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Structural analysis of amphibolite zone, Serpentine Hill DDH No. 1 (SH 1)

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CHRONOLOGY OF DEFORMATION AND METAMORPHISM

An interpretive time sequence of tectonic events recognised in thin section in the different lithologies is presented in Table 1. The lithologies and deformational features recognised in specific samples are summarised with respect to depth in the core in Figure 1.

The majority of the section of core studied (0–280 m) is amphibolite and banded epidote-amphibole rock (fig. 1). Both types of amphibolites are metamorphic rocks which have a fine-grained to medium-grained polygonal texture consisting largely of well aligned (foliated) pale green amphibole laths. As such the texture of these rocks is that of an annealed shear fabric (S_2, see Table 1). In other words, grain margins are straight and appear to have been thermally annealed either during and/or subsequent to ductile shearing. Thermal annealing of the shear fabric is supported by the general paucity of shearing, boudinage, kinking and undulose extinction of the individual amphibole grains. Consequently the mineral phases constituting the shear fabric define a metamorphic assemblage labelled M_2.

M_2 assemblages include the following in amphibolite:

- pale green amphibole-plagioclase-sphene-opaque-orange biotite.

The assemblages of the different domains in banded epidote-amphibole rock are:

- pale green amphibole-plagioclase-sphene-chlorite-opaque ± epidote,
- epidote-sphene-scapolite-chlorite-pale green amphibole,
- pale green amphibole-scapolite-plagioclase-biotite,
- biotite-epidote-plagioclase.

The assemblage in the pelitic ultra-mylonite at 260 m is:

- quartz-calcite-chlorite-plagioclase-biotite.

The mineral proportions and mineral assemblages are consistent with the protolith of the two amphibolite rock types having been basalts metamorphosed to the lower amphibolite facies (i.e. approximately 400–500°C).

The aligned granoblastic texture of these amphibolites is the typical fabric expression as a result of ductile shear of amphibolites (Goscombe, 1990). The texture is strongly foliated in most samples and is mylonitic in nature. Development of this strong foliation by shear is supported by this foliation enclosing augen of pre-existing coarse-grained amphibole and plagioclase. Biotite laths are also strongly aligned, and both enclose and abut the fine-grained S_2 amphibole grains. In most amphibolite samples 90–100 % of the rock is amphibole, and the only variations in the S_2 foliation are domains of finer grainsize. In some samples a second planar element is recognised as very thin planes of significantly finer grainsize at low angles to the S_2 foliation. The S_2 foliation swings into these planes, which are interpreted as thin zones of relatively high strain, that is C-planes (Simpson, 1984). In some samples these zones of relatively high strain (i.e. marked grainsize reduction) are thought to parallel the S_2 foliation. In the banded amphibolites the S_2 foliation not only parallels a pre-existing compositional layering (2–8 mm thick) but also excentuates this and gives rise to a finer scale (1–2 mm thick) differentiated layering.

Amphibolite samples Z358 and Z359, from 270.5 m and 275 m respectively, have 30–40 % of the sample being a much coarser grained metamorphic assemblage of augen which are enclosed by the M_2 ductile shear fabric described above. The earlier coarse-grained augen assemblage consists of pale green amphibole and plagioclase, and has been labelled M_1. Similarly the epidote-rich layers in the banded amphibolites are enclosed and boudinaged by the ductile shear fabric (S_2), thus these layers may also represent M_1 domains. Consequently it is felt that both M_1 and M_2 have similar lower amphibolite facies assemblages, except for the presence of biotite in the S_2 shear fabric.

Apart from the amphibolite facies metamorphic rocks recognised in the first 280 m of core (fig. 1), there is a component of distinctly different igneous rocks. The first 48 m consists largely of retrogressed (serpentinised and actinolitised to varying degrees) orthopyroxenite. There are also two slivers of serpentinite after orthopyroxenite at

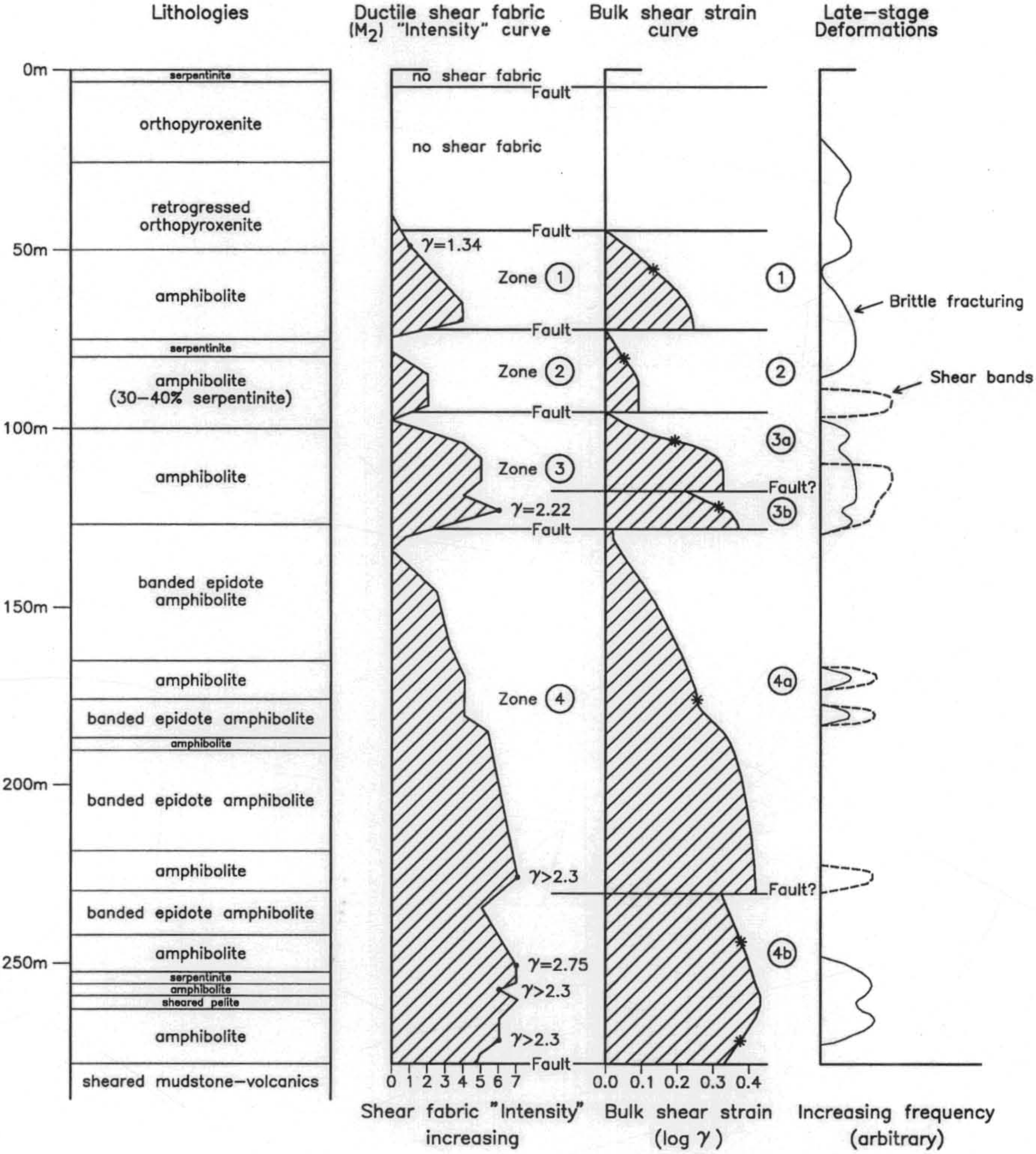
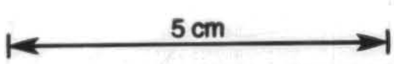

Lithologies
Ductile shear fabric (M_2) "Intensity" curve
Bulk shear strain curve
Late-stage Deformations
0m
50m
100m
150m
200m
250m
serpentinite
orthopyroxenite
retrogressed orthopyroxenite
amphibolite
serpentinite
amphibolite (30–40% serpentinite)
amphibolite
banded epidote amphibolite
amphibolite
banded epidote amphibolite
amphibolite
banded epidote amphibolite
amphibolite
banded epidote amphibolite
amphibolite
serpentinite
amphibolite
sheared pelite
amphibolite
sheared mudstone–volcanics
no shear fabric
Fault
no shear fabric
Fault
γ=1.34
Zone 1
Fault
Zone 2
Fault
Zone 3
γ=2.22
Fault
Zone 4
γ>2.3
γ=2.75
γ>2.3
γ>2.3
Fault
Fault?
Fault?
1
2
3a
3b
4a
4b
Brittle fracturing
Shear bands
0 1 2 3 4 5 6 7
Shear fabric "Intensity" increasing
0.0 0.1 0.2 0.3 0.4
Bulk shear strain (log γ)
Increasing frequency (arbitrary)

Figure 1.


5 cm

78.5 m and 253 m (fig. 1). The amphibolites which occur throughout the bulk of the core do not have assemblages (except for the presence of high Cr-spinel in some samples) consistent with their formation by metamorphism of serpentinised orthopyroxenite. It is thought that the orthopyroxenite and amphibolites are two distinct rock types, not the amphibolites being the metamorphic equivalent of the other. It is felt that both the serpentinisation of the igneous orthopyroxenite and the early amphibolite facies metamorphism (M_1) of the basalts occurred prior to the ductile shear fabric (S_2). As a consequence M_1 metamorphism and the serpentinisation event may be unrelated.

A multitude of late-stage (largely brittle and hydrous-carbonic) deformational features overprint and reactivate the earlier ductile shear fabric (S_2). These are listed below in an approximate chronological order of formation (oldest to youngest). However it is felt that these are not discrete deformational episodes, as the timing of these features do overlap.

1. The earliest features are thin (<1 mm), discrete, foliated shear bands consisting of very fine-grained phases such as serpentinite, carbonate, chlorite, actinolite and quartz. These most commonly reactivate the earlier ductile fabric (S_2) as discrete zones of very marked grainsize reduction parallel to S_2, but also form at high angles to it.

2. Closely associated with thin shear bands, but also forming in isolation from them, are brittle fractures filled with the same mineral phases but of a much coarser grainsize and no foliation development. Fracture planes are random in orientation but are largely at high angles to the early ductile shear fabric (S_2). In some samples a high spatial density of these fractures and shear bands has formed brecciated domains. Some blocks, of the earlier S_2 fabric, within the breccia are rounded and so imply movement associated with the brittle fracturing episode. Movement along individual fractures is also shown by rotation and offsetting of the S_2 foliation. Some fractures are irregular and non-planar, similarly not all fractures are filled with the retrogressive minerals.

3. Thin (<<1 mm), discrete, laterally persistent and straight planes of movement displace (<1 mm) the chlorite-serpentinite-calcite-quartz filled fractures.

4. The last generation of brittle fractures are filled with coarse-grained quartz and/or calcite only, and these are not associated with any lateral displacements.

Brittle fracturing and fracture filling are recognised in many samples throughout the first 280 m of core, but particularly so in the intervals; 20–80 m, 100–123 m and 250–270 m (fig. 1). Thin, discrete shear bands are less common but are strongly correlated with the inferred fault-thrust planes (fracturing is also) which are discussed below and marked in Figure 1. Consequently these brittle-hydrous-carbonic features may be associated with late-stage reactivation of discrete sharp thrust? planes which may have formed during the earlier ductile shear episode (S_2).

Two late-stage faults (thrusts?) are inferred at the boundaries between the vertical, 40° and 60° dipping foliation zones at the top of the drill core. Dip of the foliation down the drill core is collated in Table 2. Consequently the two inferred faults are at approximately 7 m and 45 m. No ductile shear fabric (i.e. S_2) is recognised in the two uppermost zones of serpentinite (fig. 1). Consequently it is felt that the serpentinite did not experience S_2 ductile shear (Table 1) and thus formed extraneous to the amphibolite sequence, with the result that both rock types were later brought into fault (thrust?) juxtaposition after S_2 ductile shearing of the amphibolites. This juxtaposition possibly occured during the late-stage discrete thrusting? and brittle episodes (Table 1).

ESTIMATES OF SHEAR STRAIN AND DISPLACEMENTS

The "intensity" of the early ductile mylonitic fabric (S_2) has been arbitrarily graded into seven catagories (fig. 1). The "intensity" of the fabric is based on the following:

1. Degree of parallel alignment of amphibole laths and biotite plates.

2. The aspect ratios (i.e. length vs. width) of amphibole laths.

3. The degree of grainsize reduction experienced.

4. The proportion of the sample that has developed a mylonitic fabric. In most cases this is essentially 90–100 % (except for the samples listed in Table 2).

The variation in shear fabric "intensity" with bore hole depth is plotted in Figure 1. It is noted that there is a general increase in shear fabric "intensity" with depth. Furthermore, there are four broad zones between 45 m and 280 m. Within each zone the shear fabric "intensity" increases gradually from 0 at the top of the zone to a maximum value at or immediately before the base of the zone (fig. 1). Thus, within each of these zones there is an asymmetry of strain partitioning, with most of the strain being partitioned in the base. The boundaries between the high strain base of one zone and the absense of strain at the top of the next zone down the hole is very sharp. Consequently these boundaries are considered faults (possibly thrusts?). This is supported by distinct lithological changes at these boundaries. It is proposed that these four zones are in fact a packet of ductile shear zones which over-rode each other along sharp planes (thrusts?) of relatively high shear strain. In addition, further zones are defined by distinct drops in fabric "intensity", although not to zero values.

Quantitative estimates of bulk shear strain were made in seven samples (Table 2) by measuring the acute angle between the S_2 foliation (S-plane) and discrete, thin planes of relatively high shear strain which formed coevally with S_2 (C-plane). The relationship between bulk shear strain (γ) and the angle between C-S planes (ψ) is given as;

$$\tan 2\psi = 2/\gamma \text{ (Ramsay \& Graham, 1970).}$$

Mylonites with co-planar C-S planes are generally thought to have shear strains of >2.3 (Burg and Laurent, 1978). The few approximate bulk shear strain estimates obtained are used to very roughly calibrate the fabric "intensity" curve data and so produce the shear strain curve presented in the middle of Figure 1 (with log γ axis).

The bulk shear strain curve has been used to derive estimates of the ductile shear displacement (parallel to S_2 foliation) within each delimited zone. These estimates do not incorporate possibly very large displacements along the discrete planes (thrusts?) between these zones. Displacements parallel to the shear fabric (S_2) are calculated by the following:

Assuming a vertical drill hole, the real width of the zone measured orthogonal to its margin (W) is given by;

$$W = L \cdot \cos\theta$$

where L = length of zone intersected by the core.
θ = dip from horizontal of the S_2 foliation.

The angle of rotation (due to S_2 ductile shearing) of a line originally orthogonal to S_2 (ψ) is given by the following two relationships;

$$\psi = \tan (D/W)$$

and

$$\psi = \tan\gamma$$

where D = displacement parallel to S_2
γ = bulk shear strain.

Consequently, displacement parallel to S_2 due to ductile shear is given by;

$$D = L \cdot \gamma \cdot \cos\theta$$

Maximum displacements are calculated using the maximum bulk shear strain estimate in the respective zone (Table 3). The median displacements are calculated using the average bulk shear strains (marked as a star on the shear strain curve in Figure 1). These displacement estimates and the relevant data are tabulated in Table 3. The estimates of total displacement by ductile (S_2) shear accross the packet of ductile shear zones between 45 m and 280 m are 256 m maximum displacement and 198 m average (or minimum) lateral displacement. The real total displacement across all these zones is not known because displacements due to the discrete bounding thrusts? are not known. Displacements along these discrete thrust? planes could potentially be in the order of kilometres.

CONCLUSIONS

Berry (1988) reports from the region that the foliation in the amphibolites dip to the east, and that the sense of shear is SE over NW along steeply plunging amphibole mineral lineations. Thus the 116 m wide (orthogonal to S_2 foliation) packet of ductile shear zones in amphibolites in the Serpentine Hill core involved a bare minimum of 256–198 m of over-thrusting to the NW. Further displacements were involved along discrete thrust planes within and bounding the amphibolite ductile shear zones, and in the highly sheared black muds and volcanic rocks (not discussed in this report) below the amphibolites. These un-quantified displacements were presumably large (kilometres scale) to emplace these medium-grade metamorphic rocks and cumulate ultramafic rocks in the upper crust.

The late-stage, more brittle and retrogressive deformational features may represent either of the following.

1. Brittle deformational expressions may have resulted from thrusting along the discrete thrust planes proposed by this study. These thrust planes may have formed in the final stages of S_2 ductile shear, either due to an increase in the strain rate or as a result of the body of rock moving upwards (to shallower crustal levels) into progressively less ductile deformational regimes (i.e. lower temperature and confining pressure).
2. Alternatively the more brittle deformations may be due to a totally unrelated shearing episode which reactivated parts of the S_2 ductile shear zone at lower crustal levels and at a later date than S_2–M_2.

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TABLE 1

Time sequence of tectono-thermal episodes recognised in the Serpentine Hill core. Time progresses down the page.

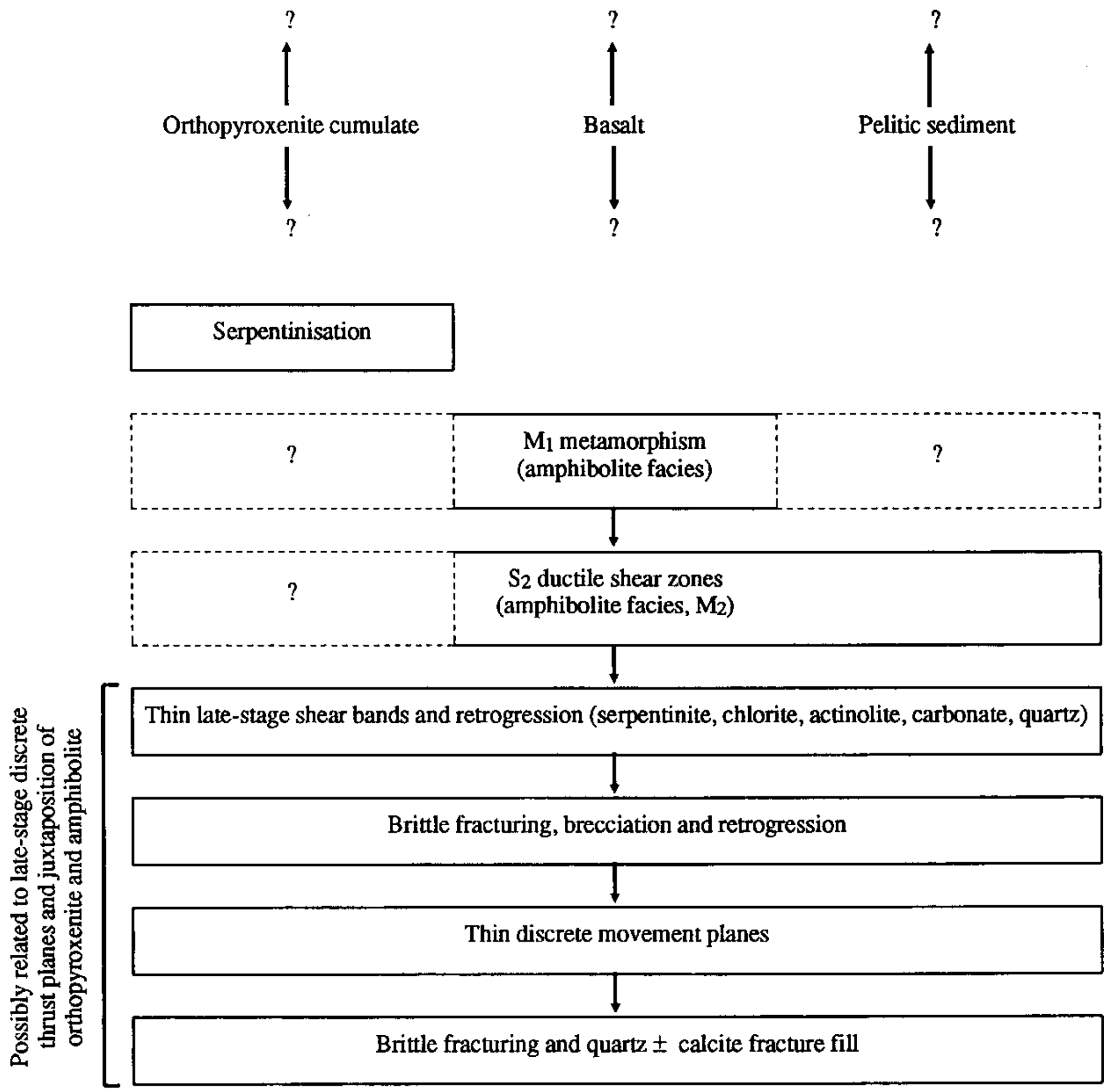

TABLE 2

Estimates of bulk shear strains (after Ramsay and Graham, 1970) from Type-1 (Berthe *et al.*, 1979) S-C amphibolite mylonites in Serpentine Hill core.
*** value after arguments of Burg and Laurent (1978).**

Drill core depth (m)	Sample	Proportion of S_2 in sample (%)	Angle between C-S planes	Bulk shear strain (γ)
48	13	20	28°	1.34
123.8	45	90–100	21°	2.22
226	83	90–100	28°	1.34
251.5	2353	90–100	18°	2.75
251.5	2353	90–100	parallel	>2.3*
256	2355	90–100	parallel	>2.3*
270.5	2358	70	parallel	>2.3*
275	2359	60	-	-

TABLE 3

Estimates of displacement parallel to S_2 foliation due to ductile shear only in the amphibolite mylonites. Displacements are for the individual zones delimited in Figure 1. Calculations by method discussed in text.

Shear zone label	1	2	3a	3b	4a	4b	Total
Vertical thickness of zone — L (m)	27.5	23	22	10	102	47.5	232
True thickness of zone — W (m)							116
Dip of S_2 foliation — θ	65°	60°	60°	75°	60°	60°	
Maximum γ	1.78	1.2	2.13	2.29	2.51	2.69	
Average γ	1.35	1.09	1.58	2.09	1.82	2.29	
Maximum displacement — D (m)	20.7	13.8	23.4	5.9	128	64	255.8
Median displacement — D (m)	16	12.5	17.4	5.4	93	54	198.3