1963, Schmid *et al.* 1980, Groshong *et al.* 1984a). This difference could be due to the difference between the strain rates of the experiments (10^{-1}–$10^{-8}\,s^{-1}$; Heard 1963, Groshong 1974, Friedman *et al.* 1976, Schmid *et al.* 1980) and rates typical of natural deformation (10^{-13}–$10^{-15}\,s^{-1}$; Pfiffner & Ramsay 1982). The lower strain rates in the natural deformation may allow for migration of crystal lattice defects out of the crystals at lower temperatures than in the experiments, thereby reducing the strain hardening effect discussed by Heard (1963).

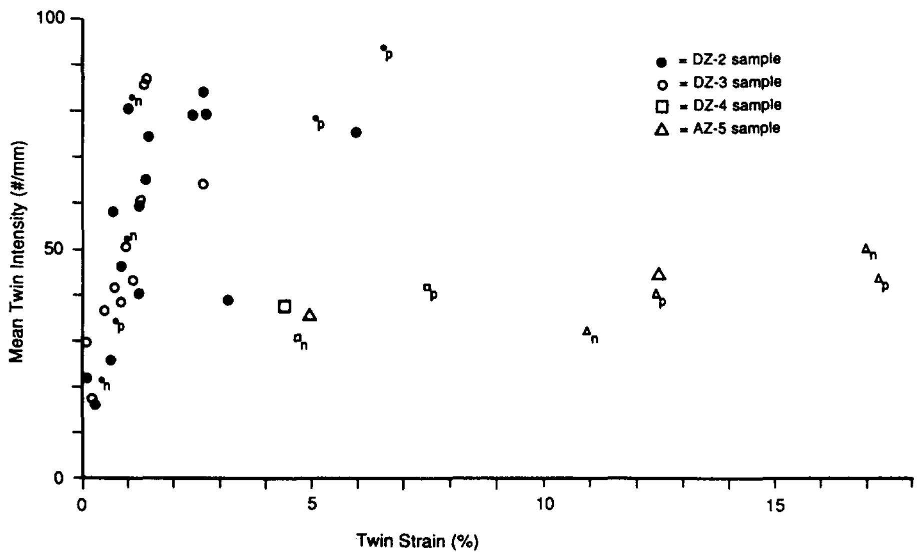

Fig. 5. Mean twin intensity plotted vs twin strain (square root of second invariant of strain). The DZ-2 and DZ-3 samples show similar twinning behavior, but the DZ-4 and AZ-5 samples reached strains of 4.41 and 12.48% (LDR) without having markedly large twin intensities. LDR data for all samples are shown using large unlabelled symbols. Small symbols labelled p and n represent PEV and NEV data, respectively.

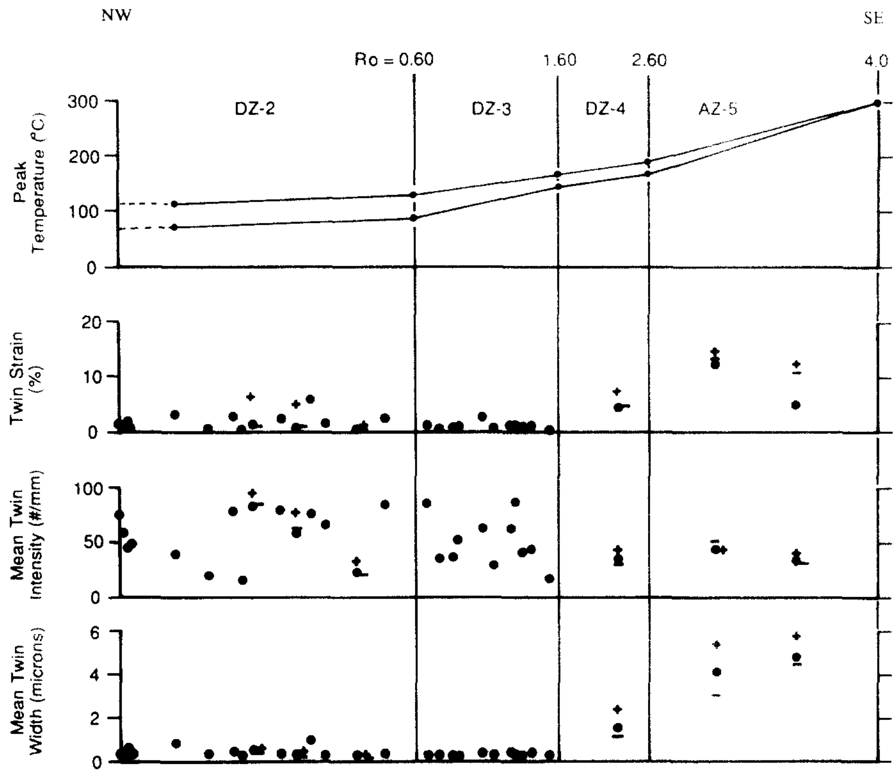

Fig. 6. Plots of (a) peak metamorphic temperature, (b) twin strain (square root of second strain invariant), (c) mean twin intensity (twins mm^{-1}) and (d) mean twin width (μm), vs cross-strike position along a restoration of the cross-strike transect along the Arve River. Large dots represent LDR data. + and − symbols represent PEV and NEV data, respectively. See Fig. 1 for location of the deformed-state profile line labelled NW–SE.

CONCLUSIONS

Changes in twin width and intensity correspond to twin strain and metamorphism in naturally deformed coarse-grained limestones. Increasing twin strain at temperatures below 150–170°C (DZ-2 and DZ-3) occurs by twin intensification. In anchizone conditions, increasing strain causes twin widening rather than twin intensification. The transition from thin twinning to thick twinning in naturally deformed limestones occurs between 150 and 200°C, below the 300°C transition temperature that has been observed in experiments.

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