PERGAMON

Journal of Structural Geology 21 (1999) 711–718

JOURNAL OF
STRUCTURAL
GEOLOGY

Are crenulation cleavage zones mylonites on the microscale?

Manish A. Mamtani[a,]*, R.V. Karanth[b], R.O. Greiling[a]

[a]*Geologisch–Paläontologisches Institut, Ruprecht Karls Universität Heidelberg, INF-234, D-69120 Heidelberg, Germany*
[b]*Department of Geology, Faculty of Science, M.S. University of Baroda, Vadodara 390002, Gujarat, India*

Received 9 February 1998; accepted 2 March 1999

Abstract

Mylonites commonly show characteristic structures such as *S–C* fabric and *C′* type shear bands. In the present paper, the presence of similar structures on the microscale is reported from the cleavage zones of differentiated crenulation cleavage in garnet biotite schists belonging to the Lunavada Group of Proterozoic metasedimentary rocks, India. These rocks have experienced three episodes of deformation. A differentiated crenulation cleavage (S_2), characterized by alternating cleavage zones and microlithons developed during D_2 by microfolding of the S_1 foliation. Although the schists under investigation do not show any macroscopic- or mesoscopic-scale evidence of mylonitization, they show the presence of shear structures within the cleavage zones. The fabric resembling *S–C* and *C′* shear bands within these zones indicates shearing within them during D_2 deformation. A model incorporating shearing along the cleavage zones is proposed to explain the genesis of shear structures within them. Accordingly, it is invoked that solution transfer and grain rotation are important deformation mechanisms during the early stages of crenulation and this results in the migration of quartz from the limbs to the hinges of the microfolds. At the later stages of crenulation the phyllosilicates (micas) forming the limbs of the microfolds are at an oblique angle to the direction of shortening and most of the mobile material like quartz has already been removed from the limbs by solution transfer. Therefore, the stress conditions are ideal for shearing and intracrystalline crystal–plastic deformation to occur along the limbs during the later stages of crenulation. It is proposed that the fabric resembling *S–C*, embryonic *C′* type shear bands and well developed *C′* (in that order) develop with increasing strain and shearing within the cleavage zones. At still higher strains, the shear bands may rotate into parallelism with the domain boundary between the cleavage zones and the microlithons. Composition of muscovite constituting cleavage zones and microlithons is discussed and it is concluded that the deformation mechanisms that operate during the later stages of crenulation, especially under upper greenschist to lower amphibolite conditions, are similar to those during mylonitization. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Mylonites are fine-grained rocks that occur in ductile shear zones (Berthé et al., 1979; White et al., 1980; Tullis et al., 1982; Passchier and Trouw, 1996) produced by crystal–plastic deformation mechanisms (Nicolas and Poirier, 1976; White et al., 1980; Tullis et al., 1982; Ramsay and Huber, 1987; Passchier and Trouw, 1996). Structures such as shear bands characterized by *S–C* and *C′* fabrics (Fig. 1) are commonly associated with mylonites (e.g. Berthé et al., 1979; Platt and Vissers, 1980; White et al., 1980; Blenkinsop and Treloar, 1995). They develop during ductile shearing along a plane of anisotropy (Platt and Vissers, 1980) and the phenomenon of intracrystalline crystal–plastic deformation is considered to be an important deformation mechanism during their formation. In the Precambrian rocks from the Southern Aravalli Mountain Belt (SAMB), western India, similar shear structures are observed on the microscopic scale within cleavage zones of differentiated crenulation cleavages occurring in garnet biotite schists. Processes such as solution transfer, volume loss and pressure solution accompanied with grain rotation are considered as im-

---

* Corresponding author. Present address: Department of Geology, Faculty of Science, M.S. University of Baroda, Vadodara 390002, Gujarat, India.

E-mail address: mamtani@hotmail.com (M.A. Mamtani)

0191-8141/99/$ - see front matter © 1999 Elsevier Science Ltd. All rights reserved.
PII: S0191-8141(99)00062-0

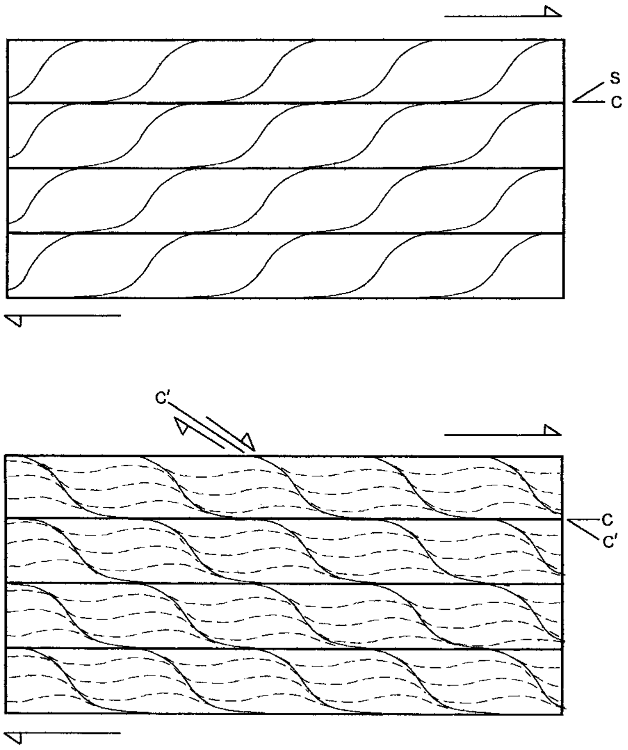

Fig. 1. Sketch showing S–C and C' fabric.

portant mechanisms during crenulation cleavage genesis (Williams, 1972, 1977; Cosgrove, 1976; Gray, 1977, 1978, 1979; Marlow and Etheridge, 1977; Gray and Durney, 1979). However, based on the presence of microscale shear structures within cleavage zones of schists from the SAMB, it is envisaged that processes similar to those operating during mylonitization might also be operative during crenulation cleavage genesis. It is this problem/question that is investigated in the present paper.

2. Geological setting and structure of the study area

The Proterozoic Lunavada Grap belongs to the Aravalli Supergroup and is dominantly a layered sequence of alternating quartzites and metapelites, mainly mica schists (Gupta and Mukherjee, 1938; Gupta et al., 1980, 1992). Along with the overlying Champaner Group and intrusive Godhra Granite (955 Ma old, Gopalan et al., 1979), the Lunavada Group builds up the SAMB and occupies an area of approximately 10 000 km^2. Mapping of the area around Lunavada, Santrampur and Kadana has revealed that the rocks have undergone regional scale polyphase folding (F_1, F_2 and F_3 related to D_1–D_3 deformation episodes) and metamorphism up to lower amphibolite facies. The superimposition of these three fold episodes has resulted in large scale interference patterns (Fig. 2). The F_1 folds have a reclined attitude with NE–SW-trending axes. The second folding coaxial with F_1 also yields NE–SW-trending axes. This coaxial superimposition of F_2 on F_1 resulted in large-scale Type III interference pattern (Ramsay and Huber, 1987), which is obvious on the map in the region to the south of Lunavada (Fig. 2). D_3 deformation was weak and developed macroscopic F_3 open flexures on the kilometer-scale limbs of F_1/F_2 folds with NW–SE to WNW–ESE axes and Type I interference patterns observable in map view to the northeast of Lunavada (Fig. 2) (Mamtani et al., 1998). A NW–SE-trending mineral lineation is observed on S_2 foliations at several places in the study area which developed due to shearing along the foliation planes during D_2. The present study concerns crenulated garnet biotite schists belonging to the Lunavada Group which show shear structures along the cleavage zones. It is important to mention that all the microstructures discussed in this paper developed during D_2 and are not related in any way with the subsequent D_3 deformation event. Not only was D_3 weak and gave rise to open folds, but the F_3 fold axes are oriented near perpendicular to the axes of the earlier folds. Therefore, if any S_3 foliation was to develop, it would lie at a high angle to the S_2 foliation and cut across the entire rock sequence. Field studies and detailed investigations of a large number of thin sections from the entire area have not revealed any such evidence. We therefore conclude that the microstructures discussed in the present paper are related only to the D_2 deformation.

3. Microstructures in garnet biotite schists

Among the various microstructures displayed by the garnet biotite schists under study differentiated crenulation cleavages or zonal cleavages characterized by alternating quartz (Q) domains and mica (M) domains are the most prominent ones. Two schistosities, S_1 and S_2 (related to D_1 and D_2), commonly lying at high angle to each other are often preserved. However, a few thin sections also show the presence of the bedding surface (S_0) which lies obliquely to S_1. S_1 is a slaty cleavage while S_2 is a differentiated crenulation cleavage due to microfolding of S_1 foliation during D_2. The schists contain porphyroblasts of garnet and biotite with S_1 inclusion trails of quartz. Using the criteria of Zwart (1962) and Passchier and Trouw (1996), the time relationship between crystallization and deformation was established. Relationships between S_i (internal foliation) and S_e (external foliation) show that the garnet and biotite porphyroblasts have grown during different stages of S_2 (crenulation cleavage) development, hence of D_2 (Mamtani and Karanth, 1997). The S_i–S_e relationships are variable—S_i in some

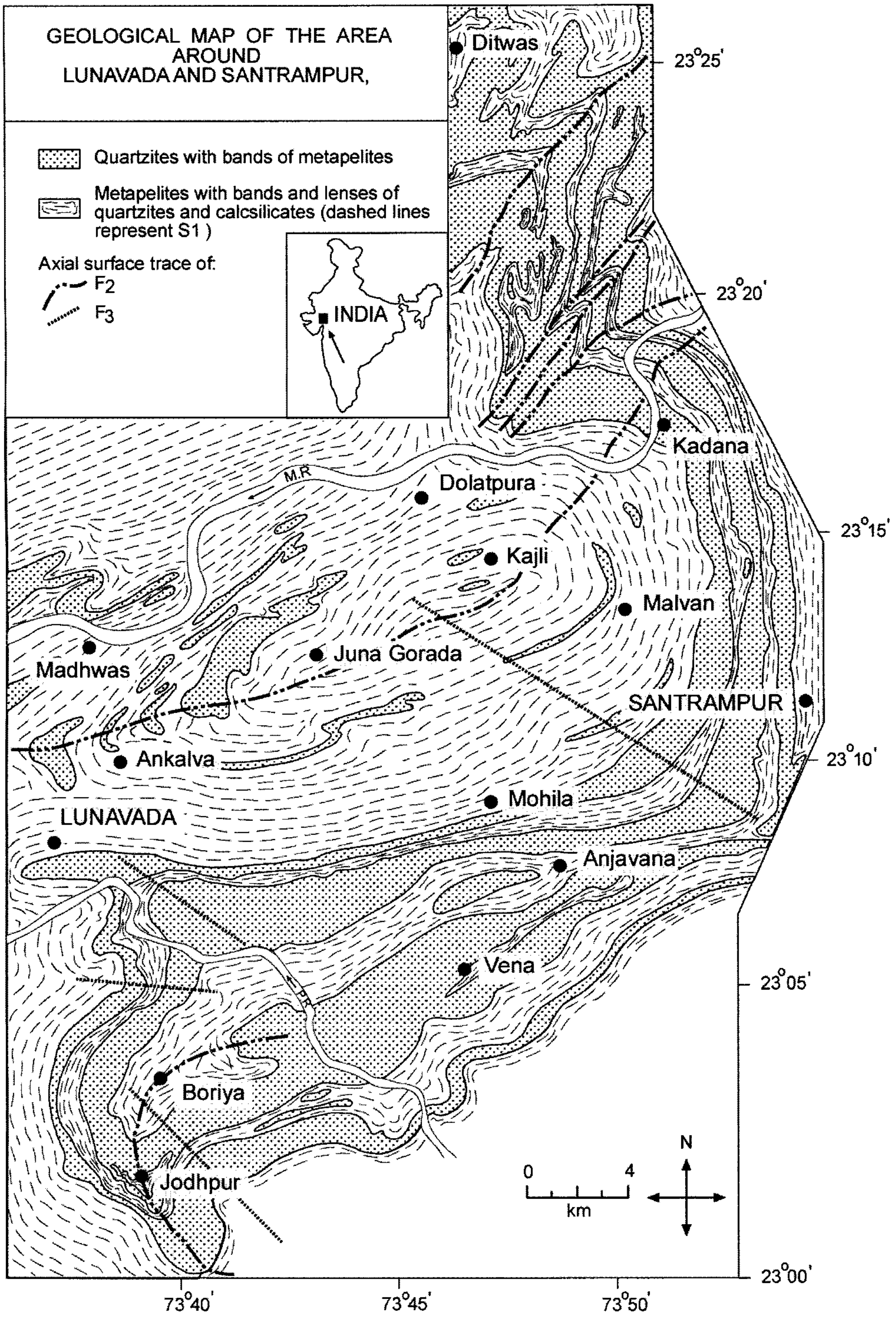

Fig. 2. Geological map of the study area. Arrow in inset points to the study area. M.R is Mahi river and P.R is Panam river.

porphyroblasts is openly folded while S_e is tightly crenulated, pointing to their early syn-D_2 growth; in others S_i is tightly crenulated while the S_e is totally homogenized into a single schistosity, hence pointing to a relatively late growth of porphyroblasts during D_2. The cleavage zones or mica domains are generally 0.1–0.3 mm in thickness but may reach 0.5 mm. They are characteristically built up of several mica aggregates across their width, showing undulose extinction and have seams of insoluble dark material (possibly graphite). Thin sections reveal that, with the exception of a few microfolds, most of them are asymmetric on the microscopic scale and that the micas are concentrated along elongated limbs of the asymmetric microfolds. This implies that during D_2 deformation, there must have been an oblique relationship between the S_1

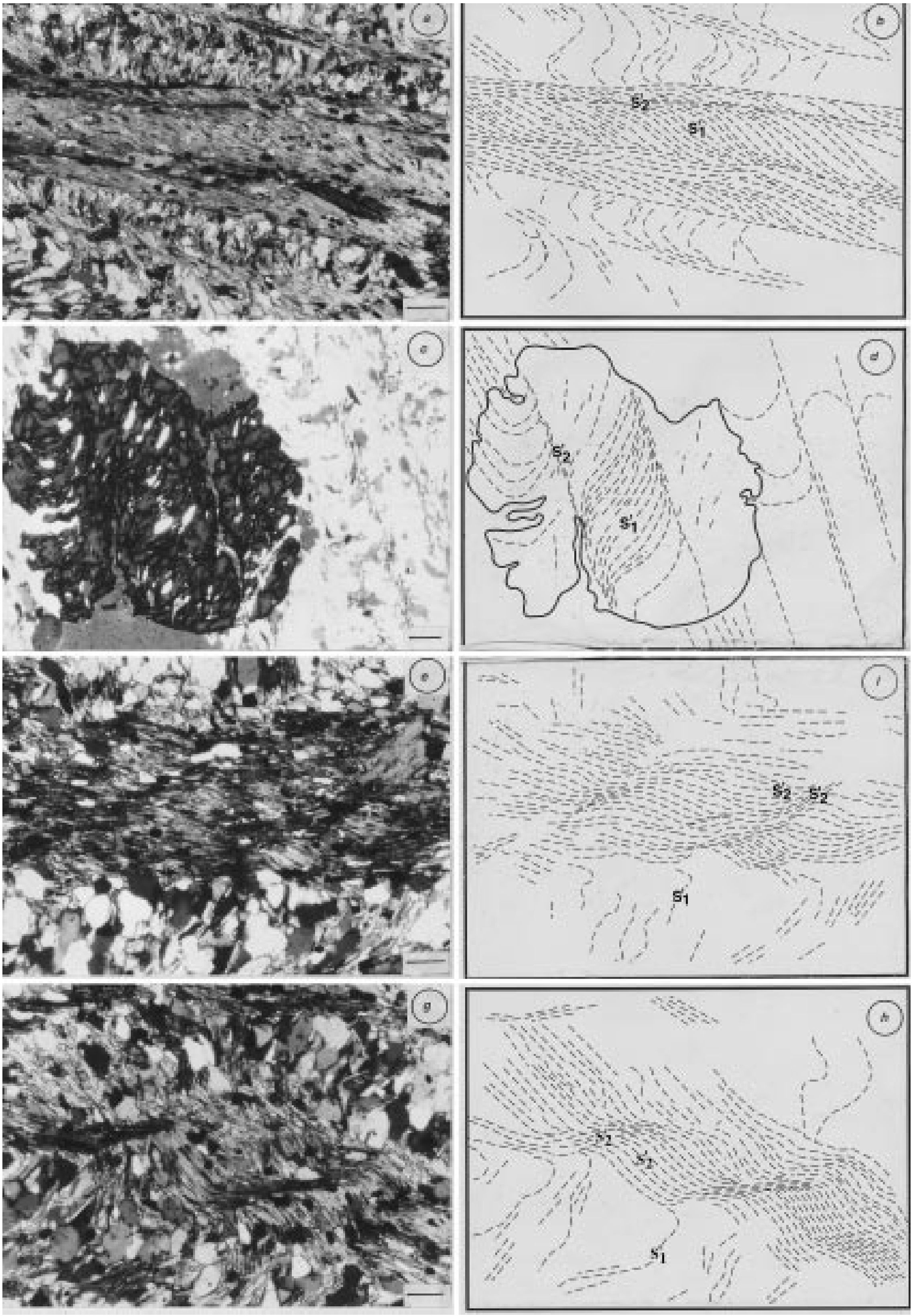

Fig. 3. (a) Photomicrograph showing the sigmoidally curving S_1 mica aggregates within the cleavage zones. (b) Explanatory line drawing of (a). (c) Photomicrograph of a garnet porphyroblast preserving the sigmoidal S_1 inclusion trails of quartz gradually curving into the S_2 cleavage. (d) Explanatory line drawing of (c). (e) Photomicrograph showing the S_2' cleavage in its embryonic stage of development within the cleavage zones. (f) Explanatory line drawing of (d). (g) Photomicrograph showing a well developed S_2' within the cleavage zone. (h) Explanatory line drawing of (g). Bar scale represents 0.1 mm in (a), (c), (e) and (g).

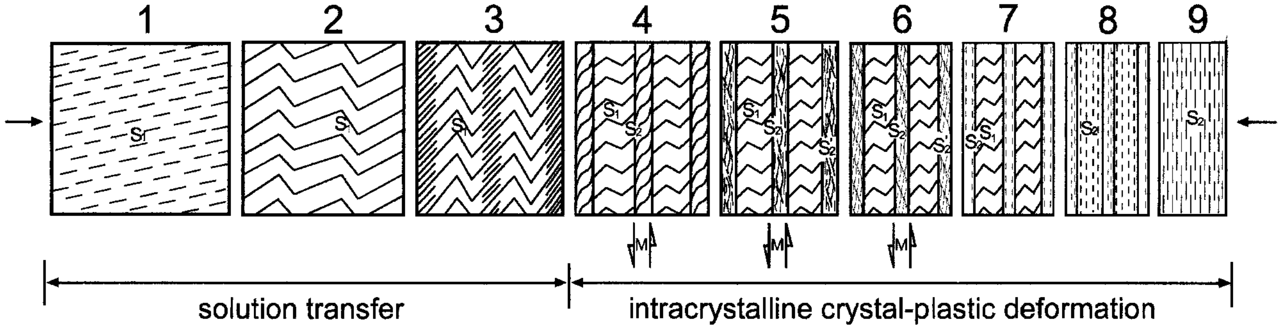

Fig. 4. Nine stage model depicting the progressive evolution of crenulation cleavage and microstructures within the cleavage zones with increasing strain. In stage 1, a pre-existing schistosity S_1 is shown which starts crenulating in stage 2. In stage 3 the rock achieves a domainal fabric wherein the limbs of the microfolds have a higher concentration of micas (M domains) and the hinges are richer in quartz (Q domains). Further deformation results in the sigmoidal curving of mica crystals into the domain boundary (S_2) on account of shearing within the cleavage zones as is shown in stage 4. This is followed by the development of S_2' cleavage within the cleavage zones. First embryonic S_2' develops in stage 5 and then a well developed S_2' develops in stage 6. With increasing strain and shearing the S_2' within the cleavage zones rotate into parallelism with the domain boundary in stage 7 but the microfolds in the Q domains are still preserved. In stage 8 the microfolds within the Q domains are destroyed and the rock possesses only a single schistosity S_2 which is totally homogenized in stage 9. Solution transfer is the dominant mechanism up to stage 3 while intracrystalline crystal–plastic deformation is dominant in the subsequent stages.

foliation and the D_2 shortening direction on the scale of observation (i.e. on the microscale), which resulted in the development of asymmetric crenulations.

A careful observation of the S_2 mica domains (cleavage zones/cleavage lamellae) shows the presence of a microstructure resembling the fabric found in mylonites (Fig. 3). Several cleavage zones show mica aggregates sigmoidally curved into parallelism with the domain boundary, i.e. the S_2 surface or contact between quartz and mica domains (Fig. 3a and b). Similar microfabrics are also preserved within a few garnet and biotite porphyroblasts, the S_1 quartz inclusion trails being sigmoidally curved into the S_2 surface trapped in the porphyroblast (Fig. 3c and d). This fabric is similar in shape to the *S–C* fabric observed in mylonites. A few cleavage zones also show a secondary cleavage S_2' (Fig. 3e–h). The S_2' is either faintly developed and is preserved in its embryonic stage in a few cleavage zones (Fig. 3e and f) or it is well developed in other cleavage zones (Fig. 3g and h). These S_2' planes always occur at low angle ($<45°$) to the domain boundary and impart a 'button schist' appearance to those cleavage zones where they are well developed. In addition, the mica crystals that comprise the S_2' planes show undulose extinction. The above characteristics suggest that the S_2' planar structures are similar to C' type shear bands or extensional crenulation cleavages found in mylonites (e.g. Berthé et al., 1979; Platt and Vissers, 1980; White et al., 1980; Lister and Snoke, 1984; Passchier and Trouw, 1996).

3.1. Evolution of crenulation cleavage

A nine-stage model for the evolution of differentiated crenulation cleavage compiled from the above observations can explain the genesis of *S–C* and C' type fabrics within the cleavage zones (Fig. 4). In this model, the crenulation cleavage (S_2) is initiated through microfolding of a pre-existing schistosity (S_1) which is itself defined by a shape preferred orientation of quartz and mica crystals. From stages 1 to 3 the process of crenulation and tightening of the microfolds occurs on account of pressure solution accompanied by passive rotation of mica grains; quartz migrated by solution transfer from the limbs of the microfolds to the hinges while the micas concentrated along the limbs of the microfolds (Williams, 1972, 1977; Cosgrove, 1976; Gray, 1977, 1978, 1979; Marlow and Etheridge, 1977). The presence of dark seams of insoluble material along the mica-domains indicates that solution transfer was an active deformation mechanism. As a consequence the rock achieved its domainal fabric characterized by alternating quartz- and mica-domains. At the end of stage 3, the cleavage zones are made of S_1 mica aggregates lying obliquely to the domain boundaries. As suggested by Williams and Schoneveld (1981), S_2 surfaces may become 'active', ready to undergo shearing, after all the mobile material has been removed from them. Accordingly, the microfabric at stage 3 (Fig. 4) is ideal for intracrystalline crystal–plastic deformation and shearing to proceed along the cleavage zones. This shearing resulted in the progressive sigmoidal curving of the S_1 mica aggregates into the domain boundary, a fabric which resembles *S–C* fabric found to develop in mylonites (stage 4 in Fig. 4). With increasing strain and shearing along the cleavage zones, the embryonic S_2' developed at low angles ($<45°$) to the domain boundaries (stage 5 in Fig. 4) and later well developed S_2' surfaces developed (stage 6 in Fig. 4). These S_2' surfaces resemble the C' surfaces as observed in mylonites. There is no evidence of volume loss accompanying the formation of S_2' because solution transfer was probably completed to a large extent during the earlier stages of the formation of the crenulation cleavage (up to stage 3 in Fig. 4). Presence of mica aggregates with undulose extinctions within the cleavage zones indicates intracrystalline crystal–plastic deformation to have operated as a deformation mechanism during the late stages of development of crenulation cleavages. Finally, the fact that several cleavage zones show mica aggregates aligned parallel to the domain boundary (stage 7 of Fig. 4) is interpreted as due to increasing shear with coeval rotation of S_2' into parallelism with the domain boundary (Dell'Angelo and Tullis, 1989). Further straining results in homogenization of the entire fabric (stage 9, Fig. 4).

4. Discussion and conclusion

The present investigation of differentiated crenulation cleavages in garnet biotite schists exemplifies the case of a fabric resembling S–C and C' fabric typical of mylonites within cleavage zones, although the schists do not show any mesoscopic scale evidence of mylonitization. As shown in Fig. 4, the microstructures such as S–C, embryonic C' and well developed C' (in that order) typify evolutionary stages towards a homogenized secondary schistosity (S_2) and represent a fabric gradient related to a strain gradient. That shearing along the cleavage zones may occur has been suggested by Williams and Schoneveld (1981) and Bell (1981) and is not a new concept. However, fabrics resembling those found in mylonites is something unrecognized which raises the following question: can crenulation cleavage zones behave as mylonites during late stages of their genesis? A mylonite is (a) fine grained, (b) occurs in ductile shear zones, (c) undergoes high strain compared to its surroundings and (d) undergoes intracrystalline crystal–plastic deformation. From the present study, it is quite clear that the cleavage zones which comprise fine-grained mica aggregates have undergone high strain compared to their surroundings.

While investigating the question of shearing along axial plane foliations, Ghosh (1982) concluded that during combination of pure and simple shear, a considerable amount of shear strain may be accommodated within the axial plane foliation. It was mentioned earlier that there are mesoscopic evidences of shearing along S_2 foliations. The presence of asymmetrical microfolds is an indication of an oblique relationship between the S_1 schistosity and the D_2 shortening. In a situation where the rock becomes more heterogeneous during the early stages of crenulation (due to pressure solution up to stage 3 in Fig. 4) and the S_1 schistosity is oblique to D_2 shortening, it is logical to envisage that phenomena such as strain and flow refraction would be quite active on the microscopic scale and the flow would be general non-coaxial type (Hanmer and Passchier, 1991). This would lead to deformation of the more competent layer (microlithons in the present case) by pure shear and that of the more incompetent layer (cleavage zones) by simple shear and would favour the formation of shear structures within the crenulation cleavage zones. Moreover, on a more regional scale, the study area comprises a heterogeneous assemblage of alternating quartzites (competent rock) and schistose (incompetent) rocks which have undergone superposed foldings and this would again support deformation by a combination of pure and simple shear. All the above factors can be considered as acceptable means of achieving ductile shearing along cleavage zones which would favour development of microscale structures such as S–C and C' fabric in cleavage zones.

The main question now is whether the mechansims that operate during mylonitization can be operative during some stage of crenulation. Williams (1972, 1977), Cosgrove (1976), Gray (1977, 1978, 1979) and Marlow and Etheridge (1977) have advocated that pressure solution, solution transfer and rotation are important deformation mechanisms during the formation of crenulation cleavages. The present study confirms the role of these mechanisms operating during the early stages of crenulation up to the achievement of a domainal fabric. However, the presence of undulose extinction in the mica aggregates within the cleavage zones indicates intracrystalline crystal–plastic deformation to be an important mechanism of deformation which occurred on account of shearing in cleavage zones during the later stages of crenulation, possibly, when the efficiency of pressure solution has diminished. Intracrystalline crystal–plastic deformation is considered to be an important deformation mechanism during mylonitization (Nicolas and Poirier, 1976; White et al., 1980; Tullis et al., 1982; Ramsay and Huber, 1987; Passchier and Trouw, 1996) during which dislocations and dislocation tangles develop. They ultimately result in strain hardening and may also cause brittle failure (Hobbs et al., 1976; Nicolas and Poirier, 1976; Passchier and Trouw, 1996). However, there is no such evidence on the microscopic scale in the garnet biotite schists presently investigated which indicates that ductile deformation within the cleavage zones occurred by a mechanism such as dislocation creep. This has been considered as a possible mechanism during mylonitization under low grade metamorphic conditions (Passchier and Trouw, 1996). Worley et al. (1997) have attempted through microstructural and microprobe studies on crenulated schists

Table 1
Composition of muscovite in microlithon and cleavage zone from garnet biotite schist of the study area

Mineral analysis	Muscovite (microlithon) anj8-15	Muscovite (cleavage zone) anj8-14
SiO_2	45.81	46.84
TiO_2	0.29	0.32
Al_2O_3	30.34	29.13
Cr_2O_3	0.03	0.00
FeO	2.73	2.47
MnO	0.03	0.00
NiO	0.00	0.00
MgO	0.74	1.07
CaO	0.00	0.00
Na_2O	1.00	0.96
K_2O	9.35	9.35
H_2O	4.25	4.26
Total	94.57	94.40

belonging to the chlorite, biotite and garnet metamorphic zones from China, to decipher operative deformation mechanisms and processes by comparing the composition of muscovite between the cleavage zones and the microlithons. They have observed that muscovite occurring in microlithons and cleavage zones in chlorite and biotite zone schists has a distinctly different composition while it is the same in schists belonging to the garnet zone. On the basis of this study, Worley et al. (1997) have argued that pressure solution and transport of material by grain boundary diffusion with associated crystallization of minerals is the dominant mechanism at chlorite to biotite zone temperatures (~520°C); conversely, intracrystalline crystal–plastic deformation accompanied with volume diffusion which enables movement of dislocations through the crystal structure is found to be the deformation mechanism in garnet zone schists at temperatures greater than 520°C. These results of Worley et al. (1997) have an important bearing on our interpretations. The composition of muscovite in cleavage zones and microlithons of the garnet biotite schists studied is tabulated in Table 1. There is a similarity in the composition of the muscovites and this is due to intracrystalline crystal–plastic deformation. Since deformation and related metamorphism are continuous processes, *P*–*T* conditions and the fabric of the rock will vary at different stages. The garnet biotite schists under scrutiny would have naturally passed through relatively lower grade metamorphic conditions to achieve the higher conditions. This would imply that the deformation mechanisms, which as shown by Worley et al. (1997), are temperature dependent, would vary with the changing/increasing metamorphic grade and increasing strain. This supports our interpretations that solution transfer is dominant during the earlier stages of crenulation while intracrystalline crystal–plastic deformation is active during the later stages of crenulation because the metamorphic conditions and the strain gradually increased from the early to late stages of crenulation. Based on the above discussion, it is clear that deformation mechanisms that operate during the late stages of crenulation are similar to those known to be operative during mylonitization. Hence, crenulation cleavage zones, especially in rocks belonging to upper greenschist–lower amphibolite facies, can behave similarly to mylonites on the microscale during the later stages of crenulation. Perhaps, cleavage zones which show microstructures similar to those described in this paper could be classified as ‘phyllonites’ which is a term used to describe ‘fine-grained mica-rich mylonites’ (Passchier and Trouw, 1996).

Acknowledgements

The present paper is an outcome of research on the Deformational history of the Lunavada Group of rocks, India. The work was financially supported during various stages by M.S. University Research Scholarship; fieldwork grant from the AGID (Association of Geoscientists for International Development), Brazil; Senior Research Fellowship from the Council of Scientific and Industrial Research, New Delhi [No. 9/114/(92)/96/EMR-I] and DAAD (German Academic Exchange Service, Bonn) Scholarship (No. A/97/00792) all awarded to M.A.M. We would like to thank Prof. S.S. Merh (Vadodara, India) for his sustained interest and encouragement to pursue the deformational studies of the Lunavada Group. Reviews by Drs J. Treagus and J.L. Bouchez helped improve the manuscript considerably. Prof. Rainer Altherr, Dr Hans P. Meyer and Gultekin Topuz are thanked for helping with various aspects of measurements using the CAMECA SX51 microprobe at Mineralogisches Institut, Heidelberg, Germany.

References

Bell, T.H., 1981. Foliation development—the contribution, geometry and significance of progressive bulk inhomogeneous shortening. Tectonophysics 127, 49–65.

Berthé, D., Choukroune, P., Jegouzo, P., 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican shear zone. Journal of Structural Geology 1, 31–42.

Blenkinsop, T.G., Treloar, P.J., 1995. Geometry, classification and kinematics of *S*–*C* fabrics. Journal of Structural Geology 17, 397–408.

Cosgrove, J.W., 1976. The formation of crenulation cleavage. Journal of the Geological Society of London 132, 155–178.

Dell'Angelo, L.N., Tullis, J., 1989. Fabric development in experimentally sheared quartzites. Tectonophysics 169, 1–21.

Ghosh, S.K., 1982. The problem of shearing along axial plane foliations. Journal of Structural Geology 4, 63–67.

Gopalan, K., Trivedi, J.R., Merh, S.S., Patel, P.P., Patel, S.G., 1979. Rb–Sr age of Godhra and related granites, Gujarat (India). Proceedings of Indian Academy of Sciences (Earth and Planetary Sciences) 88A, 7–17.

Gray, D.R., 1977. Morphological classification of crenulation cleavage. Journal of Geology 85, 229–235.

Gray, D.R., 1978. Cleavages in deformed psammitic rocks from Southeastern Australia: their nature and origin. Geological Society of America Bulletin 89, 577–590.

Gray, D.R., 1979. Microstructures of crenulation cleavages: an indicator of cleavage origin. American Journal of Science 279, 97–128.

Gray, D.R., Durney, D.W., 1979. Crenulation cleavage differentiation: implication of solution-deposition processes. Journal of Structural Geology 1, 73–80.

Gupta, B.C., Mukherjee, P.N., 1938. Geology of Gujarat and Southern Rajputana. Records of the Geological Survey of India 73, 163–208.

Gupta, S.N., Arora, Y.K., Mathur, R.K., Iqbaluddin, Balmiki Prasad., Sahai, T.N., Sharma, S.B., 1980. Lithostratigraphic map of Aravalli region, Southern Rajasthan and Northeastern Gujarat. Geological Survey of India Publication, Hyderabad.

Gupta, S.N., Mathur, R.K., Arora, Y.K., 1992. Lithostratigraphy of Proterozoic rocks of Rajasthan and Gujarat—A review. Records of the Geological Survey of India 115, 63–85.

Hanmer, S., Passchier, C.W., 1991. Shear-sense indicators: a review. Geological Survey of Canada Paper 90-17, 1–72.

Hobbs, B.E., Means, W.D., Williams, P.F., 1976. An Outline of Structural Geology. Wiley, New York.

Lister, G.S., Snoke, A.W., 1984. *S–C* Mylonites. Journal of Structural Geology 6, 617–638.

Mamtani, M.A., Karanth, R.V., 1997. Syntectonic growth of porphyroblasts over crenulation cleavages—an example from the Precambrian rocks of the Lunavada Group, Gujarat. Journal of the Geological Society of India 50, 171–178.

Mamtani, M.A., Karanth, R.V., Merh, S.S., Greiling, R.O., 1998. Regional scale superposed folding in the Precambrian rocks of the southern Aravalli mountain belt, India (Abstract). Freiberger Forschungsheft C471, 140.

Marlow, P.C., Etheridge, M.A., 1977. Development of a layered crenulation cleavage in mica schists of the Kanmantoo Group near Macclesfield, South Australia. Geological Society of America Bulletin 88, 873–882.

Nicolas, A., Poirier, J.P., 1976. Crystalline Plasticity and Solid State Flow in Metamorphic Rocks. Wiley, New York.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer, Berlin.

Platt, J.P., Vissers, R.L.M., 1980. Extensional structures in anisotropic rocks. Journal of Structural Geology 2, 397–410.

Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology, Vol. 2: Folds and Fractures. Academic Press, London.

Tullis, J., Snoke, A.W., Todd, V.R., 1982. Significance and petrogenesis of mylonitic rocks. Geology 10, 227–230.

White, S.H., Burrows, S.E., Carreras, J., Shaw, N.D., Humphreys, F.J., 1980. On mylonites in ductile shear zones. Journal of Structural Geology 2, 175–187.

Williams, P.F., 1972. Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia. American Journal of Science 272, 1–47.

Williams, P.F., 1977. Foliation: a review and discussion. Tectonophysics 39, 305–328.

Williams, P.F., Schoneveld, C., 1981. Garnet rotation and the development of axial plane crenulation cleavage. Tectonophysics 78, 307–334.

Worley, B., Powell, R., Wilson, C.J.L., 1997. Crenulation cleavage formation: evolving diffusion, deformation and equilibration mechanisms with increasing metamorphic grade. Journal of Structural Geology 19, 1121–1135.

Zwart, H.J., 1962. On the determination of polymetamorphic mineral associations, and its application to the Bosost area (central Pyrenees). Geologische Rundschau 52, 38–65.