Pergamon

Journal of Structural Geology, Vol. 17, No. 1, pp. 83 to 94, 1995

0191-8141/95 $9.50+0.00

0191-8141(94)E0021-P

Structural controls on syntectonic metasomatic tremolite and tremolite–plagioclase pods in the Molanite Valley, Mt. Isa, Australia

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(*Received* 3 *February* 1993; *accepted in revised form* 1 *February* 1994)

Abstract—In the Molanite Valley west of Mt. Isa, tremolite-bearing metasomatic pods, showing sharp contacts with enclosing rocks, occur over a strike length of 7.4 km in the biotite-zone Bortala Formation. In relatively low-strain rocks of the western part of the valley, plagioclase–tremolite pods have replaced psammite or mica schist surrounding the terminations of buck quartz veins, whereas in intensively sheared rocks to the east, pods of medium to coarse-grained massive tremolite (commonly containing greater than 95% tremolite) have replaced marble, quartzite and psammite. Talc-chlorite schists, formed by dissolution of carbonates during shearing of marble, are associated with some of the massive tremolite pods.

The direct relationship between structural domains and metasomatism suggests that migration of externally-derived fluids was controlled by fractures and the shear zone. The fluids, having migrated along fractures, interacted with wall rocks to produce plagioclase–tremolite pods. In the shear zone, buck quartz veins, some tremolite-bearing, show no obvious geometric relationship to massive tremolite pods. It is postulated that the metasomatic fluids fluxed through shear domains and penetrated progressive shortening domains to replace the host rocks and form the massive tremolite pods. Both styles of metasomatic rocks developed from late S_2 to early S_3 during a progressive E–W shortening event, which corresponds to the regional metamorphism. The metasomatic rocks represent only a small part of widespread metasomatism across the Mt. Isa Inlier.

INTRODUCTION

Considerable work has been done on geochemical aspects of metasomatism in shear zones (e.g. Beach 1980, Ferry & Dipple 1991, Selverstone *et al.* 1991), and accompanying thermal metamorphism around igneous intrusions (e.g. review of Einaudi *et al.* 1981). Major fluid infiltration systems have been proposed for some regional metamorphic terrains, such as the Beaver Brook (Rumble *et al.* 1982), the Harlech Dome (Bottrell *et al.* 1989) and the Trois Seigneurs Massif (Wickham & Taylor 1985, Bickle & Chapman 1990), but comparatively few examples of large-scale metasomatism in regional metamorphic terrains have been documented (e.g. Yardley *et al.* 1991). An important exception is the Mt. Isa Inlier where widespread metasomatic activity accompanied Buchan-type low-*P*/high-*T* metamorphism (Etheridge *et al.* 1987, Loosveld 1989, Oliver *et al.* 1990, Reinhardt 1991, Rubenach 1992). Because metasomatism is also an important factor in the formation of most of the large ore deposits in the inlier (e.g. Perkins 1984), its timing and structural controls along with the physical–chemical conditions and origin of the fluids are major concerns.

The Molanite Valley, situated just west of the Mt. Isa Mine (Fig. 1), was selected for detailed studies on aspects of the metasomatism, such as structural controls on fluid pathways and localization of metasomatism, genesis of the infiltrating fluids, fluid/rock interactions and the timing relationships between deformation, metamorphism and metasomatism. Reasons for this include: (1) the good exposure in this valley, where numerous metasomatic pods crop out; (2) this metasomatic zone is immediately adjacent to the copper and lead/zinc ore deposits, which have been demonstrated (at least for the copper) to have formed by syntectonic metasomatism (Perkins 1984); (3) various geological studies have been made in this area in the last decade (Bell 1983, 1991, Rubenach 1992), and particularly detailed structural mapping has been completed (Huang 1991, in review). This paper is based on detailed geological mapping of this area, with special attention given to the correlation between structural domains and metasomatic pods. Structural and microstructural analysis has been used to time metasomatism relative to the regional deformation/metamorphism event. Aspects of geochemical processes of this metasomatism will be dealt with elsewhere.

GEOLOGICAL SETTING

The Mt. Isa Inlier is divided by major N-striking fault zones into three essentially fault-bounded domains, the Eastern, Central and Western Fold Belts (Blake 1987, Stewart & Blake 1992). The basement, deformed during the Barramundi Orogeny at around 1870 Ma, was overlain by three cover sequences (1870–1850 Ma, 1790–1720? Ma, 1680–1625 Ma, respectively) separated by regional unconformities (Blake 1987). These cover sequences were intensely deformed by the Isan Orogeny (1610–1510 Ma), which consisted of a number of deformation phases. The first phase (D_1) consisted of

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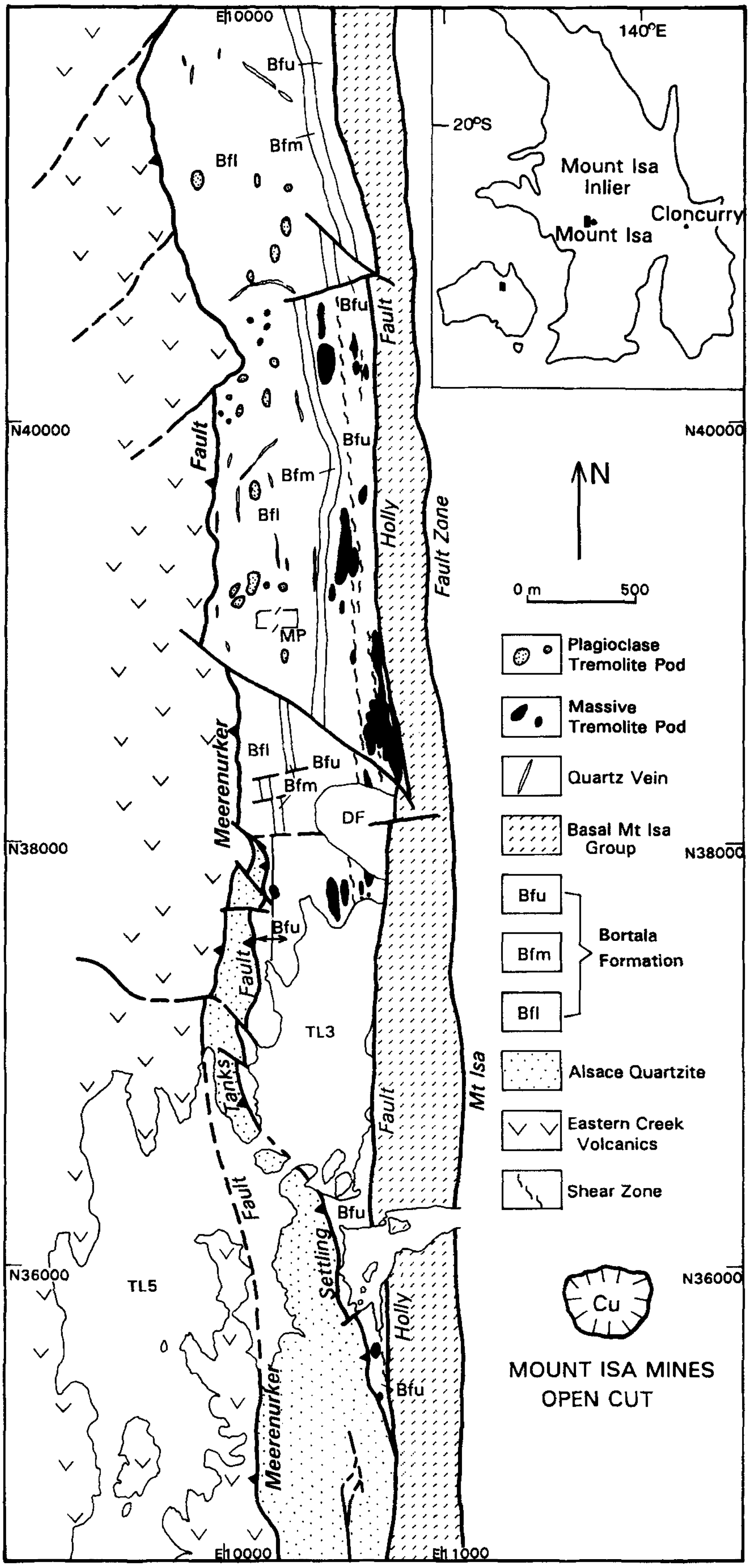


Fig. 1. Simplified geological map of the Molanite Valley. Note that the tremolite pods occur in a strip of the Bortala Formation which forms the hinge region of a large F_2 anticline which has been truncated by faults. Bfu—upper Bortala Formation; Bfm—middle Bortala Formation; Bfl—lower Bortala Formation; DF—mine dump; TL—Tailings Dam; MP—Molanite Plant. Geographic co-ordinates are based on Mt. Isa Mines grid. Inset map shows location of studied area.

Table 1. Stratigraphy in the Molanite Valley, Mt. Isa

Cover sequence 3	**Basal Mount Isa Group**	Conglomerate, pale quartzite, multicoloured meta-siltstone
Cover sequence 2	**Myally subgroup**	
	Bortala Formation	Grey-fawn pelite, pale quartzite, schist, green-grey psammite
	Alsace Quartzite	Pale quartzite and siltstone
	Eastern Creek volcanics	Quartzite, amphibolite, chlorite schist, quartz-mica schist

thrusting and folding resulting from N–S compression (Bell 1983); a later phase D_2 produced regional N-trending folds characteristic of much of the Mt. Isa Inlier (Blake 1987). The D_2 event, dated at 1554 Ma (Page & Bell 1986), produced an intense foliation and corresponds to regional metamorphism across the inlier (Blake 1987, Rubenach 1992). Also part of D_2 are several overprinting folds and foliations of sporadic and/or localized occurrence, and these include a shear zone in the eastern part of the Molanite Valley. A later widespread phase, D_3 of Bell (1983, 1991), has associated retrograde metamorphism, and is dated as 1510 Ma by Page & Bell (1986). The ages of abundant faults which post-date the metamorphic peak are uncertain.

The Molanite Valley is located immediately west of Mt. Isa in higher grade rocks of the Western Fold Belt (Fig. 1). Previous structural work in the area includes that of Carter *et al.* (1961) and Wilson (1972), with subsequent revisions by Mt. Isa Mines geologists. Recent detailed mapping includes that of Huang (1991, in review), and further south that of Proffett (1990) and Connors *et al.* (1992). Although there are still disagreements in aspects of structural observations and interpretations, there is a consensus on some structural elements. For instance, the Mt. Isa Fault Zone is considered to be a major boundary which separates two domains in terms of deformation intensity and metamorphic grade. East of this fault zone, the rocks are chlorite zone and the dominant foliation is a relatively weak slaty cleavage. To the west of the fault zone, multiple foliations are quite strongly developed, and there is a rapid westward increase in metamorphic grade from biotite zone to sillimanite/K-feldspar zone (Rubenach 1992).

In the Molanite Valley, major stratigraphic units include (1) the Eastern Creek volcanics (ECV), which are amphibolite facies. This unit consists mainly of quartzite, with some amphibolite, pelitic schist and chlorite–quartz schist; (2) the Myally Subgroup, which is biotite zone, and includes the Alsace Quartzite and the Bortala Formation. These consist mainly of psammite, schist, phyllite, quartzite, marble and calcsilicate rocks; and (3) probable basal Mt. Isa Group, consisting of quartzite, schist, and phyllite. The Eastern Creek Volcanics and Myally Subgroup are a portion of cover sequence 2, whereas the basal Mt. Isa Group belongs to cover sequence 3 (Blake 1987, Table 1). These rock units are separated by major faults: the Meernurker Fault between the Eastern Creek Volcanics and Myally Group, the Settling Tanks Fault between Alsace Quartzite and Bortala Formation, and the Holly Fault between the Bortala Formation and basal Mt. Isa Group (Fig. 1).

The Bortala Formation, containing most of the metasomatic pods, is located in the central zone of the Molanite Valley. It is composed of psammite, quartzite, schist and marble. Primary sedimentary structures include planar laminations, tabular cross-bedding, ripples and climbing ripples, and fairly common dessication cracks, and are well preserved not only in the less deformed rocks but also within boudins of the shear zone. The variation in dip and younging of these rocks delineates a gentle F_2 antiform which has a NNW-striking axis. This antiform is offset along an E–W striking cross-fault, and truncated by the Holly Fault, by the Meernurker Fault and Settling Tanks Fault to the south southeast, west and south-southwest, respectively. North of Tailings Dam 3, the rocks constitute the eastern limb of the antiform, whereas to the south they are on the western limb; the exposure of the actual crest occurs only over a short distance to the northwest of Tailings Dam 3 (Fig. 1). There are many local lower-order folds (several tens of meters in scale) on both limbs. These folds have a NNW-striking axial plane foliation (S_2) and variable shallow plunges (Huang 1993).

A complex shear zone overprints the F_2 folds in the eastern part of the valley. Heterogeneity of deformation is obvious in the shear zones, which, as outlined in Bell & Cuff (1989) can be divided into shear domains (intensely foliated schists) and shortening domains (boudins and pods enclosed by the shear zone foliation). In the shear domains, bedding has generally been obliterated by the intense foliation. Boudins of quartzite, psammite, and massive tremolite are common and preserve bedding and some open folds.

The truncating and overprinting relationships of these structures indicate five generations of foliation and related structures in this strip of the Bortala Formation, which are summarized and correlated with regional deformation sequences (Table 2).

METASOMATIC ROCKS

The most obvious metasomatic rocks in the Molanite Valley occur as scattered pods, enclosed in schist or psammite (Fig. 1). The longest axes of the pods are mainly in the range 1–35 m. Two main types are recognized: (1) plagioclase–tremolite pods (PTP), and (2) massive tremolite pods (MTP). Both crop out with positive relief, and are easily distinguished from the host rocks in the field and on aerial photographs. Typical mineralogical assemblages are given in Table 3.

Geometry of the metasomatic pods

Plagioclase–tremolite pods are restricted to the western part of the Molanite Valley. Individual pods are

Table 2. Tentative correlations of the structures between the Molanite Valley and its environ areas

Molanite Valley	Mt. Novit (Connors *et al.* 1992)	Mt. Isa Mine (Perkins 1993)	Mt. Isa Inlier (Blake 1987)
S_5 foliation and kink	D_5^N		D_3
S_4 foliation and local fold	D_4^N	D_3	
S_3 foliation and shear zone	D_3^N		D_2
S_2 foliation, regional N-striking folds	D_2^N	D_2	
S_1 foliation	D_1^N	D_1	D_1

commonly irregular circular to elliptical in plan, but in the vertical dimension take on the form of irregular mushroom-shapes (Figs. 2 and 3). Centrally-located steeply-dipping lenticular quartz veins, generally striking N–S, are a common feature of these pods. In some locations, there are several veins within one pod (Fig. 2b). Contacts with the enclosing psammitic rocks are sharp, and typically crosscut bedding, which passes without deflection across the contact. However, metasomatic tongues may extend along certain layers, indicating anisotropy of permeability of the host rocks is a factor in fluid access (Fig. 3). The spatial association of these pods and quartz veins suggests that the metasomatic fluids spread out from a central fracture now occupied by the quartz veins. In most situations, there is little to no deflection of the S_2 foliation around these pods. The tremolite clusters appear randomly-oriented in many pods, but in others clearly are aligned parallel to S_2. It is concluded that these pods formed late to post-S_2 development.

In contrast to plagioclase–tremolite pods, massive tremolite pods (MTP) occur as irregular ellipsoids in the high-strain shear zone of the eastern part of the Molanite Valley. The foliation wraps around and truncates relict bedding on the eastern and western margins of these pods, leaving strain shadows and undeformed contacts on the northern and southern sides. Marble lenses occur in some strain shadows, and in one example a marble layer occurs immediately adjacent to a tremolite pod (Fig. 4). Although scattered quartz veins are present, they show no obvious spatial relationship to the massive tremolite pods, contrasting with the centrally-located veins in the plagioclase–tremolite pods. This suggests differences in fluid access or pathways in the formation of the two styles of pod. Marble was selectively replaced, but interlayered quartzite and psammite were in part replaced, leaving relict lenses parallel to the bedding (Fig. 5a).

Talc–chlorite schists are also common in the high strain zone and probably formed by dissolution of calcite and dolomite during intense shearing. This is supported by the occurrence, in some strain shadows adjacent to the massive tremolite pods, of marbles lenses containing talc and chlorite which grade into talc–chlorite schists along the margins. It is still uncertain whether the talc in such marble and talc schist was metasomatic or whether it formed in isochemical reactions, but the former is preferred.

Table 3. Mineral assemblages, Bortala Formation in the Molanite Valley

	Mineral assemblages
Quartzites & psammitic rocks	Qtz, Ms, Chl, Hem Qtz, Ms, Bio Qtz, Bio, Chl Qtz, Ms, Bio, Chl, Kfs, Pl, Hem Qtz, Chl, Bio, Cal, Kfs, Pl, Hem Qtz, Bio, Ms, Cal, Pl, Kfs, Ep, Hem Qtz, Bio, Tlc, Cal, Kfs, Hem Qtz, Pl, Tr, Chl
Pelites & calcareous pelite	Qtz, Ms, Chl, Bio, Hem Qtz, Chl, Bio, Hem Qtz, Ms, Chl, Bio, Ep, Hem Qtz, Bio, Chl, Tr Qtz, Bio, Tr, Cal Qtz, Tr, Ep, Chl Qtz, Tlc, Chl, Cal
Marble	Cal, Tlc, Chl Cal, Tr, Tlc, Chl Dol Dol, Tlc, Chl Dol, Bio
Metasomatic rocks	Tr Tr, Ep, Qtz, (Chl) Qtz, Tr, Pl Tlc, Chl, Rt* Qtz, Cal, Ep, Ttn Tr, Ep, Bio, Cal, Rt Tr, Dol Tlc, Chl, Dol

Abbreviations, after Kretz (1983), are as follows: Bio—biotite; Cal—calcite; Chl—chlorite; Dol—dolomite; Ep—epidote; Hem—hematite; Kfs—K-feldspar; Mc—muscovite; Pl—plagioclase; Qtz—quartz; Rt—rutile; Tlc—talc; Tr—tremolite; Ttn—titanite.

*Talc–chlorite schists were formerly marbles; calcite and dolomite were removed by dissolution during shear-zone development.

Mineralogy of the metasomatic rocks

The mineral assemblages in the plagioclase–tremolite pods and massive tremolite pods, along with their host rocks, are summarized in Table 3. A typical plagioclase–tremolite pod consists of about 25% tremolite, 65% quartz, 10% plagioclase. The quartz and feldspar form a medium-grained polygonal matrix, whereas the tremolite typically forms garbenschiefer clusters up to 3 mm long, with the long axes either randomly oriented or aligned parallel to the S_2 foliation in the surrounding psammitic rocks. The country rock is mainly quartz–biotite psammite or schist, with or without muscovite,

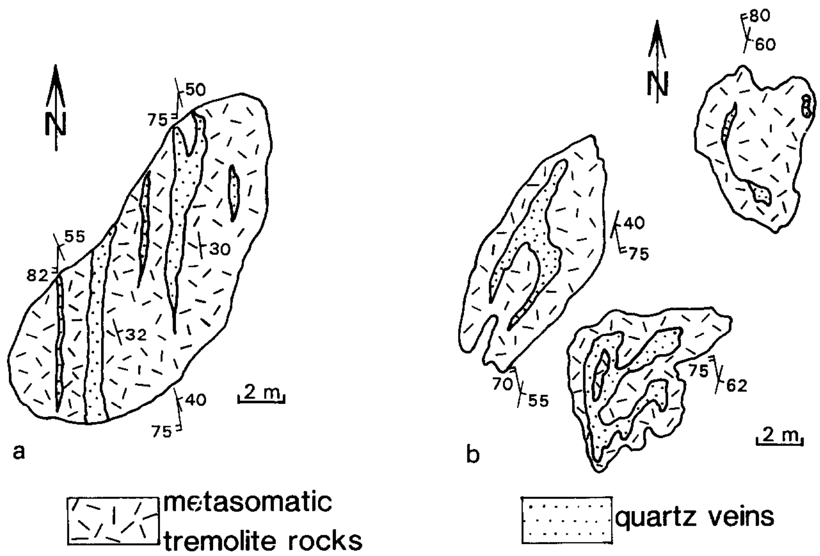


Fig. 2. Plan-sections illustrating outcrop patterns of the plagioclase–tremolite pods in the western Molanite Valley. Dip and strike symbols refer to bedding (S_0, one tick) and pervasive foliation (S_2, two ticks). Quartz veins are central to the pods, and S_2 rarely occurs in these pods. The outcrops are located just northeast of the Molanite Plant (Fig. 1).

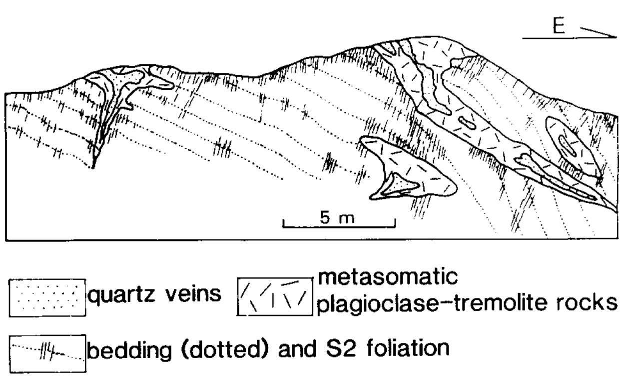


Fig. 3. A cross-section illustrating the geometry of the plagioclase–tremolite pods and their relationships with quartz veins and host rocks. This diagram shows the direct correlation between the quartz veins and tremolite–plagioclase metasomatic rocks. S_2 foliation is rarely developed in these pods.

chlorite, plagioclase and hematite. Mineralogical differences indicate that the formation of these plagioclase–tremolite pods involved addition of Ca and Na and removal of K.

The massive tremolite pods contain between 60% and 99% tremolite, with most containing 90–99%. Tremolite typically occurs as green, randomly-oriented prisms, with grainsize in the range 2–5 mm. Other minerals include quartz, chlorite, epidote, calcite, dolomite and titanite. They typically show no mineralogical zoning parallel to pod shapes or fractures; rather minor variations in mineral proportions reflect relict bedding. Exceptions are talc-rich haloes around several tremolite pods. In nearly all cases relict bedding can be observed, and patches or lenses of country rocks occur within metasomatic pods.

Details of the phase relations, geochemistry, stable isotope and fluid inclusion data relevant to the chemical origin of both types of pod will be dealt with elsewhere (Rubenach, unpublished data). The pressure has been estimated at 2 kbar, and the peak metamorphic temperature, determined from several low-variance meta-

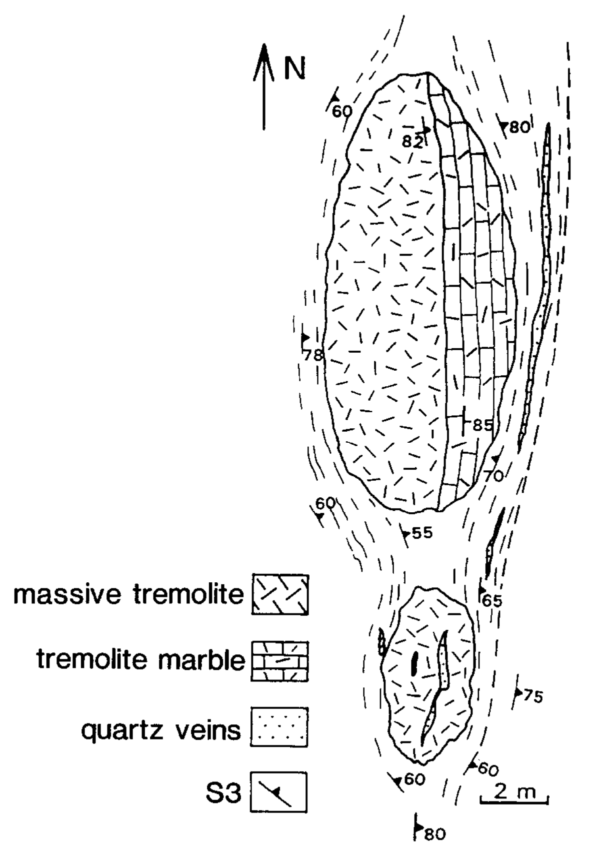


Fig. 4. A plan-section illustrating the outcrop pattern of massive tremolite pods in a shear zone. Note that S_3 deflects around the massive tremolite pods, suggesting that the shearing lasted until late in the metasomatism. The outcrop is located on the northeastern shore of Tailings Dam 3.

morphic assemblages in the valley, is 430°C (Rubenach 1992, unpublished data). The *T–X* conditions are constrained by reactions 1–4 and the phase relations shown in Fig. 6.

(1) 3 dolomite + 4 quartz + H_2O = talc + 3 calcite + 3 CO_2

(2) 5 talc + 6 calcite + 4 quartz = 3 tremolite + 3 H_2O + 6 CO_2

(3) 2 talc + 3 calcite = tremolite + dolomite + CO_2 + H_2O
(4) tremolite + 3 calcite + 2 quartz = 5 diopside + H_2O + 3 CO_2.

Diopside has not been observed, the assemblage tremolite + dolomite is relatively rare, and talc + calcite is common. If the metasomatic assemblages formed at peak metamorphic temperature, X_{CO_2} would have been less than 0.12 for tremolite pods and less than 0.24 for talc + calcite assemblages. Lower values of X_{CO_2} would apply for tremolite-bearing rocks formed below the metamorphic peak.

Referring to reactions (1) and (2), to form near-monomineralic tremolite pods isochemically within siliceous marble would be highly unlikely, as to consume all the talc in reaction (2) would produce a tremolite–calcite rock, even assuming the very restricted composition that would allow no residual quartz or dolomite. The formation of massive tremolite rocks is therefore consistent with an infiltrational origin, analogous to the genesis of skarn within carbonates (e.g. Einaudi *et al.* 1981). Field evidence for metasomatic origin of the massive tremolite rocks is abundant. For instance, bedding ghosts in massive tremolite are continuous with that of relict psammite and quartzite lenses within the pods themselves. Moreover, relict ripples typical of those in quartzite and psammite are preserved in massive tremolite rocks (Fig. 5b). Replacement of marble was observed in only a few localities in the field, but is more obvious in core from two holes drilled by Mt. Isa Mines Pty Ltd in 1992–1993. Therefore, the protoliths for the massive tremolite were primarily marble, quartzite and psammite. The plagioclase–tremolite pods provide more clear-cut evidence for metasomatism, with the alteration surrounding centrally-located buck quartz veins and the continuity of bedding from psammite host rocks through the pods.

Isotopic evidence for metasomatism, namely that the tremolite is in equilibrium with the quartz veins but not in equilibrium with the original marble nor related through isochemical decarbonization reactions, will be presented elsewhere (Rubenach & Cartwright, unpublished data).

Structural and microstructural observations

Bedding is well preserved in both pod types. In the plagioclase–tremolite pods, the rocks commonly show planar bedding, with the S_2 foliation developed in some pods and absent in others. This contrasts with the intense foliation developed outside of the plagioclase–tremolite pods.

The massive tremolite pods exhibit more complicated structures. Relict bedding is generally shallowly dipping in contrast to that in the enclosing shear zone. Some folds, gently plunging to the north, were observed through tracing the relict bedding, and these are typically not as tight as those in the strongly sheared rocks surrounding the pods. In the most massive tremolite pods, a spaced cleavage (S_3) is also present on a hand-specimen scale; this cuts throughout the pods, but is more intense in the surrounding highly strained rocks (Fig. 4). Some tremolite marble specimens provide good evidence for the timing of metasomatic tremolite development. An early foliation (S_2) defined by biotite and calcite has been overgrown by tremolite. The tremolite is in turn clearly truncated and/or deformed by the shear zone foliation S_3, which can be traced through the pods into the enclosing schists. In other locations, the S_3 foliation truncates and wraps around the pods, so that they appear to be rootless (Fig. 4).

Dilation veins filled with fibres of tremolite and quartz cut through the massive tremolite pods. These veins, containing subhorizontal fibres, strike nearly E–W (normal to the strike of shear zone), and dip steeply north or south, which is strong evidence for syntectonic development of the tremolite pods. It is argued that metasomatic fluids entered shortening domains to form new minerals, whereas shearing dissolved pre-existing minerals in shearing domains (Bell & Cuff, 1989). In this case, early-formed tremolite in shortening domains was fractured and pulled apart during progressive deformation, and the fluids entered these extension fractures to form tremolite. In the shear domains, quartz and calcite were preferentially dissolved, forming mica schists and talc–chlorite schists from psammite and marble, respectively.

Timing of metasomatism

The extensive metasomatism, resulting in the formation of both the MTPs and PTPs in the Molanite Valley, took place during a period from late-S_2 to early-S_3 foliation development (Fig. 7). The critical structural constraints on timing of metasomatism include:

(1) Metasomatism overprinted and largely obliterated the S_2 foliation in both PTPs and MTPs. In the rocks surrounding the plagioclase–tremolite pods, the S_2 foliation is intensely developed, but it is truncated at the contacts (Fig. 2). S_2 has rarely developed within the plagioclase–tremolite pods, but where present it parallels that in the surrounding rocks (Fig. 3). On the microscopic scale, tremolite grains have randomly overgrown the quartz–feldspar matrix in most samples (Fig. 8a), but several samples show alignment of tremolite clusters in S_2. These observations indicate that the formation of the plagioclase–tremolite pods were late or post-S_2. Tremolite prisms in some metasomatized marble specimens have clearly overgrown S_2 in matrix, which is defined by calcite, biotite and quartz grains (Fig. 8b). One specimen contains metasomatic tremolite and epidote aligned in S_2, with biotite inclusion trails within epidote also parallel to S_2. Consequently, both structural and microstructural observations suggest that the massive tremolite pods formed late-or post-S_2.

(2) S_3 foliation commonly overprints the metasomatic rocks. On the outcrop scale, S_3 can be traced from the shear zone into the tremolite pods, but strongly deflects around the latter (Fig. 4). Moreover, in many locations the massive tremolite rocks were boudinaged due to

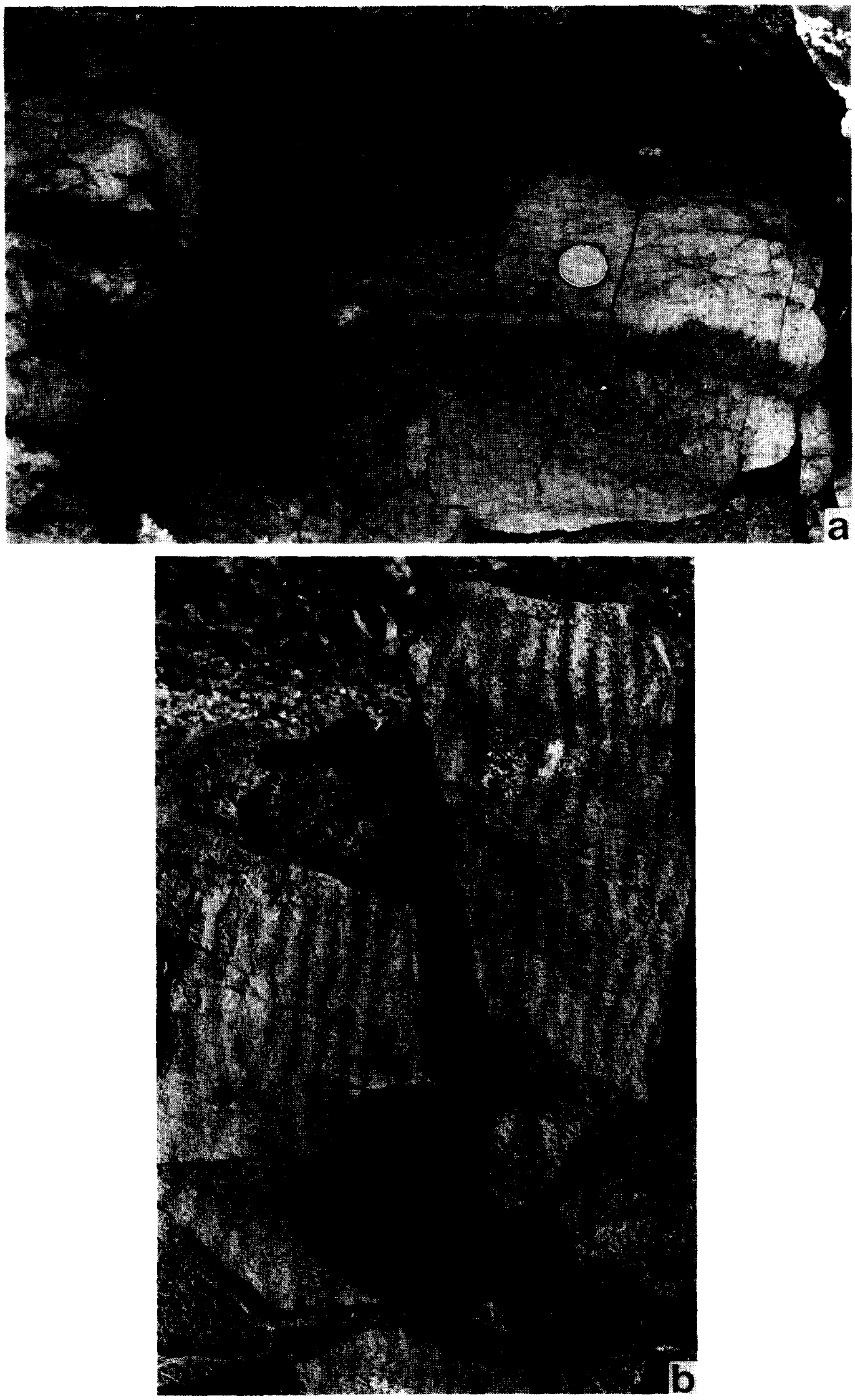
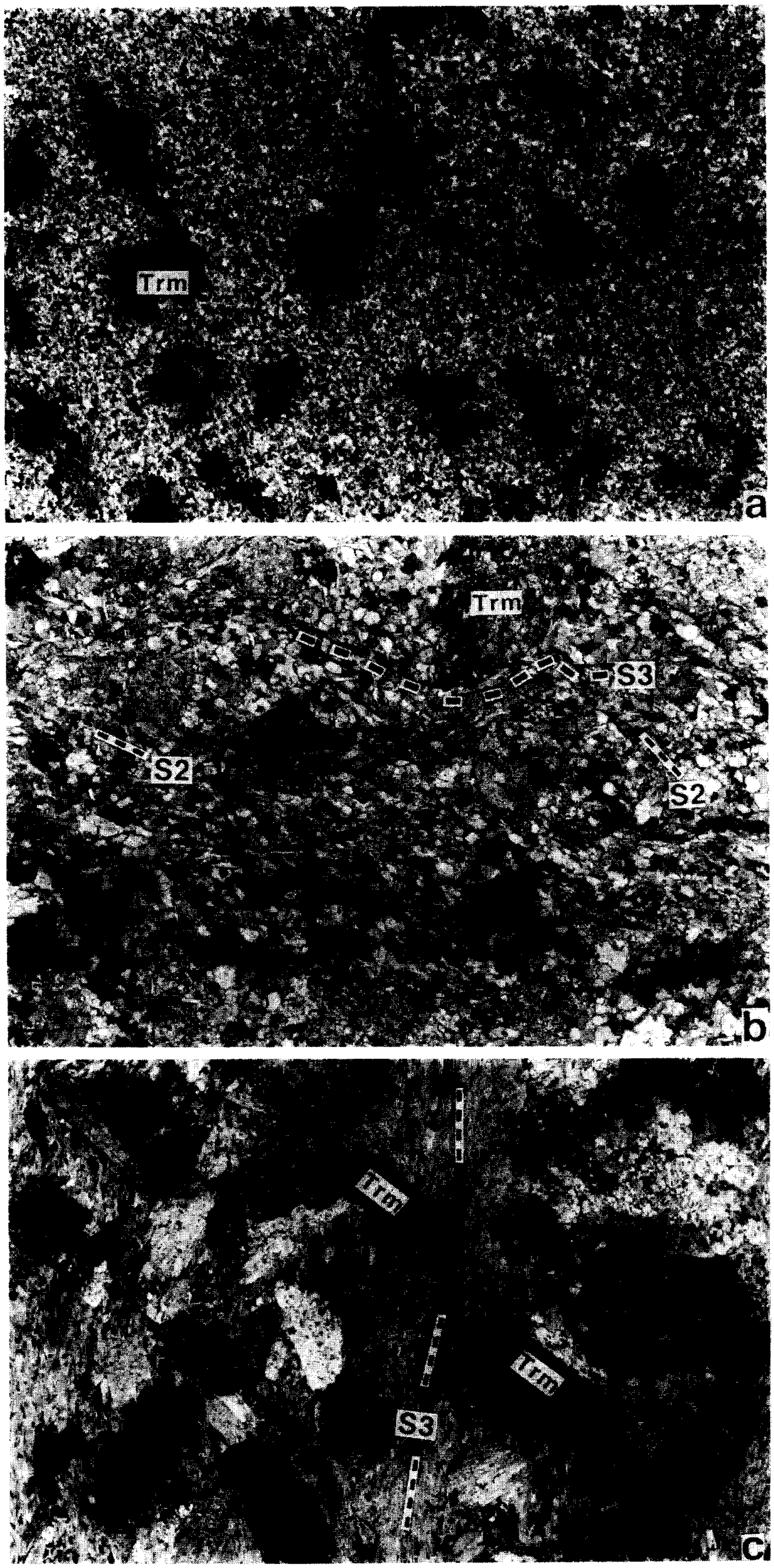


Fig. 5. (a) Details of irregular tremolite replacement and relict quartzite. Note the sharp contact between them. The bedding trace is roughly parallel to the length of the photo. The location is about 200 m east of the Molanite Plant. (b) Relict ripples preserved in massive tremolite rocks. Such ripples are quite common in psammites and quartzites of the Bortala Formation, indicating replacement of such rocks by massive tremolite. Location is on the northeastern shore of Tailings Dam 3.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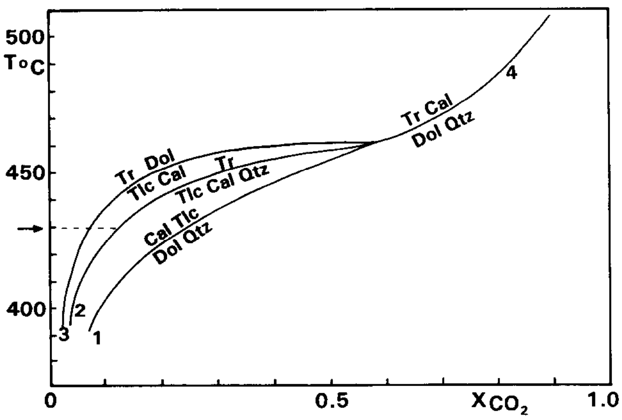

Fig. 6. Phase relationships in system $CaO–MgO–CO_2–H_2O$ at 2 kbar determined using Thermocalc (Powell & Holland 1988). The likely conditions for the formation of the tremolite pods is indicated with the arrow (see text for details).

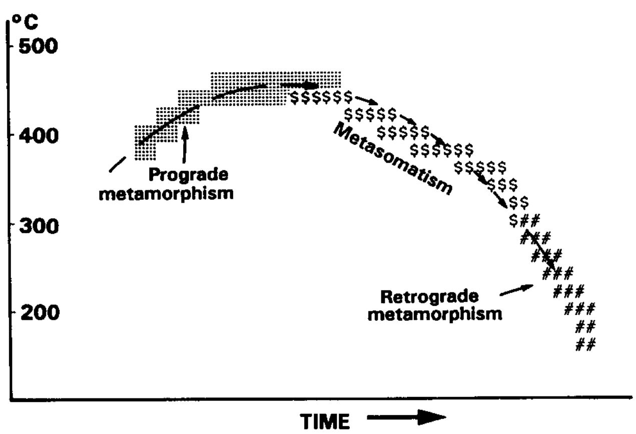

Fig. 7. A simplified temperature-related time path to illustrate the approximate timing of metasomatism during progressive deformation/metamorphism of the Bortala Formation, Molanite Valley. The metasomatism began at the metamorphic peak.

progressive shearing. On the microstructural scale, the S_3 foliation clearly truncates tremolite grains (Fig. 8c). It would appear, therefore, that the massive tremolite rocks formed pre-S_3. However, some dilation veins filled with tremolite-quartz fibres, observed in massive tremolite pods, suggest that precipitation of the tremolite at least partially is synchronous with development of the shear zone, or probably at the early stages of S_3 development.

The developing S_3 foliation probably also corresponded to a decrease in temperature, as tremolite has been partly replaced by talc along S_3 (alternatively, a more CO_2-rich fluid was associated with S_3). Continuing shortening resulted in overprinting by S_4 crenulations.

DISCUSSION

The tremolite and tremolite–plagioclase pods comprise 5% of an area of 5.4 km^2, and are distributed over the entire outcrop (7.4 km long) of the Bortala Formation to the west of Mt. Isa. They indicate regional metasomatism, on a scale comparable to the diopside and tremolite metasomatic rocks in the Connemara marbles (Yardley 1986, Yardley *et al.* 1991), but smaller in extent when compared to the scapolitization and albitization over a strike length of 100 km in the Corella Formation of the Mary Kathleen Fold Belt east of Mt. Isa (Oliver *et al.* 1990). The pods in the Bortala Formation are just one type of metasomatic rock in the western part of the Mt. Isa Inlier. Immediately west of the Judenan Zone, there is a strip, over 25 km in length, along which metasomatic cordierite rocks have replaced mica schists adjacent to amphibolite pods (Rubenach 1992, unpublished data). These examples illustrate the extent and variety of metasomatism in the Mt. Isa Inlier. In the case of the Molanite Valley, structural criteria suggest that the metasomatism developed during late-S_2 to early-S_3, late to immediately post the peak of metamorphism. It is a general observation that deformation, metamorphism, and metasomatism were synchronous with a regional E–W shortening event across the whole inlier (D_2 of Bell 1983, Blake 1987), which although it could show differences in absolute age, exhibits considerable similarity in the sequence of events (i.e. crustal shortening–thickening, regional HT/LP metamorphism, metasomatism). This has considerable significance regarding further exploration, as many large ore deposits in the Mt. Isa Inlier are related to metasomatic processes (e.g. the Mt. Isa copper orebodies, Perkins 1984).

In the Bortala Formation, it appears unequivocal that there are relationships between the distribution of metasomatic pods and structural processes. The pathways of metasomatic fluids may be grouped into fractures and shear zones. The fractures have been largely filled by buck quartz veins, which have coarse random fabrics and abundant fluid inclusions. The central location of quartz veins within plagioclase–tremolite pods indicates that they are probably the primary channelway for the passage of the fluids (Fig. 9a-1, cf. Walther & Orville 1982). It is postulated that the fluids were trapped locally, for example, at the ends of the fractures, and then these fluids penetrated into the wall-rock as a result of an increase in fluid pressure (Fig. 9a-2). The fluids interacted with the wall-rocks to form the new assemblage of plagioclase, quartz and tremolite from phyllosilicate-rich psammite and schist (Fig. 9a-3). Where several fractures were in close proximity, the

Fig. 8. Microphotographs illustrating typical textures of metasomatic rocks. (a) Tremolite clusters which have overgrown the matrix of granoblastic quartz and plagioclase. S_2 is well developed in the host rocks immediately outside the tremolite–plagioclase pod. Length of the baseline of the photograph is 5.4 mm; cross-polars. Sample from 500 m north of the Molanite Plant. (b) Marble with metasomatic tremolite. Note that S_2 is defined by calcite and biotite grains, and has been overgrown by tremolite prisms. S_3 is only weakly developed. Baseline is about 5 mm, crossed polars. (c) Microphotograph illustrating the relationship between tremolite prisms and matrix fabrics. Tremolite prisms have overgrown a previous fabric (S_2) formed during peak of metamorphism, but have been truncated by an intense shearing foliation (S_3). Length of photo is 5.4 mm, crossed polars. Samples for (b) & (c) are from the northeastern shore of Tailings Dam 3.

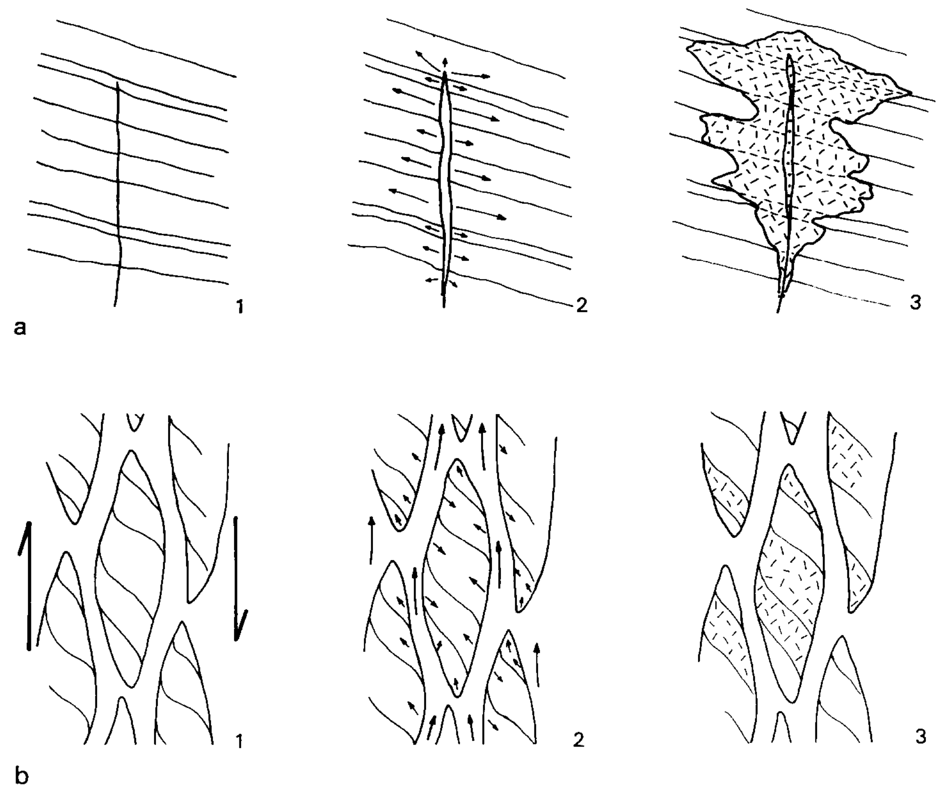

Fig. 9. Sketches synthesizing two probable processes of tremolite metasomatism: control by fractures and by a shear zone. (a) PTP-type metasomatism; (b) MTP-type metasomatism. Note selective replacement of lithologies, with marble layers altering first.

metasomatic haloes coalesced to form a larger metasomatic patch (Fig. 2).

In the shear zone, the massive tremolite pods cannot be related to individual quartz veins or fractures, as is the case for the plagioclase–tremolite pods. This may indicate that the shear zones replaced the fractures to become dominant pathways for passage of externally derived fluids during progressive deformation. Studies of shear zones have provided many examples of fluid infiltration and metasomatism during shearing (Beach 1980, Dipple *et al.* 1990, Jamtveit *et al.* 1990, Selverstone *et al.* 1991). The manifestation of fluid/rock interaction in shear zones usually displays considerable variety, as the strain and fabrics of shear zones typically show a quite heterogeneous development at all scales: that is, different domains (particularly shear vs shortening domains) due to deformation partitioning (Bell & Cuff, 1989). The externally-derived fluids could have infiltrated along the shear domains, accelerating the dissolution of host rock phases (Figs. 9b-1 & b-2). A dramatic example of such dissolution is provided by the talc-bearing marble lenses, which are best preserved in the strain shadows of tremolite pods, for elsewhere they have mainly been converted to talc schists as a result of calcite dissolution during shearing. Fluids entered the shortening domains (i.e. boudins) and replaced interlayered marble, quartzite, and psammite by tremolite (Fig. 9b-3). Although fractures within the shortening domains were the primary control of fluid access, bedding was an additional factor, as marble was selectively replaced in preference to quartzite and psammite layers. Early-formed talc and tremolite marble were sheared, the carbonate being removed in solution and tremolite retrograding to talc. At the same time, a series of extension fractures formed within the progressive shortening domains, and were filled with tremolite–quartz veins.

The quartz veins in the shear zone, and those spatially related to the plagioclase–tremolite pods, have a number of features in common. Both groups strike close to N–S, have identical $\delta^{18}O$ values, and are associated with metasomatic tremolite. They are therefore considered to have developed in a similar deformation setting, that is the E–W shortening which resulted in the formation of the regional antiform. Fractures developed on both limbs of the antiform, but especially in its hinge. These fractures were the dominant pathways for the fluid which passed through different lithologies in the hinge zone of the antiform (Fig. 10). However, with progressive shortening and deformation partitioning, intense shearing took place on both limbs of antiform, providing additional pathways for the passage of these externally-derived fluids (Fig. 10).

The abundance of tremolite pods, and the fact that the oxygen isotopes in most rocks (unmetasomatized as well as metasomatized) have been reset, are testimony to the large quantities of externally-derived fluid that must have pervaded these rocks. It is postulated, on the basis of similarities in oxygen isotopes and dissolution of potassium from psammite in both cases, that the same infiltrating fluid was involved in the formation of two types of metasomatic pods, even though the latter show

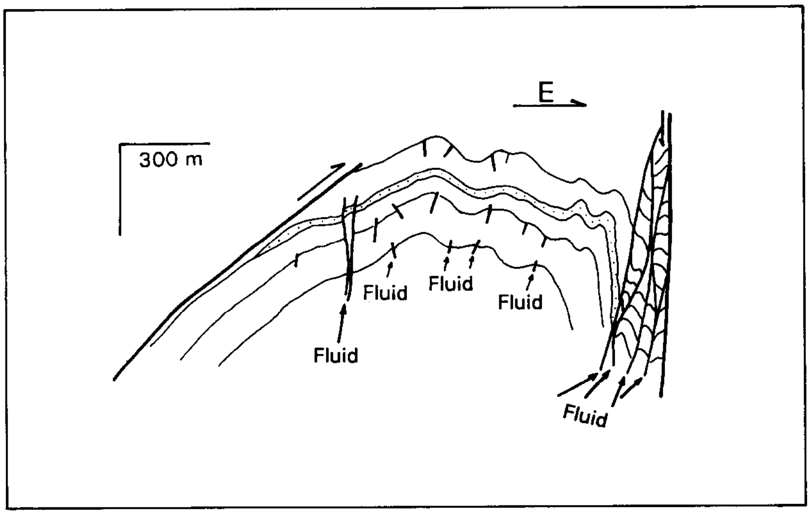

Fig. 10. Schematic cross-section, illustrating the structural controls on fluid migration in the Molanite Valley. Also shown are quartz veins associated with the plagioclase–tremolite pods in the hinge of the regional antiform, and the shear zone in the east of the valley.

differences in mineralogy, which may be due to the differences in protolith and structural setting. Such widespread metasomatism would require large quantities of fluid to access these rocks. However, the sources and pathways for migration of such fluids are controversial (e.g. Etheridge *et al.* 1983, Wood & Walther 1986, Oliver *et al.* 1990). Unpublished isotopic data indicate that the fluid affecting the Bortala Formation was not derived from local dehydration reactions, but its ultimate origin is not yet clear.

CONCLUSIONS

(1) The tremolite pods in the Molanite Valley are the result of metasomatism caused by infiltration of externally-derived fluids. The nature of these fluids remains to be resolved through on-going geochemical and isotopic studies.

(2) There are two types of metasomatism resulting from infiltration of fluids through well-defined fractures into the wall rocks, and from shear domains into shortening domains. The former metasomatism is represented by plagioclase–tremolite pod alteration haloes surrounding buck quartz veins, and the latter is represented by formation of massive tremolite layers in domains of progressive shortening in a shear zone. The selectivity of such alteration is clear, suggesting that host rock composition is another factor controlling fluid/rock interaction.

(3) The direct correlation between structures and metasomatic styles suggest structural controls on migration pathways of metasomatic fluids. Fractures and shear zones provided major channels for passage of these externally-derived fluids, and both developed progressively during an E–W shortening orogeny.

(4) Formation of the metasomatic plagioclase–tremolite pods and massive tremolite pods took place during a period from late-S_2 to early-S_3 foliation development. Metasomatism was syntectonic, involving an E–W progressive shortening that folded the Bortala Formation into a regional antiform in association with the development of fractures and a shear zone.

Acknowledgements—Mt. Isa Mines Exploration Pty Ltd is thanked for their financial support for WH. We are indebted to Bill Perkins, Tim Bell, Ian Cartwright, Ken Maiden, and Bruce Yardley for their support and fruitful discussions. Mt. Isa Mines Pty Ltd, in particular Bill Perkins and Bob Dennis, are thanked for allowing MJR to examine diamond drillcore from a number of holes in the Molanite Valley. WH undertook this work with a James Cook University Postgraduate Research Scholarship. The work of MJR was funded by an Australian Research Committee Grant. R. Norris and two anonymous reviewers are thanked for their extensive, and careful reviewing on this paper.

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