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Synmagmatic deformation patterns in the Old Woman Mountains, SE California

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Abstract

Synmagmatic structures within granitic plutons may provide insight into the interplay between plutonism and regional deformation at mid-crustal levels. Within the Late Cretaceous Old Woman pluton (Mojave Desert, SE California), synmagmatic structures include; magmatic fabrics parallel to wall rock foliations, melt-filled shear zones, folded gneissic xenoliths and schlieren with axial planar magmatic fabric. Deformation continued below granite solidus temperatures in shear zones on the pluton margins.

These structures permit reconstruction of a sheet-like pluton that was emplaced under regional extension. Taken together with published thermochronometric data the synmagmatic structures constrain the role played by magmatic events in the collapse of a thickened crustal section. The post-plutonic cooling history suggests rapid uplift and denudation ending by 65 Ma. We argue that extensional deformation overlapped and post-dated pluton emplacement and may have contributed to tectonic unroofing. We suggest that magma emplacement can trigger subsequent extensional collapse in overthickened crustal blocks.

1. Introduction

Structures formed in granitic plutons before full crystallisation, herein termed ‘synmagmatic structures’, may provide information on pluton emplacement and/or the regional tectonic framework. High rates of pluton cooling compared to the estimated duration of tectonic events in orogenic belts mean that the length of time during which even a deeply emplaced pluton remains partially molten is short (< 1 Ma) (Paterson and Tobisch, 1992). Clearly, the identification of synmagmatic structures is useful as they can represent a ‘snapshot’ of their strain environment during pluton consolidation (Schofield and D’Lemos, 1998).

Granitic plutons may contain a variety of pervasive and non-pervasive synmagmatic structures. A pervasive alignment of early formed crystals (including megacrysts) by rotation and hence displacement of melt is common. These are the ‘primary structures’ of Balk (1937), the ‘magmatic state’ fabrics of Blumenfeld and Bouchez (1987) and the ‘pre-full crystallisation’ fabrics of Hutton (1988). Evidence for ductile behaviour of the magma is suggested by macroscopic-scale folds (Abbott, 1989; Pitcher, 1993). Granitic magmas may also undergo extreme deformation localisation, e.g. early healed shears or cross-cutting schlieren of Balk (1937) and Berger and Pitcher (1970) and similar structures described by McCaffrey (1994) that have the appearance of fractures that offset internal contacts. Synplutonic dyke intrusion (Pitcher, 1993) may also be considered an example of phenomena that produce non-pervasive synmagmatic structures.

The Late Cretaceous Old Woman Mountains pluton was emplaced within deformed and metamorphosed continental crust in the southwestern US Cordillera (Mojave Desert). In this paper, we describe the nature, geometry and significance of a range of superbly developed synmagmatic structures. We discuss this information in the context of a possible emplacement mechanism, the Late Cretaceous regional tectonic

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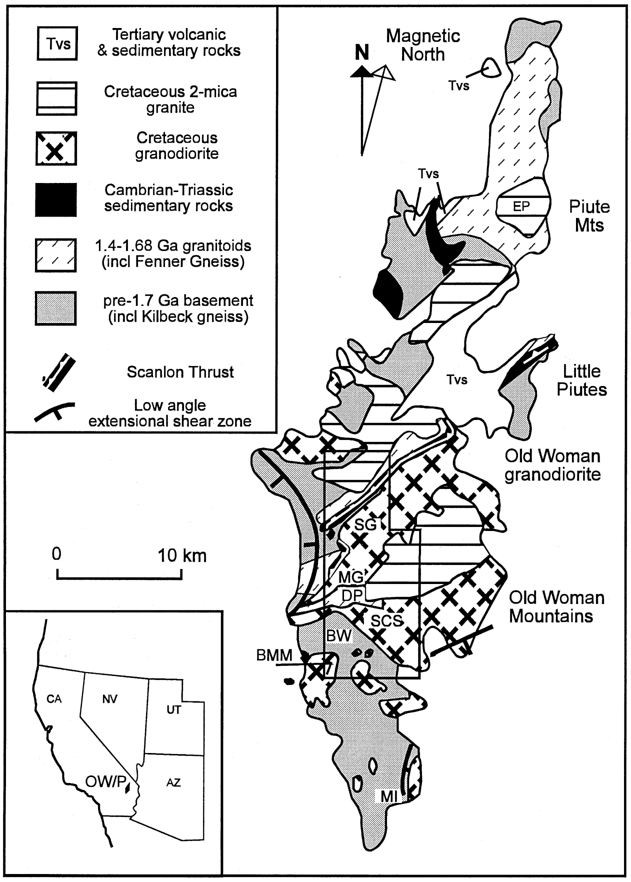

Fig. 1. Simplified geological map of Old Woman–Piute Mountains, SE California. Box indicates area of detailed map in Fig. 2(a). Abbreviations: BMM = Black Metal Mine, BW = Brown's Wash, DP = Dark Plateau, MG = Meteor Gulch, MI = Milligan, SCS = Sheep Camp Spring, SG = Scanlon Gulch, EP = East Piute pluton. Inset map of southwestern United States shows position of Old Woman–Piute Mountain range (OW/P).

framework, and more generally of plutons emplaced in crust undergoing post-orogenic collapse.

2. Geological setting

2.1. Regional geology

The Old Woman/Piute Mountains (Fig. 1) are located within the Mojave crustal province, a region underlain by rocks with isotopic inheritance suggesting more than 2 Ga crustal residence (e.g. Bennett and DePaolo, 1987; Wooden et al., 1988). The oldest exposed rocks are contained within supracrustal sequences that are intruded by 1.4–1.7 Ga granites and subordinate intrusive mafic rocks. The oldest intrusions are synorogenic and strongly metamorphosed, whereas those younger than about 1.7 Ga are variably metamorphosed, primarily during the Mesozoic (Wooden and Miller, 1990). During the Palaeozoic and early Mesozoic, stable platform sediments were deposited upon the Proterozoic basement (Stone et al., 1983). Protracted arc magmatism in this province during the Mesozoic resulted in voluminous intermediate to felsic plutons and minor gabbros (e.g. Miller and Wooden, 1994) and was accompanied by deformation and metamorphism (see Table 1 for summary).

2.2. Geology of the study area

Meta-supracrustal rocks that form the oldest basement were intruded in the southern portion of the area by (ca. 1.7 Ga) granodioritic to monzogranitic magmas. These rocks have experienced Mesozoic deformation and partial melting that imparted a strong gneissic banding defined by alternating mafic and felsic stripes to form the Kilbeck gneiss (cf. Wooden et al., 1988; Howard et al., 1989). To the north, the supracrustals were intruded by a distinctive 1.68 Ga megacrystic granitic to granodioritic magma (known as Fenner orthogneiss) (Bender et al., 1990) and 1.62 Ga mafic granodiorite and 1.41 Ga syenogranite in the central part of the range (Akers and Miller, 1991). The meta-supracrustal rocks and Fenner gneiss form the basement of the distinctive Cambrian through Triassic sequence of quartzites, pelitic schists, calc-silicates and abundant carbonates. These rocks were subjected to intense deformation and metamorphism with individual formations having been reduced to 5–50% of their original thickness by ductile attenuation (e.g. Miller et al., 1982). Metamorphosed mafic to felsic dykes of Jurassic age intrude both the Cambrian through Triassic sequence and the Proterozoic basement (Gerber et al., 1995).

The Scanlon shear zone, a major ductile structure that transects the central Old Woman Mountains, is most clearly exposed within the Cambrian through Triassic sequence (Howard et al., 1980, 1989; Miller et al., 1982; Nicholson and Karlstrom, 1990). This structure contains a number of fault discontinuities that separate imbricated thrust nappes, including the Scanlon thrust which placed inverted Lower Palaeozoic strata onto upright Palaeozoic and Mesozoic beds. Proterozoic Fenner Gneiss and supracrustal rocks lie structurally above the inverted sequence in the hanging wall to the Scanlon thrust. The Scanlon shear zone is folded by a large-scale, upright synformal fold causing it and the underlying Old Woman pluton to be exposed in the northern part of the Old Woman Mountains (see Fig. 2). This is associated with small-scale, minor upright folds with steeply NW-dipping axial planar cleavage observed within the Scanlon shear zone structure.

Mesozoic metamorphism within the Old Woman Mountains reached upper amphibolite facies (Miller et al., 1982). Nappe emplacement resulted in burial to ca.

Table 1
Geological summary of the Eastern Mojave Desert, southeastern California

Age	Rock types	Events
Palaeocene–Miocene		Slow uplift (0.1–0.2 mm/y)/Basin and Range extension
Late Cretaceous (70–75 Ma)	**Old Woman Pluton and 2-Mica granites**	**Peak of metamorphism and plutonism, onset of rapid uplift, (1–2 mm/y). Later upright NE-trending folding. Extensional deformation**
Late Cretaceous (80–90 Ma)	Minor felsic plutons	Contractional deformation produced major basement cored nappes. Onset of metamorphism
Late Jurassic (145–150 Ma)		Bimodal plutonism
Middle Jurassic (160–170 Ma)		Arc magmatism, Mafic to intermediate plutonism
Cambrian–Triassic	Accumulation of 1–2 km carbonate dominated sediment	Passive continental margin
1.1 Ga	Doleritic dykes	Minor intrusion
1.4–1.45 Ga	granites and syenites	Minor intrusion
1.62–1.69 Ga	Intermediate/felsic rocks	Minor intrusion
1.70–1.72 Ga	Granite/Gabbro intrusion	High *T*/Mod to High pressure, deformation and metamorphism (Ivanpah Orogeny)
1.73–1.76 Ga	Granite and granodiorite plutons	Intrusion
1.8 Ga	Supracrustal metasedimentary rocks	
2.0 Ga		Early Crust formation

Sources: Wooden et al. (1988), Miller and Wooden (1994).

15 km as estimated from thermobarometry and mineral assemblages in the metasedimentary rocks (Hoisch et al., 1988; Foster et al., 1992; Rothstein and Hoisch, 1994). The age of the onset of crustal thickening remains uncertain. It may have begun in the Jurassic and continued until the Late Cretaceous (Foster et al., 1992). Peak metamorphic grade formed in the Late Cretaceous and generally increases to the south, suggesting progressively deeper levels in the crust (Foster et al., 1992; Rothstein et al., 1994).

2.3. Late Cretaceous felsic plutons

The Old Woman–Piute batholith consists of two suites of felsic plutons (Foster et al., 1989a, 1992; Miller et al., 1982, 1990, 1992; Miller and Wooden, 1994). In the Piute Mountains (Fig. 1), the East Piute pluton (85 Ma) was emplaced synchronously with metamorphism and deformation in an active ductile thrust (Karlstrom et al., 1993). The meta-aluminous Old Woman pluton, ca. 73 Ma, is the main focus of this paper and occupies much of the central, the southern and all of the eastern Old Woman Mountains (Fig. 1). Equigranular, medium-grained biotite ± hornblende granodiorite is dominant. In the east and south, it grades to a more felsic, porphyritic phase with 1 cm K-feldspar phenocrysts (Howard et al., 1989) with mafic tonalite present locally. There are two main intrusions of two-mica granite in the Old Woman Mountains: the Sweetwater Wash pluton, which lies structurally above the Old Woman pluton, and the Painted Rock pluton, which was intruded directly into the pluton. These peraluminous rocks are light coloured, medium grained and equigranular biotite–muscovite ± garnet monzogranites and are associated with a series of N-striking, generally steeply-dipping two-mica granite dykes found throughout the southern and central Old Woman Mountains. Although both plutonic suites are identical in age within analytical uncertainty, field relations indicate the granodiorite to be the older. Isotopic and trace element data suggest that both suites were derived from a heterogeneous lower crust (Miller et al., 1990, 1992). Late Cretaceous leucogranite sheets are also present in the area (Howard et al., 1989). These are locally pegmatitic with large K-feldspar megacrysts and form pods that intrude or are gradational with the Kilbeck gneiss. Howard et al. (1989) suggested that they were derived by partial melting of the Kilbeck gneiss during Mesozoic metamorphism.

Pluton emplacement depths of ca. 15 km have been estimated from plutonic mineral compositions and from metamorphic assemblages in country rocks (Foster et al., 1992; Rothstein and Hoisch, 1994). Thermal modelling based upon this initial depth and cooling rates indicated by $^{40}Ar/^{39}Ar$ thermochronometry suggest that rocks of the Old Woman Mountains were rapidly uplifted 1–2 mm/y between 72 and 65 Ma (Carl et al., 1991; Foster et al., 1992). This was followed by much slower uplift rates of 0.1–0.2 mm/y

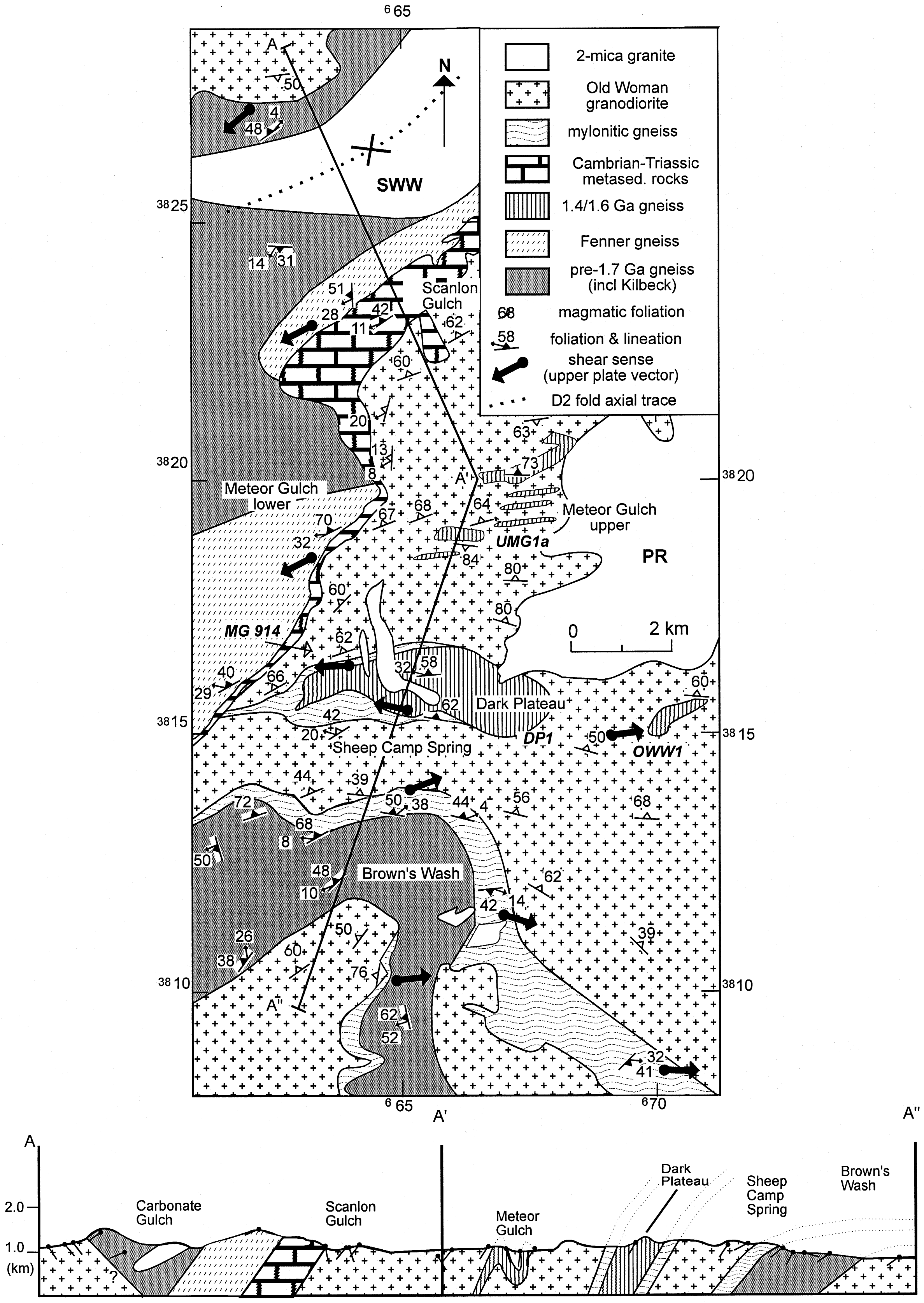

Fig. 2. Structural summary map and cross-section of central part of Old Woman Mountains and locations of samples UMG1a, MG914, OWW1, and DP1. SWW = Sweetwater Wash pluton, PR = Painted Rock pluton.

until the pluton reached the surface in the Miocene (Foster et al., 1991).

3. Old Woman pluton contact geometry and emplacement kinematics

3.1. Contact rocks

The eastern Old Woman Mountains, entirely underlain granodiorite, may represent the core of the pluton (Howard et al., 1989) (Fig. 1). On the western side of the range, the pluton displays a map-scale sheet structure with large lobes of granodiorite interfingered with the wall-rock gneiss units (Figs. 1 and 2). Adjacent to the contacts a mylonitic version of the wall-rock gneiss is generally present (Fig. 2). This is a granodiorite or tonalite gneiss containing biotite and hornblende. It displays a blastomylonitic to ultramylonitic texture, characterised by a very strong foliation and lineation defined mainly by quartz and biotite. It is equivalent to the 'dark gneiss' of Howard et al. (1989).

Most contacts dip moderately to the northwest. The northernmost lobe, herein termed the Meteor Gulch sheet, lies structurally above the Dark Plateau block, a body that comprises primarily 1.62 Ga granitic gneiss (Fig. 1). The Sheep Camp Spring sheet underlies the Dark Plateau block (Fig. 1). Mylonitic gneiss adjacent to this contact is up to 75 m thick and dips to the north, with a lineation plunging moderately to the northwest. This zone links with similar rocks on the northern contact of the Dark Plateau block, thus mylonitic gneiss envelopes the Dark Plateau block in the west (Fig. 2). Shear sense indicators in this region indicate that the hanging wall moved to the west (Fig. 3a).

Mylonitic gneiss is best developed along the base of the Sheep Camp Spring sheet in the east (Fig. 2) and is up to 150 m thick. Mesoscopic shear sense indicators such as asymmetric feldspar tails, boudins and shear bands consistently indicate top to the east movement on this shear zone (Fig. 3b). Fig. 3(c) and (d) illustrate the difference in fabric intensity between this mylonitic gneiss at the contact (Fig. 3c) and the standard wall-rock gneiss in an outcrop less than 20 m structurally

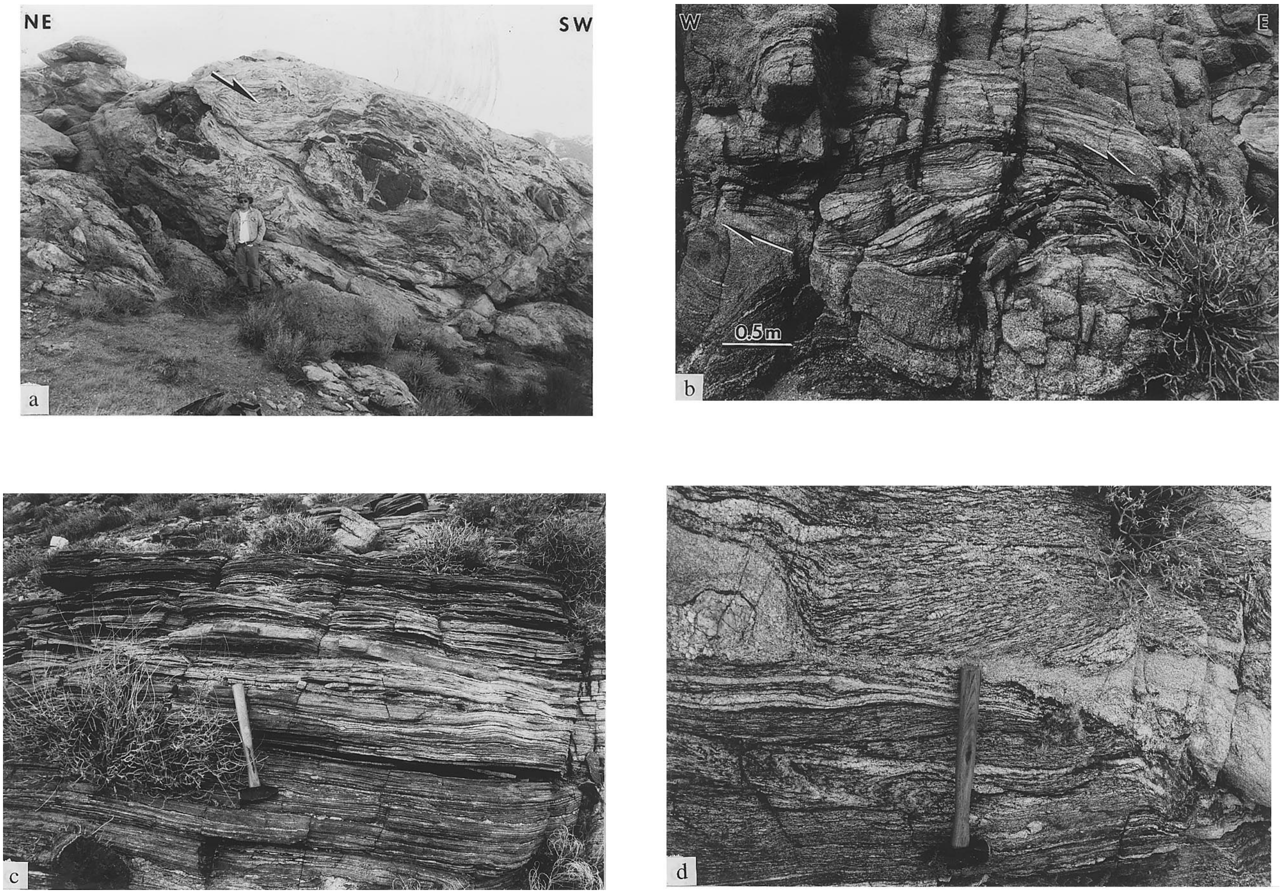

Fig. 3. (a) Asymmetric boudin structure formed by a mafic gneiss xenolith in Meteor Gulch. Movement sense is down to the southwest. (b) Asymmetric boudin structure in strongly banded granodiorite at base of the Sheep Camp Spring sheet, Brown's Wash, indicating top to east displacement in the syn-magmatic shear zone. (c) Mylonitic dark gneiss from lower contact of Sheep Camp Spring plutonic sheet in eastern part of Brown's Wash (Fig. 2). (d) Less than 20 m structurally below the contact is the typical felsic striped texture of the Kilbeck gneiss.

below it (Fig. 3d). The mylonitic fabrics are parallel to and continuous with the foliation in the plutonic sheet above, indicating that this mylonitisation is not older than Late Cretaceous in age.

In several areas to the north of Milligan, Kilbeck gneiss is in contact with, and underlies, small (km scale) exposures of granodiorite. Howard et al. (1989) mapped several ca. 1 km^2 areas of dark gneiss in the southern parts of the range between the Kilbeck gneiss and the Old Woman pluton (Fig. 1). This dark coloured gneiss always displays a mylonitic foliation that is gently or moderately inclined to the southeast with a down-dip stretching lineation. Shear sense is top down to the east. A granodiorite sheet at Black Metal Mine underlies the Sheep Camp Spring sheet. A thin (5–10 m) mylonitic gneiss occurs along the eastern contact of this body (Fig. 2) and here the shear sense is top to the east. Howard et al. (1989) mapped small fragments of dark gneiss separating the pluton from metasedimentary rocks in Scanlon Gulch (Fig. 2); however, it is likely that these are deformed metasedimentary rocks. In summary, kinematic data from the Dark Plateau northwards indicate that the hanging wall moved to the west. To the south of Dark plateau, in the area below the pluton, the hanging wall moved to the east.

4. Synmagmatic deformation within the Old Woman pluton

4.1. Banded granodiorite

A medium grey banded rock is found in the contact zones next to the mylonitic gneiss but always on the pluton side. At the basal contact of the Sheep Camp Spring sheet (Fig. 2), it is composed of plagioclase, minor K-feldspar, quartz, biotite and hornblende with sphene, apatite and magnetite. This mineralogy suggests that it is a strongly deformed version of the Old Woman pluton. Felsic and mafic banding is present and mafic gneiss xenoliths are common (Fig. 4a). The presence of elongate quartz aggregates indicates that deformation continued after the granodiorite had fully crystallised. Kinematic indicators such as asymmetric boudins and discontinuous shear zones are preserved in the basal contact section of the Sheep Camp Spring sheet. These confirm the top to the east shear sense shown by the adjacent mylonitic gneiss.

4.2. Strongly foliated granodiorite

A light grey intensely foliated granodiorite separates the banded granodiorite from the more weakly foliated rock in the centre of the pluton. It is best developed on the northern contact of the Dark Plateau block (Fig. 2). Its mineralogy is identical to that of the banded granodiorite, but the foliation is less intense and there is little evidence of compositional banding. Foliation is defined by strong alignments of biotite and hornblende accompanied by a less obvious plagioclase shape fabric. Quartz in places has a shape fabric, but the aspect ratios rarely exceed 1.5:1 and elongate aggregates or ribbons have not been observed. Some samples also display evidence for the development of two planes of mafic alignment that may represent inci-

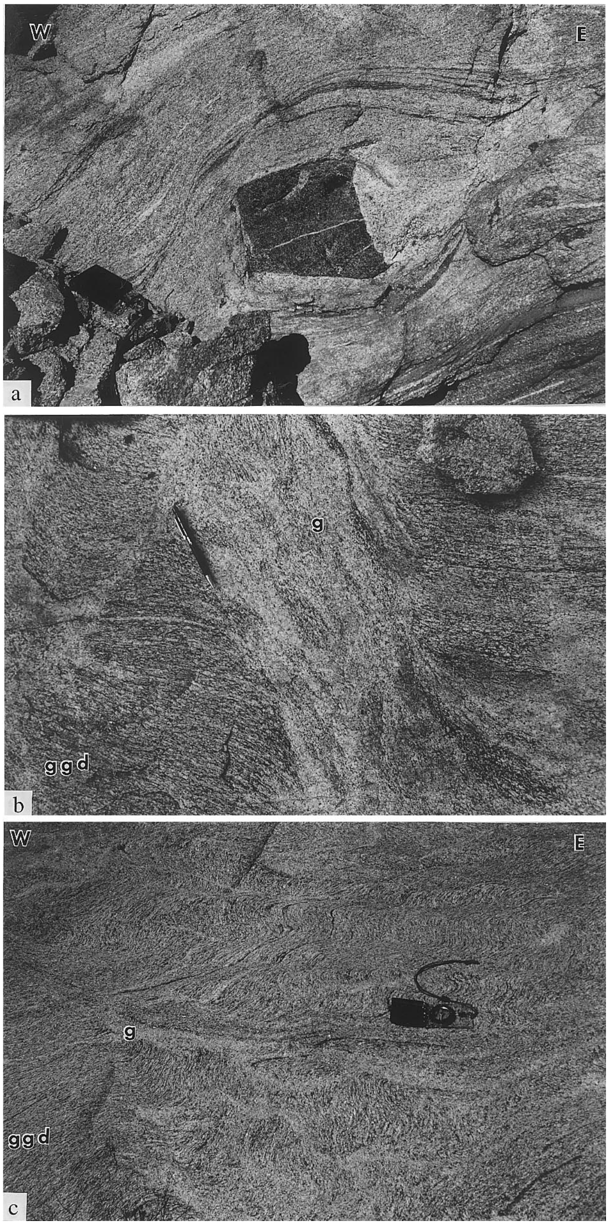

Fig. 4. (a) Example of banded granodiorite unit at the lower contact of the Sheep Camp Spring sheet, Brown's Wash. Banding is deflected around a mafic xenolith. (b) Example of a mesoscale shear zone in gneissose granodiorite [ggd] close to the contact between Sheep Camp Spring sheet and Dark Plateau block. Granitic material [g] is present in central part of the shear zone. (c) Folded gneissose granodiorite from the same locality as (b) with cross-cutting granitic veins.

pient shear bands or *S–C* fabrics (cf. Berthé et al., 1979). Continuous shear zones, folds and granitic veins are common in this zone. The central 5–20 cm portion of each shear zone contains a granite vein that is more felsic in composition and less foliated than the wall rocks (Fig. 4b). Other granitic veins cross-cut the foliation and 5 cm amplitude folds at high angles (Fig. 4c). These veins have wispy gradational boundaries and are generally less than 15 cm long and 5 cm wide. The relationship between granite veins, shear zones and folds suggests that deformation was taking place before full crystallisation of the pluton.

4.3. Main foliation within the pluton

The main foliation within the Old Woman pluton is characterised in hand specimens by a pervasive mineral alignment or shape preferred orientation (SPO) of biotite and/or hornblende accompanied by a less obvious SPO of plagioclase. There is little discernible quartz shape fabric. Fabric analysis was carried out on the grain shapes that were digitised from four thin sections of Old Woman pluton to compare fabric intensity in the strongly foliated contact rocks with that in the remainder of the pluton (Fig. 5). Samples MG914 and UMG1a, from the central part of the pluton, are weakly foliated (see Fig. 2 for locations). Sample DP1 was from the contact zone at the Dark Plateau (Fig. 2) and sample OWW1 was from the central area of the pluton between the Sheep Camp Spring sheet and the Meteor Gulch sheet; both are strongly foliated. The samples with stronger foliation have a noticeably finer grain size (0.75–1 mm) compared to the moderately foliated samples (1.5–2 mm) (Fig. 5). Results are presented for plagioclase, biotite and quartz as these were the only phases to have more than 100 grains per thin section and thus provide more significant data compared to minor phases such as K-feldspar and hornblende. Both strongly foliated samples (DP1 and OWW1) generally yielded higher vector mean lengths (>0.8). This is compared to the samples with moderate foliation which yield vector mean lengths (<0.8) confirming that the SPO data do reflect the degree of foliation development. A strong plagioclase SPO is present in all samples whereas quartz fabrics are only strong in samples DP1 and OWW1. Biotite data also indicate much stronger SPO in the more foliated rocks (Fig. 5).

Individual minerals also show textural differences between less and more deformed states (Fig. 5). Quartz in less foliated samples (MG914 and UMG1a) is present in large (1–2 mm) grains that are interstitial to a framework of plagioclase and mafic minerals (Fig. 5). Individual grains show undulatory extinction but otherwise little evidence that they have been subjected to deformation. Quartz in the contact sample (DP1) and the highly foliated OWW1 sample, in contrast, displays a weak ribbon texture (Fig. 5). Quartz *c*-axis distributions in the more foliated samples (OWW1 and DP1) are clustered in a single girdle at a high angle to the stretching lineation and foliation plane (Fig. 6). This type of pattern has been interpreted as indicating that basal $\langle a \rangle$ was the dominant slip system (Bouchez, 1977). The moderately foliated sample MG914 has *c*-axes concentrated in a partial girdle about the lineation direction and UMG1a has a partial girdle at a high angle to the foliation plane. The main difference, however, is the lack of a maximum parallel to the *y*-axis as in the highly foliated samples.

Plagioclase also exhibits textural differences depending on foliation intensity. In MG914 plagioclase is euhedral with well developed twinning and zoning structures preserved, typical of igneous textures. The twin boundaries are often aligned parallel to the foliation, suggesting a lattice preferred orientation of the plagioclase. In the more foliated samples, plagioclase grain size has a bimodal distribution (Fig. 5). Larger grains (up to 2 mm) tend to be isolated in the quartz and feldspar matrix and have twin boundaries parallel to the foliation. In contrast, finer grained (0.5–75 mm) plagioclase forms domains or aggregates of interlocking grains. These grains are generally unzoned and often untwinned. Grain boundaries are straight and intersect at 120° triple junctions, giving the appearance of an equilibrated texture. In the most highly foliated sample (DP1) from the contact zone, elongate plagioclase mosaics alternate with quartz ribbons.

Biotite in all samples shows no internal structures such as bent or kinked cleavage planes. In MG914 and UMG1a, 2 mm biotite 'plates' may be almost square in cross-section, whereas in OWW1 and DP1 they form irregular shaped aggregates aligned parallel to the foliation. Hornblende, where present, is more elongate in the strongly foliated samples and rarely preserves internal structures such as twinning. K-feldspar, mainly orthoclase, forms large grains with numerous inclusions at their edges, suggesting late growth in relation to other minerals.

4.4. Geometry of deformed schlieren and xenoliths

Numerous examples of deformed schlieren are preserved in the internal parts of the Old Woman pluton. Schlieren in the upper Meteor Gulch section (Fig. 2) are generally faint layers that are richer in hornblende and biotite than the host granodiorite (Fig. 7a). Akers and Miller (1991) suggested that the schlieren formed by extreme disaggregation of xenolithic material (Fig. 7a). Tight to isoclinal folds of wall-rock fabrics in the xenoliths and schlieren have axial planes that are parallel to the main magmatic foliation in

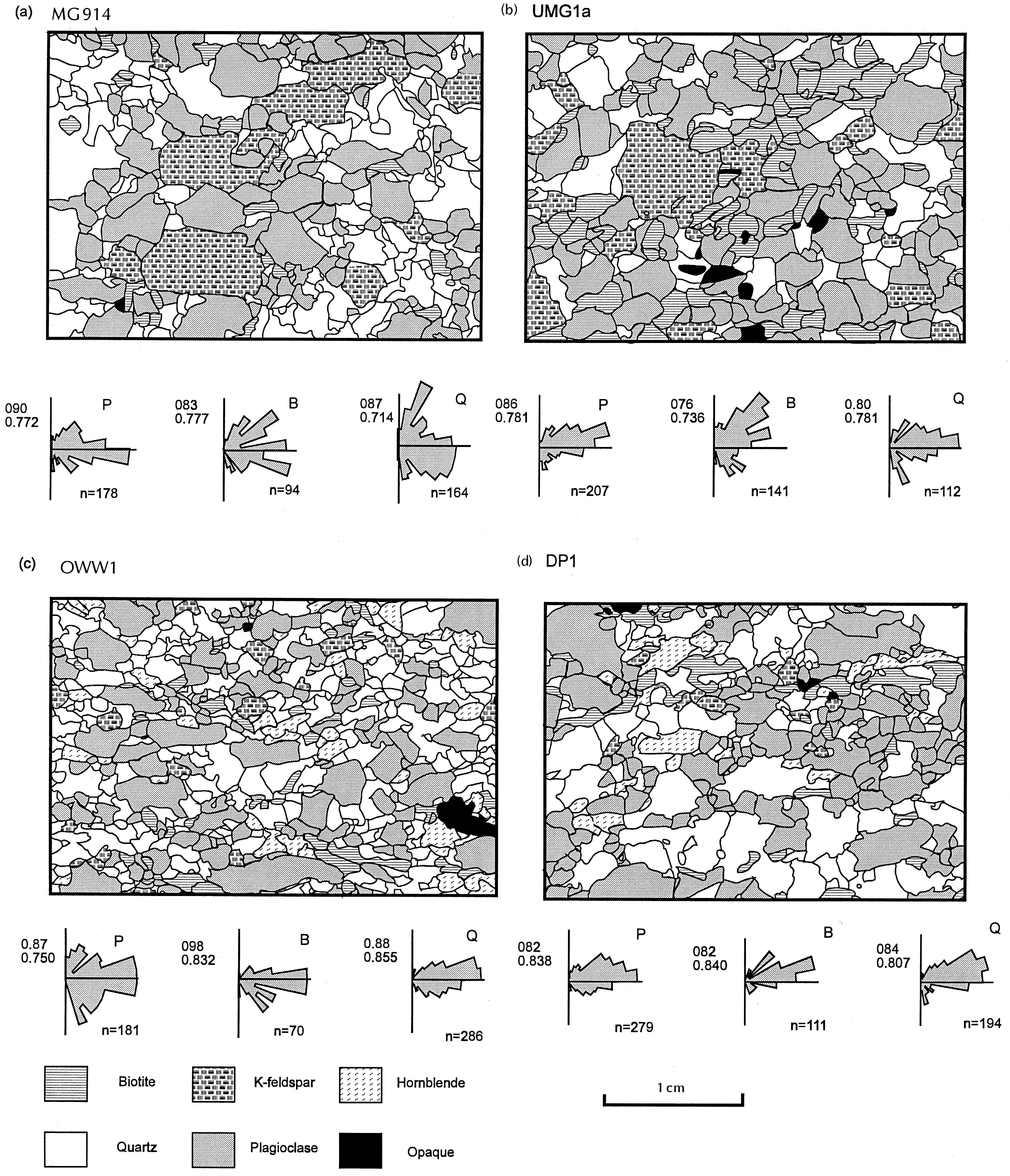

Fig. 5. Results of shape preferred orientation analysis on four samples of Old Woman pluton (localities on Fig. 2). Tracings of parts of each sample are shown. Long axes of plagioclase (P), biotite (B) and quartz (Q) are plotted as rose diagrams for each sample relative to the foliation (aligned east–west). Orientation and length of mean vector are given for each plot.

the granodiorite and fold axes that are generally sub-horizontal. Fold data are compiled in Fig. 8 and are consistent with NNW–SSE contraction.

Xenoliths of wall-rock material are widely preserved throughout the Old Woman pluton and particularly abundant close to the western contacts. Large map-scale gneiss bodies (e.g. Dark Plateau, Fig. 2) within the pluton may be xenolithic, but connection with the roof cannot be discounted and they may be large roof pendants. Outcrop-scale examples of xenoliths are

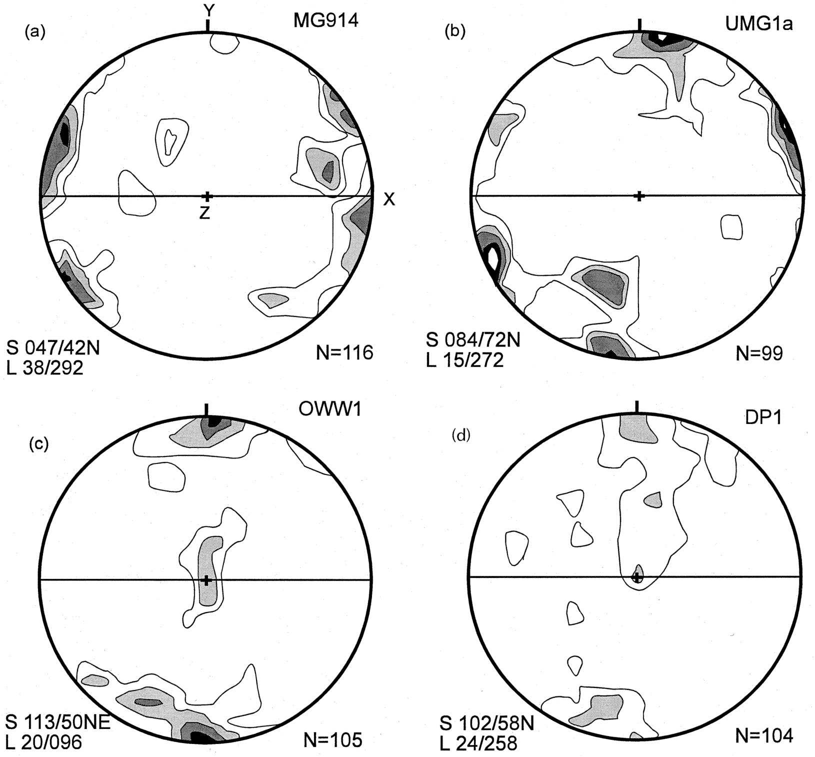

Fig. 6. Contoured equal-area plots of the orientation of quartz *c*-axes in each of four samples. (a) MG914, (b) UMG1a, (c) OWW1, (d) DP1. The foliation is aligned vertical, E–W and the lineation (X), horizontal E–W in each sample. Contours at 1, 3, 5, 7, 10%.

abundant in the upper Meteor Gulch section. These are mainly coarse- to medium-grained mafic gneiss or fine-grained granitic gneiss. In addition, Akers and Miller (1991) described xenolithic metasedimentary material and K-feldspar megacrystic metagranite enclaves from this area.

Folded granitic gneiss xenoliths are common in the upper Meteor Gulch section. Interlimb angles range from close to isoclinal with axial planes parallel to the main foliation in the host granodiorite. Fold axes have shallow ENE or W plunge. Some xenoliths contain folded granite veins that are clearly connected to the host granodiorite, indicating that folding is syn-magmatic (Fig. 7b). The more mafic gneiss xenoliths show evidence of competent behaviour; they have fractured and granitic veins were intruded along the fracture planes (Fig. 7c). These granitic veins are also gradational with the host granodiorite. Schlieren and the main foliation wrap around the rigid mafic blocks (Fig. 7d) whereas they pass through the granitic xenoliths without deflection. Mafic gneiss xenoliths are also asymmetrically boudinaged in the plane of the foliation.

4.5. Heterogeneous deformation

Internal parts of the Old Woman pluton preserve evidence of truncation and displacement of banding, schlieren and gneiss xenoliths along planar surfaces. In the upper Meteor Gulch section (Fig. 9a), schlieren and banding are folded and truncated, with the fold limbs displaced horizontally by up to 2 m. The sense and amount of apparent displacement is usually obvious from the offset of marker layers. These planar structures must have formed at high temperatures because they are overprinted by normal granitic textures; they may be early fractures or ‘hot shears’ that have subsequently healed. Many of these early fractures occur in the plane of the foliation and are extensional in nature (Fig. 9a); others cut across the foliation at high angles and facilitate net shortening perpendicular to the foliation (Fig. 9b). All observed apparent displacements in the upper Meteor Gulch area are consistent with the regional NNW-directed contraction indicated by the fold data.

5. Characteristics of synmagmatic deformation

Inward from the contact rocks, there is a noticeable decrease in foliation intensity and an increase in grain size. Estimates of the conditions under which the Old Woman pluton was deformed may be made from the microstructural characteristics of both quartz and feldspar. Quartz grain shapes change from ribbon-like at the contact to large and irregular in the centre. These

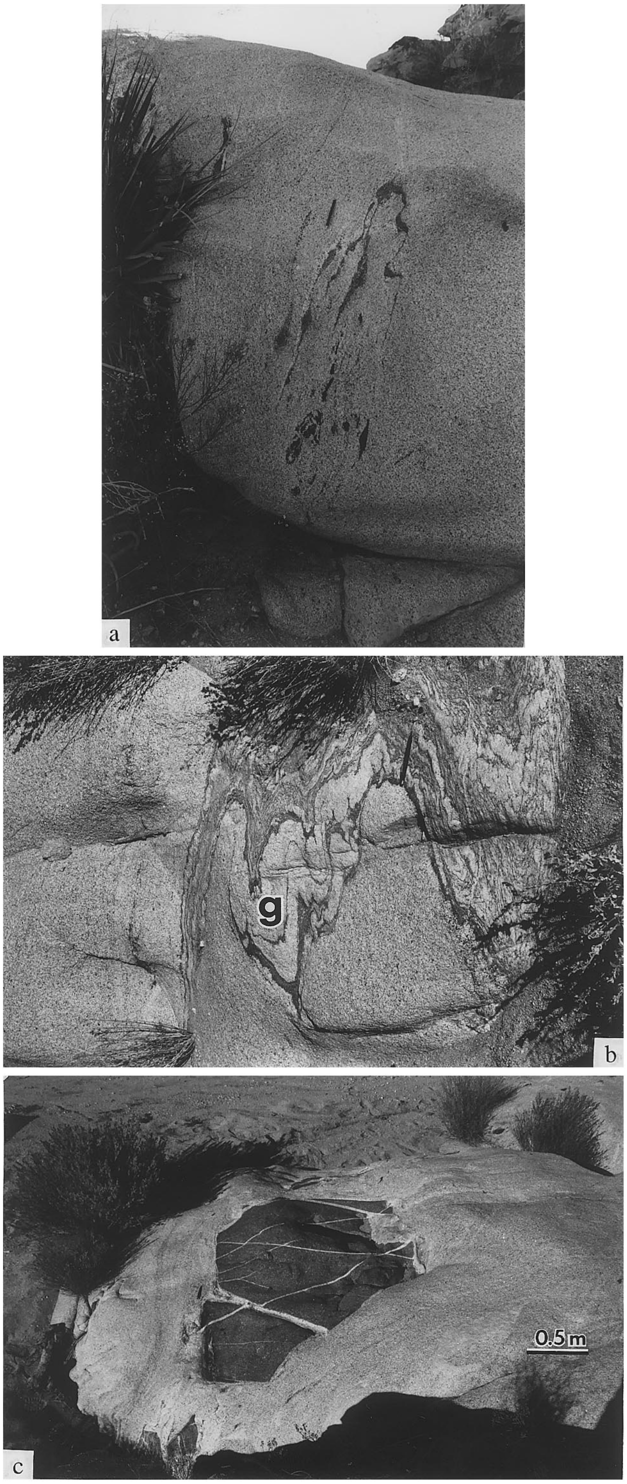

Fig. 7. (a) Folded biotite schlieren in granodiorite at upper Meteor Gulch. Main magmatic foliation within granodiorite is axial planar to the folds. (b) Folded gneiss xenolith at upper Meteor Gulch. Note: folded granite vein [g] continuous with host granodiorite. Main magmatic foliation in the granodiorite is axial planar. (c) Rigid mafic gneiss xenolith with granite veins that are continuous with the host granodiorite.

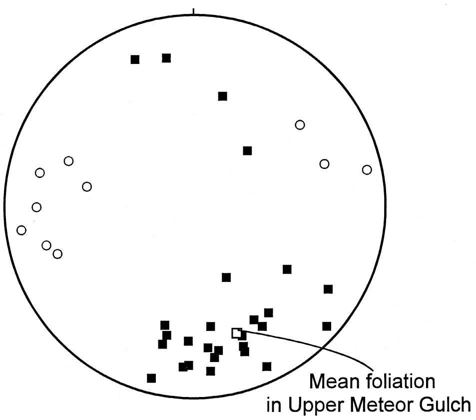

Fig. 8. Equal-area stereoplot of orientation of fold axes and axial planes in gneissic xenoliths in the upper Meteor Gulch area.

larger quartz grains have weak shape fabric and quartz *c*-axes distributions are clustered around the *x*-axis. Blumenfeld et al. (1986) and Mainprice et al. (1986) interpreted similar patterns to have been produced by prism ⟨*c*⟩ slip. They considered ⟨*c*⟩ slip to be limited to high temperature (650°C) in the presence of hydrous conditions; however, O'Hara and Gromet (1985) observed quartz *c*-axis distributions typical of ⟨*c*⟩ slip

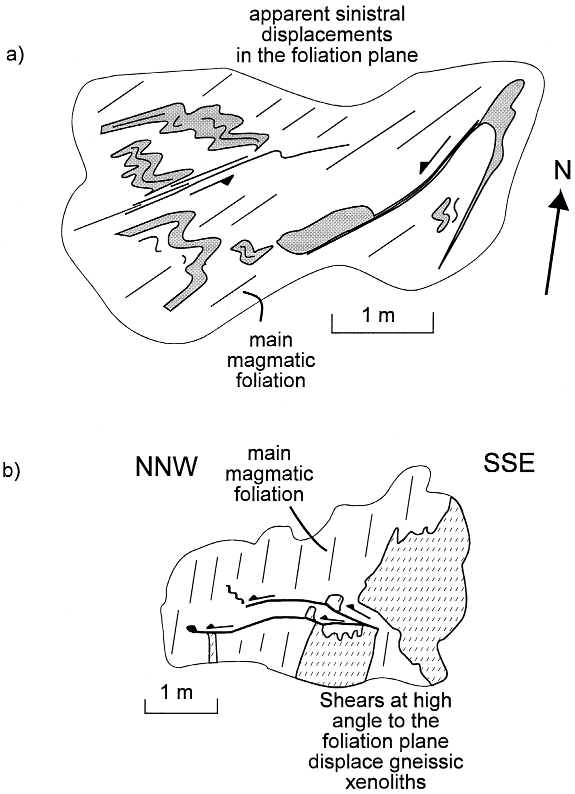

Fig. 9. Field sketches of gneissic xenoliths (shaded pattern) offset along early fractures in granodiorite at Upper Meteor Gulch. (a) A horizontal outcrop illustrates extensional deformation in the plane of the foliation. (b) Contractional deformation at a high angle to the foliation in a vertical section.

in amphibolite grade rocks in New England. These patterns might also be due to growth or crystallisation of quartz grains from the residual melt with their *c*-axes close to the extension direction (Gapais and Barbarin, 1979; Paterson et al., 1989). The more highly foliated samples yield *c*-axes distributions that are typical of slip on the basal ⟨*a*⟩ system; characteristic of lower temperatures (Mainprice et al., 1986; Blumenfeld et al., 1986).

Plagioclase grains, remote from the contacts, are euhedral and display evidence of sharp twinning aligned sub-parallel to the foliation and strong zoning features suggesting that they were original igneous phenocrysts. This alignment fabric may have formed because plagioclase passively rotated before the magma had fully crystallised or grew in the regional strain field. In the highly foliated contact rocks, relict phenocrysts and recrystallised plagioclase mosaics suggest that a solid state deformation was superimposed on the magmatic state fabric. Both fabrics are parallel to the mylonitic gneiss foliation in the wall-rocks. Recrystallisation processes in feldspar predominate over cataclastic processes above 450–500°C in naturally deformed rocks (Voll, 1976; Simpson, 1985), suggesting that the contact rocks were deformed above 450°C.

Basal ⟨*a*⟩ slip in quartz and recrystallised mosaics of plagioclase in the highly foliated rocks at the contacts provide evidence for crystal plastic deformation of both quartz and feldspar. This type of deformation has been termed 'high temperature solid-state deformation' by Paterson et al. (1989). The aligned phenocrysts surrounded by quartz with a weak shape fabric and evidence for prism ⟨*c*⟩ slip together with the deflection of the foliation around rigid xenoliths is good evidence for deformation in the magmatic state toward the centre of the pluton.

Heterogeneous deformation may indicate transitional conditions between magmatic state deformation and solid state granite deformation (Ingram and Hutton, 1994; McCaffrey, 1994). This style of deformation can be seen in the highly foliated granodiorites found inside the contact. Rapid viscosity changes in granitic rocks are predicted during crystallisation (Arzi, 1978; van der Molen and Paterson, 1979; Tribe and D'Lemos, 1996). During crystallisation, a framework will have formed with a trapped residual melt component in a similar manner to that described from experiments by Dell'Angelo and Tullis (1988). The changing viscosity of this framework, perhaps combined with the presence of more competent xenoliths acting as stress risers, may have led to a situation in which the framework fractured. Temperatures were still hot enough to have 'healed' the fracture. This mechanism could produce internal contacts that were offset and discontinuous shear zones that deformed banding and xenoliths such as those displayed in the Old Woman pluton. Some of the structures produced by the heterogeneous deformation contain weakly foliated granitic material that is more felsic than the main granodiorite. This granitic material probably represents a residual melt phase 'kneaded' from the granodiorite during the last stages of crystallisation when localised deformation is favoured.

In summary, several observations when taken together suggest that the Old Woman pluton was emplaced syntectonically with respect to Mesozoic deformation in its wall-rocks. The parallel orientation of the magmatic and solid state fabrics in the wall-rock mylonites, the banded granodiorites, and the strongly foliated granodiorites suggest that the local strain field remained constant throughout the late-crystallisation and early sub-solidus history. There is a decrease in fabric intensity moving inward from the contacts. The fabrics preserve microstructures typical of higher temperatures in central parts of the pluton implying that the pluton margins passed through the magmatic/solid state transition whilst the centre was still sufficiently molten to behave as magma. Structures typical of the magmatic/solid state transition are preserved, i.e. heterogeneous deformation containing evolved melt phases superimposed on the ductile high temperature fabrics.

6. Mesozoic tectonics in the Old Woman Mountains

The tectonic framework in the Old Woman Mountains prior to the intrusion of the Old Woman pluton was dominated by crustal thickening. The emplacement of the Scanlon thrust nappe caused burial to approximately 15 km. However, the original thrust geometry and transport direction has been obscured by Late Cretaceous deformation related to granite emplacement (Rothstein et al., 1994). Crustal thickening continued to at least 85 Ma in the nearby Piute Mountains (Karlstrom et al., 1993). Geometrical and kinematic information from synmagmatic structures within the Old Woman pluton observed during this study may be used to constrain the tectonic framework at 73 Ma. Synmagmatic fold axes and axial planes in the gneissic xenoliths and schlieren in the Upper Meteor Gulch section and the magmatic state foliation within the pluton indicate flattening on moderate to steep planes aligned ENE–WSW swinging to WNW–ESE in the eastern part of the pluton (Fig. 2).

In the nearby Piute Mountains (Fig. 1), Fletcher and Karlstrom (1990) recorded a late NE–SW-striking, steep crenulation cleavage that is synchronous with the emplacement of the Lazy Daisy pluton. This pluton is indistinguishable in radiometric age from the Old Woman pluton, but it is thought to be closely related in time to N-striking two-mica granite dykes that cut the Old Woman pluton after consolidation. These late dykes and cleavages formed during the open folding of the Scanlon shear zone and suggest regional NW–SE directed contraction and NE–SW extension at the end of the Late Cretaceous magmatic episode (Rothstein et al., 1994).

Foster et al. (1989a,b, 1991, 1992) used detailed thermochronology and thermobarometry to constrain the timing of Mesozoic metamorphic, plutonic and uplift events in the Old Woman Mountains. Crustal thickening associated with thrusting and greenschist facies metamorphism began in the Jurassic (170–150 Ma) although most of the ductile deformation in the region is Late Cretaceous in age. The granite emplacement event at 73 ± 1 Ma can be used as a time marker to constrain the evolution of the Old Woman Mountains area. The calculations of Rothstein and Hoisch (1994) have shown that the sheet-like Late Cretaceous felsic plutons provided sufficient heat for the observed amphibolite facies metamorphism in the area. Thermobarometry suggests that the emplacement event took place at 650°C in the southern Old Woman Mountains and at 3.5–5.3 kbar pressure. The kinematics and geometry of synmagmatic deformation show that the Old Woman pluton was emplaced whilst the crust was undergoing E–W-directed extension at 73 ± 1 Ma. This was closely followed by very rapid cooling to below 350°C in 1–2 Ma, primarily due to conduction, but also requiring unroofing at rates of 1–2 mm/y (Carl et al., 1991; Foster et al., 1992).

7. Granite emplacement during extensional collapse

Kinematic information from the wall-rock mylonitic gneiss and synmagmatic deformation in the banded and gneissose granodiorite within the pluton adjacent to the contacts indicate a component of non-coaxial deformation during pluton consolidation. Sinistral oblique, hanging wall to the west shear, predominates above the pluton in the Scanlon shear zone and in the region of Meteor Gulch and the Dark Plateau (Fig. 2). This is consistent with detailed structural observations within the Scanlon shear zone (Rothstein et al., 1994). In the footwall to the pluton, however, this study has shown that dextral, oblique top-to-the-east shear predominates. The presence of both senses of shear may indicate that the bulk geometry is that of general shear (Simpson and DePaor, 1993) and is partitioning into simple shear zones within a thrust-pile that separate zones of predominantly pure shear deformation.

Overall the kinematic evidence from the synmagmatic shear zones on the pluton contacts indicate an oblique sense of shear that may be a result of a vertical component of shortening and NW–SE contraction. Indeed, Owen and Karlstrom (1992) have suggested that the overall strain geometry during the Late Cretaceous was prolate with NE–SW extension. It can

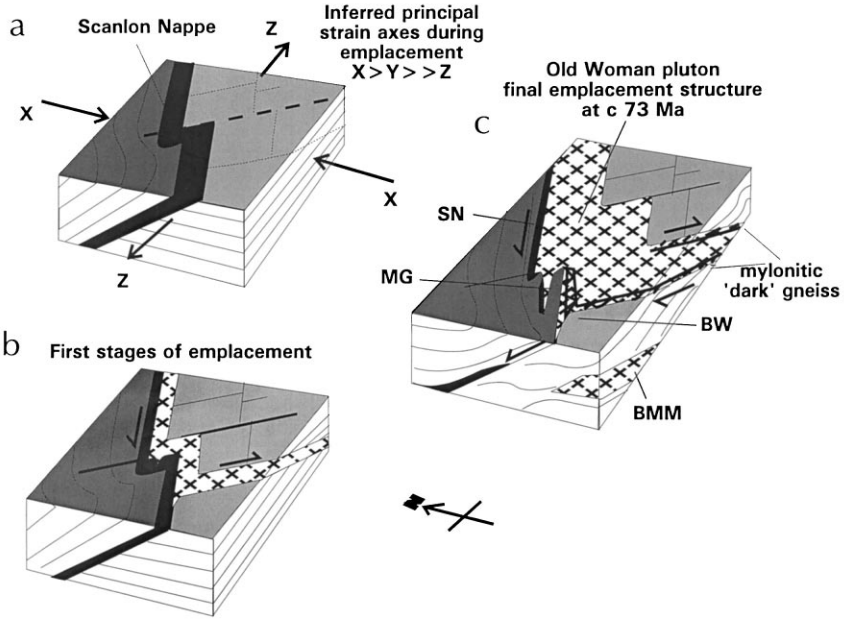

Fig. 10. The emplacement mechanism for the Old Woman pluton. (a) Pre-emplacement geometry. (b) Early emplacement with top-to-the-west shear in the north and top-to-the-east in the south resulting in overall NE–SW extension. (c) Final emplacement structure. The Scanlon nappe is folded about a NE–SW axis in bulk general shear partitioned into flattening within the plutons and its wall rocks and shear zones (mylonitc 'dark' gneiss) on the contacts where competency contrasts are greatest. Abbreviations: BMM—Black Metal Mine, BW—Brown's Wash, MG—Meteor Gulch, SN—Scanlon nappe.

be envisaged that Old Woman pluton was emplaced as a series of sheets that interfingered into its wall-rocks whilst they were undergoing approximately E–W-directed oblique extension (Fig. 10).

Previously, Howard et al. (1987) suggested that the pluton was emplaced in nappe-like lobes and the dark mylonitic gneiss, present on the contacts, had been dragged into place as a distended skin. This mechanism suggests forceful magma emplacement in a type of diapiric process with the accompanied transport of basement nappes on the sheets of granite magma. In this scenario, the kinematic information from the contact dark gneiss and deformed granite would record the flow of viscous magma past the wall-rocks. However, to be consistent with the kinematic evidence, magma would have to have been intruded from the west. This contradicts field evidence for the main plutonic sheets pinching-out to the west and the core of the pluton being exposed in the eastern part of the range, presumably closer to the magma source (Fig. 10). An extensional model satisfies the kinematic requirements and in this situation the dark gneiss shear zones are formed by the basement blocks sliding past each other in the early stages of pluton emplacement (Fig. 10). Then, when magma was intruded between the blocks it was also subjected to a shear deformation forming the banded and gneissose granodiorite and the transitional magmatic and solid state fabrics. Apparent problems with the emplacement of kilometric-scale sheet intrusions during average tectonic strain rates have been discussed by Paterson and Tobisch (1992). Karlstrom et al. (1993) proposed that strain rates were faster ($10^{-11}\,s^{-1}$) than average tectonic rates ($10^{-14}\,s^{-1}$) during emplacement of the East Piute pluton. Similar fast local strain rates and partitioning of deformation into the pluton, as modelled by Pavlis (1996), mean that problems of 'space creation' are minimal.

Rapid denudation may have been facilitated by thermal weakening of the crust due to the emplacement of magmas (Foster et al., 1992). Pavlis (1996) has shown how deformation may be localised in thin sheet-like plutons. Kinematic evidence from the synmagmatic shear zones on the pluton contacts support this hypothesis. Carl et al. (1991) described a low-angle extensional fault (Western Old Woman Mountains shear zone) with top to the west shear sense located along the western edge of the Old Woman Mountains (Fig. 1). This is the same shear sense as recorded by the synmagmatic deformation on the hanging wall pluton contacts in the Dark Plateau region (Fig. 10). Top-to-the-east shear observed below the main plutonic sheets in Brown's Wash (Fig. 10) is identical to a low-angle extensional shear zone to the north of Milligan (Fig. 1). We suggest that the localised zones of non-coaxial synmagmatic deformation formed at the hanging wall and footwall pluton contacts during pluton emplacement influenced the kinematics and geometry of the subsequent low-angle extensional faults that caused denudation. Thus the thermal effect of magma emplacement effectively partitioned deformation into shear zones and triggered the subsequent uplift and denudation of the orogen at the end of the Cretaceous in the eastern Mojave.

8. Conclusions

Synmagmatic deformation in syntectonic plutons may be used to provide information on the regional tectonic framework. Structures preserved within the Old Woman pluton provide an excellent example of a pluton deformed before it had fully crystallised. Magmatic state fabrics are continuous with high-temperature solid state fabrics near the pluton margins and also with mylonitic fabrics in the wall-rock gneiss. The geometry and kinematics of the synmagmatic deformation may be used to constrain the emplacement mechanism and the tectonic framework in the Old Woman Mountains at ca. 73 Ma. The pluton was emplaced during approximately E–W-directed extension which may have resulted from a combination of NW–SE-directed compression and vertical shortening due to collapse of the overthickened thrust pile.

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