Table 5.1

Table 5.1 Recognised senses of shear from locations in SE NPHM & Dichil/E. Astor

Area / loction no.	Sinistral	Dextral	Thin section (weight)	outcrop/hand sample (weight)	Width of Zone	Sample Name or Rock type
Lower Rupal Valley						
#13	x		5-sin	1-dex & 1-sin	>50 m	NE95/29-VI
# 11	x		4-sin	2-sin	>100 m	NE95/28-IX NE95/28-X
top of Churit Fan	?	x	3-dex & 1-sin	no	>25 m?	NE95/29-V
100 m E of #12		x	5-dex	no	~50 m	NE95/29-III
~50 m E of #12		x	4-dex	3-dex	~50 m	NE95/29-IV
#12		x	4-dex	1-dex & 1-sin	<100 m	NE95/29-II
50 m E of # 10	x		4-sin	2-sin	<50 m	NE95/28-XI
400 m E of #14		x	4-dex	no	<20 m	NE95/29-IX
Ghurikot Valleys						
#17		x	no	2-dex	>100 m	gnt-pelite
50 m E of #66		x	no	1-dex	>25 m	str. spag. gn
100 m E of #69	x		no	3-sin	<25 m	cse bnded gn
50 m E # 69		x	no	2-dex	<25 m	thin bnded gn
#69	x		no	2-sin	>25 m	E6/10/8-I
30 m W of #69	x		no	2-sin & 1-dex	>30 m	mig-gnt-pel-gn

Table 5.1 Recognised senses of shear from locations in SE NPHM & Dichil/E. Astor

Table 5.1 (continued) Recognised senses of shear from locations in SE NPHM & Dichil/E. Astor

Area	Sinistral	Dextral	Thin section (weight)	outcrop/hand sample (weight)	Width of Zone	Sample Name or Rock type
Bulan Gah						
75 m W of "MMT"		x	no	3-dex	>50 m	gnt-pelite
100 m E of # 70A	x		no	3-sin	>30 m	marble/amph
Rama						
#64		x	no	3-dex	>25 m	str f'spar gn.
#62	x		2-sin	no	>50 m	E6/10/7-I
#R1	x		no	2 sin	>30 m	bt-gn/amph
1 km E of #RL71		x	3-dex	no	>25 m	E6/6/21-I
E Astor						
300 m W of #71		x	4-dex	3-dex	>20 m	E6/6/27-V
200 m E of #71		x	4-dex	2-dex	>100 m	E6/6/27-IV
Dichil Gah						
~750 m E of #7	x		3-sin	1-sin	>50 m	E6/10/10-I

Table of selected outcops where a domain with a sense of shear was determined. In each case, sinistral or dextral is indicated, followed by a confidence weighting of between 1 and 5 for thin section and hand sample, respectively.

Table 5.1 (cont.) Recognised senses of shear from locations in SE NPHM & Dichil/E. Astor deeper into the massif at SE NPHM (RCSZ). Both of these shear zones are associated with plutonism over the last 10 or 15. Ma. They define a doubly-vergent local orogen (e.g., Koons, 1990) with WNW directed shortening.

2. The section in SE NPHM between the RCSZ and the MMT has been passively overturned but not reworked, and is recognisably Himalayan. The preserved Himalayan fabrics show the highest grade (Passchier and Trouw, 1996, p52) inferred for deformation seen in southern NPHM, and both Himalayan thrust and normal displacement are recorded. The equivalent section in SW NPHM has been cut by ~5 km structural thickness.

5.9 CHAPTER APPENDICES

5.9.1. Sense of shear analyses.

I include here a partial review of the sense of shear indicators in high strain rocks that have been used in this thesis. Mylonites and high strain rocks in general typically develop a strong mineral lineation (Passchier and Trouw, 1996, p103) that, in most cases, is a linear shape fabric or "stretching lineation" (single grains or aggregates of grains that are deformed and form a lineation). Occasionally the lineation can be partly a result of hinge lines of sheath folds - folds that are normal to "flow folds" (Cobbold and Quinquis, 1980). I have are cut all thin sections parallel with mineral lineation, perpendicular to main foliation (for fuller details, see tables in 5.9.3

The structures that I used as indicators of sense of shear include:

(1) *Throughgoing fabrics* including oblique foliations defined by elongated shape of grains oblique to the main (compositional) foliation or trend of C-surfaces (e.g. Means, 1981; Lister and Snoke, 1984).

(2) *Shear zones in fabric* (cleavages, surfaces or bands). C/S fabric (also C-S or S-C fabric) involves S ("schistosité") surfaces that are transected by C-surfaces (Berthé et al., 1979; Lister and Snoke, 1984). C-surfaces are discrete discontinuities (i.e. true shear zones) on which there has been some displacement, while the S surfaces are developed in response to the general shortening (Hanmer and Passchier, 1991). C'-surfaces (Berthé et al., 1979, also termed "Shear band foliation" - White et al., 1980; "asymmetrical extensional crenulation cleavage" - Platt and Vissers, 1980; and "asymmetrical extensional shear bands" - Hanmer and Passchier, 1991) typically develop at an angle of 15-30° to the shear zone margin (Passchier, 1991) and to the C-plane (more usefully for this study where the shear zone margin is frequently not seen). C'-surfaces are extensional shear zones that often develop preferentially in more foliated portions of rocks (e.g., in micaceous domains of compositionally layered gneisses), and typically anastamose around and transect portions of an older foliation giving a recognisable shear direction for the C'-surface (White, 1979; Berthé et al., 1979; Platt and Vissers, 1980; Dennis and Secor, 1987).

(3) *Porphyroclasts* (remaining grains of the parent rock within the high strain zone) typically develop characteristic shapes as they deform as stiff inclusions in a soft matrix (e.g. Hanmer, 1984; Passchier and Simpson, 1986). Dynamic recrystallisation of a feldspar grain (e.g.) by grain boundary migration (see deformation mechanisms below) will allow new fine grains to form "tails" (trails) and "wings" that form δ- (delta) σ- (sigma) and quarter structures ("mantles" of Passchier and Trouw, 1986) whose asymmetry (stair stepping) can be used to determine sense of shear (Hanmer, 1984; Passchier and Simpson, 1986; Hooper and Hatcher, 1988; Hanmer and Passchier, 1991; Passchier and Trouw, 1996). Strain shadows are areas flanking porphyroclasts (and porphyroblasts - see below) that contain a mineral(s) that is different from the porphyroclast. The asymmetry of these can be used (often in conjunction with porphyroclast wings) to determine the general overall shortening

direction for the porphyroclast or porphyroblast in question based assuming the shadows are low strain sites.

(4) Synkinematic Porphyroblasts are grains that grow in a deforming matrix. The most studied type of porphyroblast, (and the only examined in this thesis) is garnet. It has long been recognised that inclusions in porphyroblasts are incorporated in a passive manner that can be used to identify how the porphyroblast has rotated relative to the fabric of the immediate matrix in which it occurs (Zwart, 1962; Spry, 1969; Vernon, 1975; Bell, 1981). Based upon this rotation, a sense of shear can be inferred, but must not be taken for granted in the absence of a clear relationship between the shear zone reference frame and the garnet porphyroblasts reference frame (Bell, 1985).

(5) Mica "fish" (Eisbacher, 9170; Choukroune and Lagarde, 1977; Simpson and Schmid, 1983; Lister and Snoke, 1984) have their long axis in the general extension direction of the strain, trails that often stair step in the displacement direction. Additionally, they may have one side curved and one side planar affording a monoclinic symmetry that can be further used as a shear sense indicator (e.g. Lister and Snoke, 1984).

(6) *Obvious features* including strain markers (e.g., fractured grains with observable shear) can also be used to infer sense of shear. Note that care must be taken when using offsets on fractures at a high angle to the foliation (Rutter e al., 1996)

In the various high strain rocks that I have examined, I have avoided using the scheme of "type I and type II S-C mylonites" (Lister and Snoke, 1984) as this is a potentially confusing distinction between continuous (e.g. "strain sensitive simple fabrics" of Ramsay and Graham, 1970) and discontinuous fabrics (Berthé et al., 1979). I maintain the scheme of Berthé et al. (1979) where the C-surfaces/planes are required to be discrete (i.e., discontinuous) shear zones (as in the Lister and Snoke

(1984) type II mylonite) and may not be narrow zones of ductile strain as is frequently the case for C' surfaces ("shear bands" or "asymmetrical extensional shear bands" of Hanmer and Passchier, 1991 - the Lister and Snoke (1984) type I mylonite). Note that (e.g.) Passchier and Trouw (1996) discourage the Lister and Snoke (1984) "type I and type II S-C mylonites" classification based upon the usage of trails stepping off mica fish to define C-surfaces. Passchier and Trouw (1996) note that not always do such trails form by partitioning along shear bands. Where observed to be well developed in this study, however, these mica trails have commonly been developed parallel with, and in addition to, C-surfaces.

5.9.2 Deformation mechanisms inferred from microstructure

I include here a partial review of certain deformation mechanisms in quartzofeldspathic rocks to see how far history of temperature and strain can be remarked upon based upon deformation mechanisms inferred from microstructure. Preparation of thin sections used for microstructural analyses is discussed in *5.9.3.2 samples lists*.

Data from load testing experiments of both monomineralic samples (e.g., Tullis and Yund, 1985; 1991; Dell Angelo & Tullis, 1989) and granitic (i.e., quartz feldspar) aggregates (e.g., Fitzgerald and Stünitz, 1993; Stünitz and Fitzgerald, 1993) allows extrapolation of strength and temperature information. Subsequent observation of microstructures resulting from loading experiments together with naturally deformed examples (e.g., Simpson, 1985; Gapais, 1989; Pryer, 1993) has lead to a number of conclusions regarding microtextures and microstructures that characteristically develop within specific temperature ranges. The following is summarised from the previous references and from Passchier and Trouw (1996).

Above about 300°C, feldspar is thought to be brittle while quartz undergoes ductile deformation due to dislocation glide (little to no climb) and creep. This results in uneven and patchy extinction of quartz grains. Feldspar grains commonly show the beginings of core and mantle texture. "Cores" are large (strong) porphyroclastic feldspar grains, possibly microfractured, while the "mantle" (also termed "mortar") is composed of relatively finer grains of (typically) feldspar. The finer grained feldspar mortar is derived from the porphyroclastic feldspar grains and has separated largely through grain boundary migration recrystallision in attempts to recover from dislocation tangles (these can be reduced through dislocation climb only at higher temperature; >400°C). Between approximately 400-600°C, diffusion assisted-dislocation processes in quartz are more prevalent and extensive quartz subgrain development and subgrain rotation recrystallisation operates. Passive flattening of quartz grains passes to wholesale recrystallision at higher strains and leads to very continuous monomineralic ribbons of quartz. Feldspar grains develop extensive augen/mantled porphyroclasts with finer grained feldspar also forming ribbons. Above about 600°C, quartz and feldspar show somewhat similar textures; grain boundaries may be cuspate/lobate, and diffusion creep processes (Nabarro-Herring, or "volume diffusion" and Coble, or "boundary diffusion") are thought to play a major role. Such finely-grained microtextures (e.g., 20-40μm) were not observed, however, in any of the thin sections examined from NPHM.

5.9.3. Samples and thin sections from Nanga Parbat

5.9.3.1 Samples from Nanga Parbat

All samples that I collected in Nanga Parbat are detailed in three tables (5.2, 5.3, and 5.4) for 1995, 1996, and 1997, respectively. Nomeclature is straightforward: In 1995, NE95/27-V indicates 1995, 27th (of August), 5th sample collected since begining of day. NE95/8-V indicates 1995, 8th (of September), 5th sample collected since begining of day. In 1996 and 1997, a longer field season necessitated using a term for the month; E6/10/10-I indicates 1996, 10th (of October), 1st sample