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Mechanism of frictional fusion in fault zones

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Abstract— Spherulitic pseudotachylytes from the Arunta Block formed by frictional fusion of mylonitic parent rocks during high-level reactivation of a previously ductile fault zone. Fusion occurred preferentially in mica-rich domains due to release of water through disruption of the mica lattice by frictional sliding. This generated selective localised melting of mica during frictional heating, with the production of initial pseudotachylyte melts enriched in water and ferromagnesian components. Subsequent fusion of adjacent salic phases, promoted by the high water content of the existing melt, would tend to shift the trend of later melts towards a total melt composition. Therefore, under conditions of frictional sliding, fusion appears to be favoured in crystalline quartzo-feldspathic rocks possessing both a high shear strength, and a significant water content locked up in the lattices of hydrous minerals, principally biotite.

The presence or pre-existence of glass in many pseudotachylytes demands that they cooled in a near-surface environment, i.e. at depths of less than about 5 km. Thus glassy pseudotachylytes must postdate associated mylonite series rocks, generally forming subsequent to exhumation of the mylonites to a higher level in the crust. Some non-glassy pseudotachylytes, however, may possibly form towards the end of movements in a ductile regime, as strain hardening sets in.

INTRODUCTION

PSEUDOTACHYLYTES are the ultimate product of shearing in fault zones. Their origin, disputed for almost a century still remains somewhat enigmatic, although a better understanding of their genesis and their relationship to the other products of shear displacement has emerged from the recent work of Francis (1972) and Sibson (1975, 1977). Nevertheless, uncertainties still remain over many aspects of their genesis.

In this paper, unusual pseudotachylytes from the Arunta Block, central Australia are described. These rocks are of particular interest since fusion has taken place only on a very limited scale and much of the fabric of the parent rock has survived relatively unmodified. This has enabled recognition of the factors which have controlled fusion, and the mechanisms by which fusion has taken place. It has also been possible to identify the parent rock type and so determine its structural history prior to generation of the pseudotachylyte. In the light of the evidence derived from these rocks, comments on several unresolved aspects of pseudotachylyte genesis can be made.

GEOLOGICAL SETTING

The Arunta Block, a 150 000 km ^{2} gneiss terrain of mid-Proterozoic age in central Australia (Fig. 1), is composed of a number of tectonic units of different metamorphic grade and compositional character separated by E–W shear zones and NW–SE faults. The metamorphic evolution of the Arunta Block has in the past been interpreted in terms of two main events, a mid-Proterozoic orogenic episode which established the regional character of the terrain, and a mid-Palaeozoic retrogressive event 'the Alice Springs Orogeny' which resulted in bulk deformation in the overlying Amadeus Basin sediments, but only localized retrogressive effects in the Arunta basement (Shaw & Stewart 1975). Age limits of 1860–1600 and 500–320 Ma are placed on these events on the basis of a number of K/Ar, ^{40}Ar/^{39}Ar and Rb/Sr dating studies (e.g. Stewart 1971, Marjoribanks & Black 1974, Armstrong & Stewart 1975, Woodford *et al.* 1976, Iyer *et al.* 1976, Allen & Stubbs in press). Other more localised anorogenic events intermediate in age to the above two orogenic events are now also being established (e.g. Allen & Black 1979, Allen 1979).

The Harry Creek area, 55 km north-northeast of Alice Springs, lies in an E–W belt of high grade character occupying the southern part of the block between the intracratonic Ngalia Basin and the penecontemporaneous late Proterozoic-Palaeozoic Amadeus Basin (Fig. 1). In this region, a granulite facies tectonic unit, the Utralanama Block, and an amphibolite facies unit, the Ankala Block, are separated by an E–W trending shear zone of epidote amphibolite grade—the Harry Creek Deformed Zone. Emplaced within the shear zone and intruding both the Utralanama and Ankala Blocks is a small deformed porphyritic biotite granite pluton, the Gumtree Granite. The Harry Creek Deformed Zone is a 1 km wide zone of transposition composed of schists, mylonites and blastomylonites derived from the gneissic and granofelsic rocks of the Utralanama and Ankala Blocks. Detailed investigation of the zone indicates that it has undergone a polyphase deformational history (Allen & Black 1979). The shear zone originated as a deep-seated transcurrent fault bringing the Utralanama and Ankala Blocks into their

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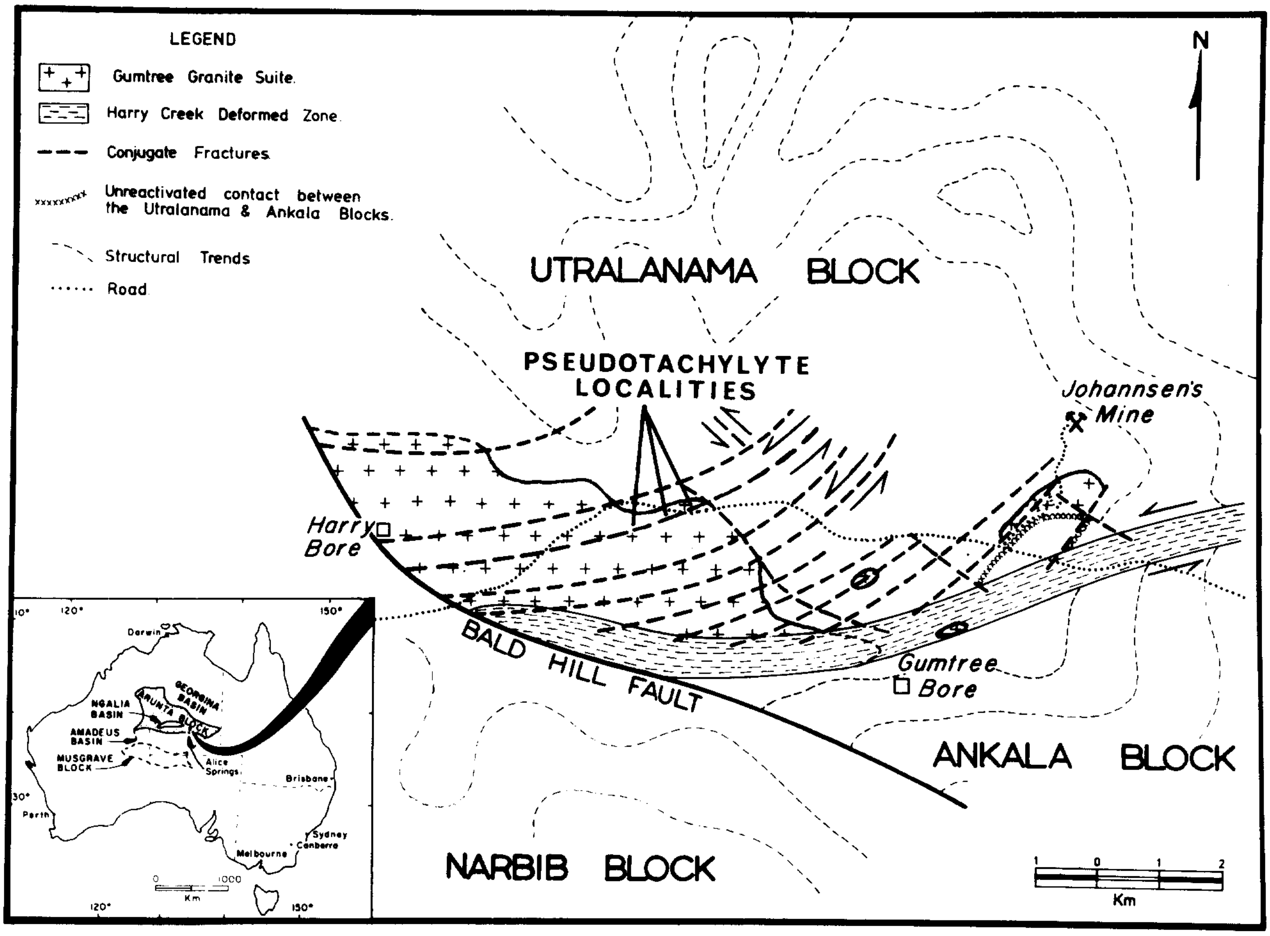

Fig. 1. Simplified geological relations in the Harry Creek area showing location of the Harry Creek Pseudotachylytes.

present juxtaposition, with intrusion of the Gumtree Granite into the fault zone following almost immediately. Emplacement of the Gumtree Granite and its off-shoots, mainly to the north of the zone in the granulite facies block, was controlled by a system of pinnate fractures genetically related to the deformed zone. Later reactivation of the Harry Creek Deformed Zone and the related pinnate structures during the Alice Springs Orogeny brought about the development of the schistose character of the zone, and intense deformation of the granite, particularly at its southern margin.

FIELD RELATIONS

The Harry Creek Pseudotachylytes are not recognizable as pseudotachylytes in the field, nor are they obviously associated with brittle faulting. The black glassy veins and stringers characteristic of classic pseudotachylyte localities are absent, and the pseudotachylyte melt occurs as a dispersed greenish phase, resembling chlorite, in coarse-grained quartzofeldspathic rocks. Only when thin-sectioned was the fused nature of this material recognized.

The Harry Creek Pseudotachylytes occur in a narrow zone, 2 km long and 100 m wide, 2 km to the north of the Harry Creek Deformed Zone. The zone is close to the northern contact of Gumtree Granite with its granulite facies country rocks of the Utralanama Block (Fig. 1). Exposure in the immediate area is poor, so local field relations are not well defined. Although highly deformed and mylonitised granitic rocks are typical of this area, no brecciated or cataclastic rocks, indicative of brittle faulting were observed. However the zone containing the Harry Creek Pseudotachylytes is continuous with a narrow Alice Springs Orogeny mylonite zone cutting granulite facies country rocks outside the Gumtree Granite. This is one of a number of such zones (Fig. 1) which have been interpreted as overprinting a system of Riedel and *P* shears related to the Harry Creek Deformation Zone, and formed at the time of its initiation as a transcurrent fault (Allen & Black 1979). The Harry Creek Pseudotachylytes are thus interpreted as having developed during reactivation of this particular mylonite zone.

PETROGRAPHY

In thin-section, the Harry Creek Pseudotachylytes are seen to be characterized by a distinct layering and intense fracturing; bands of highly fractured quartz and feldspar grains alternate with domains composed of a brown, partially-crystalline material, which is also injected into microfractures transecting the dismembered quartzofeldspathic layers (Fig. 2). The fused domains consist of a chaotic mixture of partially-fused crystals, coarse spherulitic devitrification microstructures, and cryptocrystalline material (Fig. 3a). The devitrification microstructures give clear evidence for the pre-existence of a glass. In addition, transmission electron microscopy (T.E.M.) has revealed small amounts of glass preserved within the lattices of quartz and feldspar (J. K. Funk personal communication 1979).

The layering of fused and porphyroclast domains suggests that slip has taken place parallel to the pre-existing foliation and layering of the parent rocks. No offsets are observed across the microfractures cutting quartzofeldspathic domains, the only other possible slip surfaces. Microstructures indicative of flow, observed in many glassy pseudotachylytes (e.g. Scott & Drever 1953, Park 1961, Phillpotts 1964, Sibson 1975, Wallace 1976, Wenk 1978), are absent from the Harry Creek Pseudotachylytes. The fused domains would appear, therefore, to have formed *in situ*, with little or no migration of the melt apart from minor injection into the microfractures cutting the quartzofeldspathic domains.

Despite the intense fracturing and the development of a melt phase, much of the fabric and mineralogy of the parent rocks of the Harry Creek Pseudotachylytes survives. The disaggregated silicic layers of the rocks are composed of dismembered porphyroclasts of quartz, alkali feldspar and minor plagioclase; matching fragments of which indicate that little modification of grain shapes accompanied cataclasis. Rare, small, granular zircons, highly fractured magnetites and partially-fused plates of biotite and white mica also survive within the melt domains of the pseudotachylytes. Fusion has taken place mainly in apparently finer-grained ferromagnesian-bearing bands alternating with the quartzofeldspathic layers. All mineral phases have undergone some degree of fusion, apart possibly from zircon, a mineral noted for its refractory behaviour (Karakeda 1961, Schidlowski 1963).

Porphyroclast relics

Relict quartz occurs as coarse, highly elongate ribbons, now fractured and dismembered, which are composed of mosaics of polygonal grains with smooth, straight boundaries. The individual polygonal grains are optically strain-free, and T.E.M. studies reveal low dislocation densities within the grains, a lack of high dislocation density at or near grain boundaries, and the absence of the high pressure polymorph coesite (J. L. Funk personal communication 1979), thus discounting an impact origin for the melt phase (cf. Carter 1965). Quartz ribbon fabrics, some with length to width ratios exceeding 20, identical to those in the Harry Creek Pseudotachylytes are common in Alice Springs Orogeny mylonites and blastomylonites derived from the aplite and porphyry dykes of the Gumtree Granite. Such fabrics were not developed in the country rocks of the Harry Creek area which were recrystallised at that time. Thus the parent rocks of the Harry Creek Pseudotachylytes appear to be mylonitic rocks formed during the Alice Springs Orogeny. Similar quartz ribbon fabrics have also been described from mylonites of the Woodroffe Thrust, central Australia (Bell & Etheridge 1976, fig. 9).

The alkali feldspar relics in the Harry Creek Pseudotachylytes are highly deformed microcline microperthites displaying wedge twins and intense undulatory extinction. Plagioclase is much rarer, untwinned and less porphyroclastic, but it is also highly deformed. Microstructurally, both feldspars resemble relict primary feldspar porphyroclasts in deformed and recrystallised Gumtree Granite (see Allen & Black 1979).

Relics of biotite are far less common than those of white mica in the Harry Creek Pseudotachylytes, although in other rocks of the Harry Creek area where both phases coexist white mica is always much less abundant. All white mica in the Harry Creek area is of Alice Springs Orogeny age, but it is rare, and is mainly developed as a secondary phase in the Gumtree Granite. Biotite although a primary phase of the Gumtree Granite was almost invariably recystallized during the Alice Springs Orogeny.

Fusion microstructures

Despite the general resistance of the quartz-rich domains to fusion, quartz shows considerable local evidence of fusion (Figs. 3a & b). Quartz is commonly found mantled with bubble-rich glass, and displays fusion characteristics similar to the quartz in glass-rich pseudotachylyte from the Himalayas (Scott & Drever 1953, plate 5, fig. 2). The process has apparently been promoted by injection of melt material into fractures in the quartz (e.g. Fig. 3b).

The feldspars also display fusion characteristics similar to those described by Scott & Drever (1953). Fusion is normally observed as corrosion to the margins of the grains, but in some grains an advanced stage of fusion has resulted in degeneration of the feldspar into vermicular interfingerings of melted material and unfused relics (Fig. 3c). In such grains all twinning has been obliterated, and the interfaces between the crystalline and fused materials have become diffuse. Crystallographic control of melting of feldspar, as observed by Busch *et al.* (1974) in experimental studies of melting, is minimal, and apart from one case where a string of bubbles line an (00*1*) cleavage, has not been observed. However, the experiments of Busch *et al.* (1974) were carried out under stress-free conditions, whereas fusion in the Harry Creek Pseudotachylytes developed under conditions of intense stress which would minimize crystallographic control on melting.

The micas, particularly biotite, appear to have been more extensively fused than the salic phases. Both micas are found mainly as isolated grains within the fused domains, and are typically strongly embayed and partially dismembered along the (00*1*) cleavage which is commonly curved or sinuous (Fig. 3d). Cross-fracturing and intrusion of the melt phase into fractures and cleavage planes is characteristic of the fusion process in the micas, which unlike that in the feldspars and quartz appears to have been crystallographically controlled. This may be due to the strong orientation of these phases parallel to the tectonic layering in the parent rocks formed during the Alice Springs Orogeny, which provided the surfaces on which slip apparently took place during pseudotachylyte formation.

Chemistry of the micas

Electron microprobe analyses of partially-fused relict micas from the Harry Creek Pseudotachylytes and of Alice Springs Orogeny biotite and white mica from the Gumtree Granite (Table 1) reveal a close compositional correspondence between the two sets of micas, particularly the white micas. Both white micas are phengitic with a similar substitution of the celadonite molecule (see Velde 1965). However, the partially-fused white micas of the pseudotachylytes (columns 2 & 3), have lower Ti and total Fe, and higher Mg/Mg + Fe ratios, than those of the Gumtree Granite (column 1). These trends appear to become intensified with increasing fusion. Partially-fused biotites from the pseudotachylytes (columns 5 & 6) correspond less closely to Alice Springs Orogeny biotite (column 4). Although the two analyses of the partially-fused biotites differ considerably, both are characterized by depletion of K, and total Fe. These deficiencies appear to be partially offset by increases in either Si or Al. As with the white mica, an increase in the Mg/Mg + Fe ratio is concomitant with the decrease in total Fe.

Table 1. Probe analyses of partially-fused micas from the Harry Creek Pseudotachylytes and Alice Springs Orogeny micas from the Gumtree Granite

	1	2	3	4	5	6
		WHITE MICA			BIOTITE	
	Gumtree Granite	Partially-fused relics in the pseudotachylytes		Gumtree Granite	Partially-fused relics in the pseudotachylytes	
SiO_2	46.32	46.11	45.44	35.50	35.51	42.45
TiO_2	0.70	0.22	0.27	2.15	1.03	0.73
Al_2O_3	28.32	29.01	28.46	14.48	19.29	13.25
FeO	5.57	4.89	3.97	22.54	19.46	18.20
MnO	—	—	—	0.26	—	—
MgO	1.75	1.77	2.10	8.86	7.87	8.90
Na_2O	0.22	0.26	0.28	—	0.41	—
CaO	—	—	—	0.10	0.20	0.15
K_2O	10.14	10.56	9.79	8.89	6.19	6.80
Total	93.03	92.81	90.31	92.77	89.96	90.59
Si	6.462	6.439	6.468	5.665	5.611	6.549
Al^{IV}	1.538	1.561	1.532	2.335	2.389	1.451
Al^{VI}	3.117	3.214	3.242	0.387	1.203	0.977
Ti	0.074	0.023	0.028	0.257	0.122	0.085
Fe	0.650	0.571	0.473	3.007	2.572	2.349
Mn	—	—	—	0.035	—	—
Mg	0.364	0.368	0.446	2.108	1.853	2.047
Ca	—	—	—	0.012	0.034	0.024
Na	0.061	0.069	0.079	—	0.126	—
K	1.804	1.881	1.778	1.809	1.249	1.338
Total	14.070	14.126	14.043	15.615	15.159	14.820
$\frac{Mg}{Mg + Fe}$	35.9	39.2	48.6	41.2	41.9	46.6
%Celadonite Molecule	25.6	26.4	25.5	—	—	—

The above field, microstructural and chemical evidence thus suggests that the Harry Creek Pseudotachylytes are the products of frictional fusion on a microscopic scale and were formed as a result of the reactivation of pinnate fractures related to the adjacent Harry Creek Deformed Zone. The immediate parents of the Harry Creek Pseudotachylytes were mylonitic or blastomylonitic rocks of Alice Springs Orogeny age developed in the Gumtree Granite or its dyke rocks. The deformed alkali feldspar and plagioclase porphyroclasts resemble primary igneous relics of the Gumtree Granite, whilst the micas and the ribbon aggregate of quartz appear to have formed during the Alice Springs Orogeny. The absence of optical strain features or high dislocation densities in the quartz suggest that fracturing of the quartz and feldspar during the pseudotachylyte-forming event took place under low temperature, low pressure conditions and did not involve plastic deformation (cf. Tullis & Yund 1977).

Furthermore, biotite, much the most abundant hydrous phase in rocks of the Gumtree Granite, which recrystallized during the Alice Springs Orogeny, was the most susceptible phase to fusion during the subsequent formation of the Harry Creek Pseudotachylytes, selectively releasing total Fe, K and Ti, and probably water. Scott & Drever (1953) also recognised selective melting of biotite during the formation of their Himalayan pseudotachylytes, with consequent concentration of Fe and K in the melt phase. They regarded the role of biotite as critical in the frictional fusion of these rocks.

DISCUSSION

In the light of the field and microstructural features of the Harry Creek Pseudotachylytes, comments can be made about four general areas of disagreement amongst pseudotachylyte workers: (a) the role of water in the production of pseudotachylytes; (b) the mechanism for generation of melts by frictional sliding; (c) the depth of formation of pseudotachylytes; and (d) the relationship of pseudotachylytes to mylonites.

The recent T.E.M. study of Wenk (1978) suggests that many if not most pseudotachylytes are products of extreme cataclasis rather than frictional fusion. However, several documented examples of glass or its pre-existence in pseudotachylytes (e.g. Scott & Drever 1953, Park 1961, Phillpotts 1964, Sibson 1975, Wallace 1976) indicate that in at least some instances frictional fusion has occurred. Although Scott & Drever's (1953) classic glassy pseudotachylytes from the Himalayas have recently been shown to have had a landslide origin (Masch 1979), they still represent an important example of frictional fusion and are included in the following discussion.

Phillpotts (1964) proposed a genetic subdivision of pseudotachylytes into those formed by frictional fusion (pseudotachylytes *sensu stricto*) and those of cataclastic origin (more properly termed ultracataclasites). However, such a distinction is impossible to make either in the field or by petrographic means. A potentially more useful subdivision of pseudotachylytes is into those for which a frictional fusion origin can be demonstrated through the presence or pre-existence of a glass, and those which lack evidence of a glassy stage, and thus may be of cataclastic origin. However, the absence of a glass does not preclude the pre-existence of a melt phase,

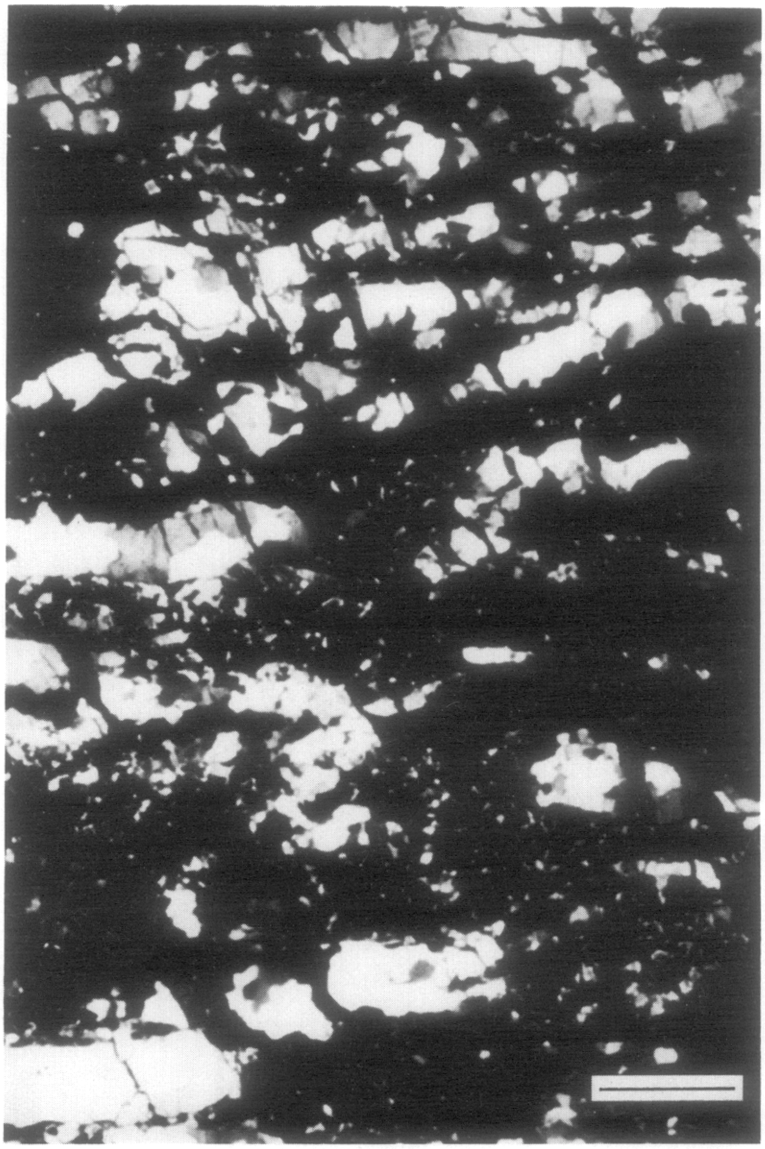

Fig. 2. Fabric of the Harry Creek Pseudotachylytes illustrating the relict ribbon-quartz aggregates of the parent blastomylonitic fabric. Dark regions are melt domains. Crossed nicols. Scale bar is 1mm.

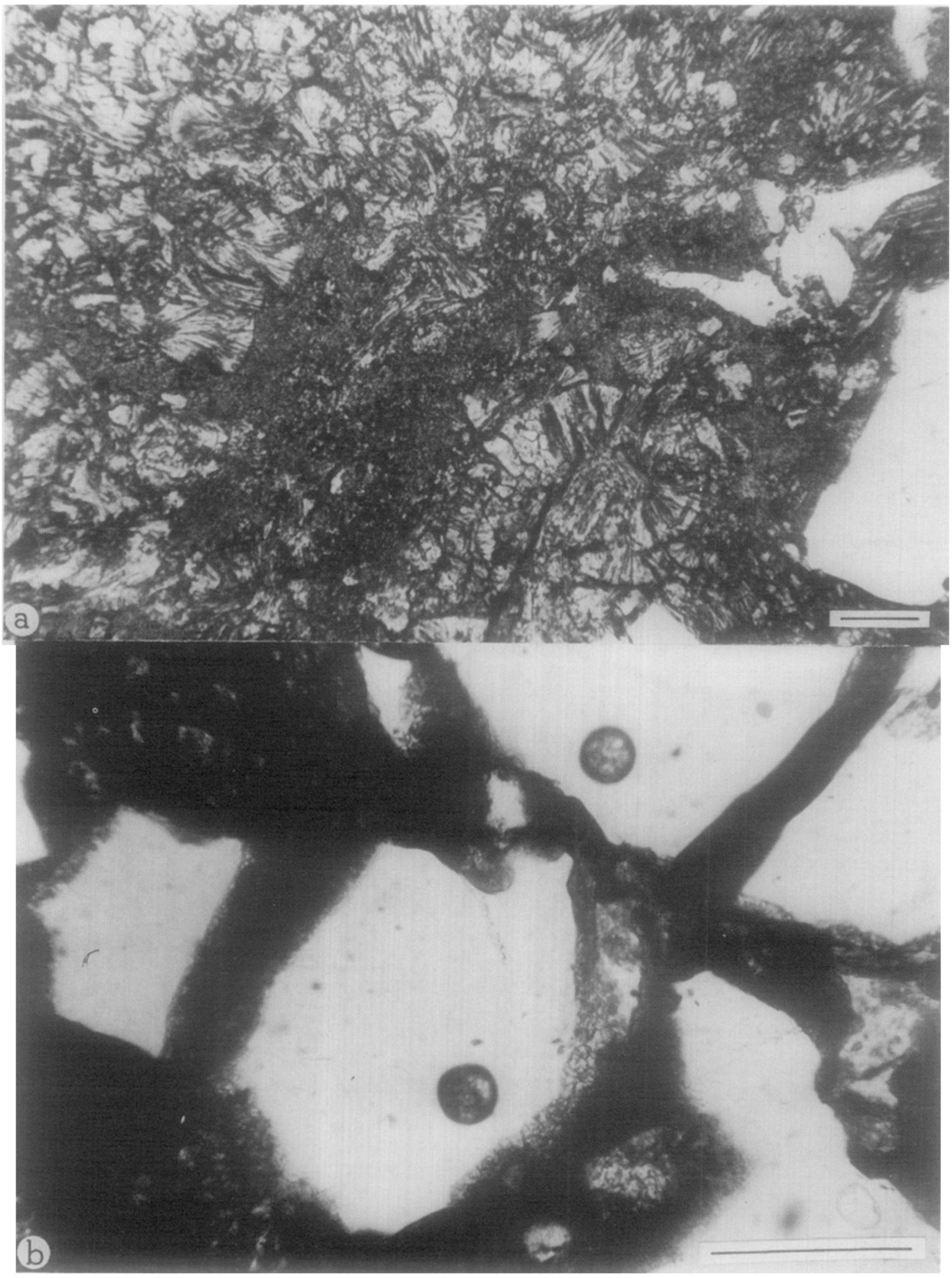

Fig. 3. Microstructural features of the Harry Creek Pseudotachylytes. (a) Melt domain composed of partially-fused quartz grains, spherulitic intergrowths and finely devitrified glass. Plane polarized light. (b) Partially fused quartz grains mantled by bubble-rich glass. Prominent spherical structures at top centre and middle are bubbles in the mounting medium. Plane polarized light.

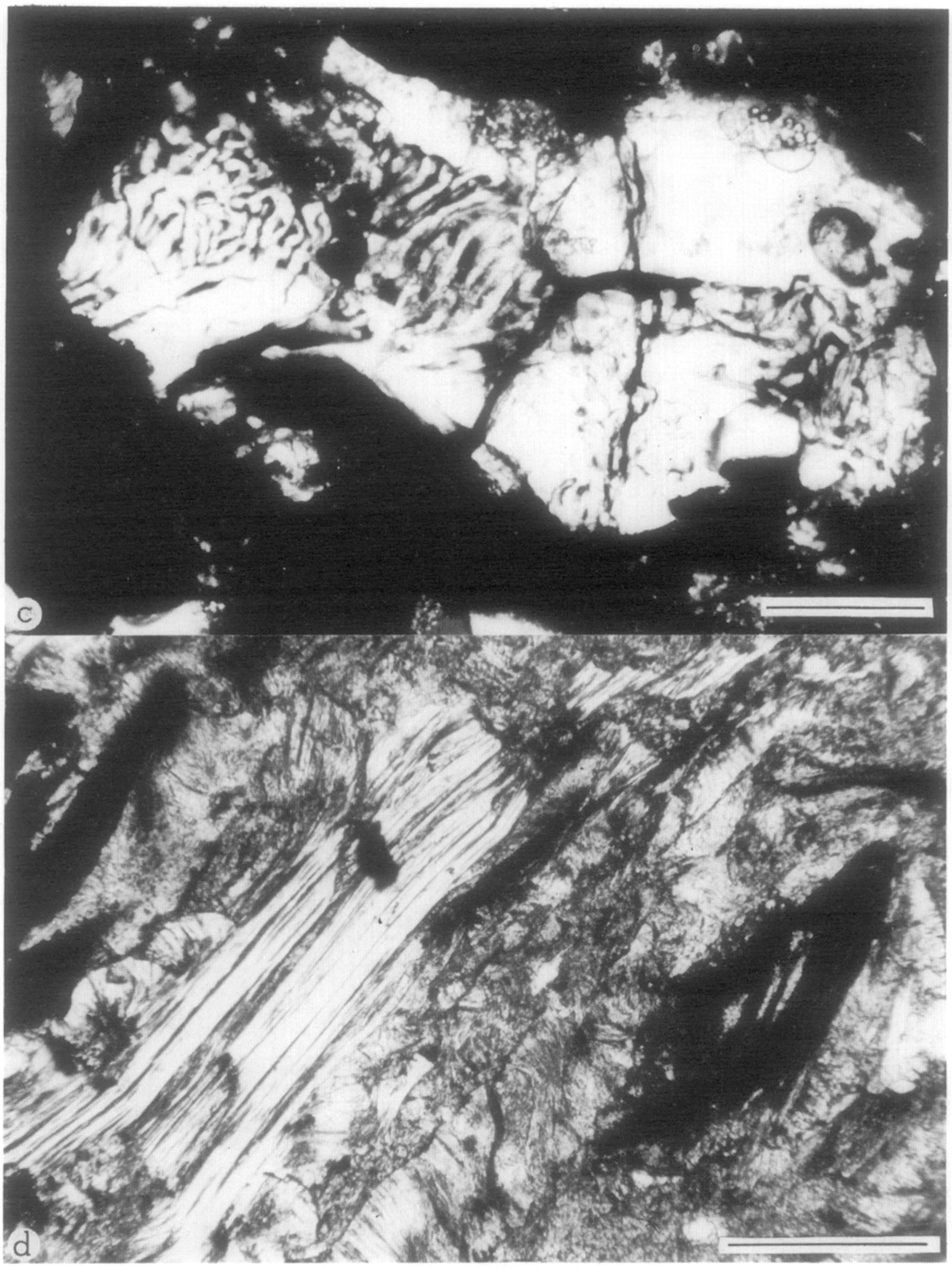

Fig. 3. (c) Advanced stage of fusion of feldspar which now consists of vermicular interfingerings of fused and relict material. Crossed nicols. (d) Relict white mica grain, buckled and wedged apart along the (00*l*) cleavage, surrounded by spherulitic growths formed by devitrification of the glass. Plane polarized light. Scale bars are 100 μm.

since many pseudotachylyte melts may not have cooled rapidly enough for glass to form. As yet no criteria for the recognition of a crystallized pseudotachylyte melt have been described. In the following discussion, whilst emphasis is placed on the fractional fusion mechanism for pseudotachylyte formation, it is acknowledged that a complete gradation between pseudotachylytes of mainly frictional fusion origin and those of mainly cataclastic origin probably exists.

Role of water in the production of pseudotachylytes

The role of water in the genesis of pseudotachylytes is still unresolved (see Francis 1972, Ermanovics *et al.* 1972, Sibson 1973, 1975, Wallace 1976). Melts formed by frictional fusion have a very transient existence, with cooling half-lives for injection veins of 1 cm in width, of the order of 40s (Sibson 1975). Under such conditions water will be critical to melting, not only because it reduces the temperature of fusion and lowers the viscosity of the resultant melt, but primarily because it acts as a catalyst during fusion. However, Francis (1972) and Sibson (1973) have argued that low intergranular pore fluid pressures are essential for pseudotachylyte genesis, because the presence of the fluid phase decreases shear resistance by reducing the effective normal stress on a sliding surface. Thus, the water must be contained either in crystal lattices or in fluid inclusions (Sibson 1975), which suggests that frictional fusion will be confined mainly to crystalline rocks. The absence of pseudotachylytes in the granulite facies country rocks adjacent to the Harry Creek Pseudotachylyte locality in the Gumtree Granite implies that pseudotachylyte generation has been favoured in rocks with higher water contents. Thus a significant water content locked up chiefly in the lattices of hydrous minerals, principally biotite, may significantly promote melting, whilst the absence of sufficient water may inhibit the production of a melt regardless of the strain rates involved. This is borne out by the T.E.M. study of Wenk (1978) who found that by the T.E.M. study of Wenk (1978) who found that pseudotachylyte veins within granulite facies host rocks showed little evidence for large-scale fusion, and concluded that the rocks were the products of cataclasis rather than melting. Nevertheless that fusion can occur even in relatively anhydrous rocks provided the strain rates are high enough is confirmed by the sliding friction experiments of Friedman *et al.* (1974) on Tennessee Sandstone.

Water will also control the generation of melts by frictional sliding in a more fundamental way through its influence on brittle–ductile behaviour in crystalline rocks. It is now well known that minute quantities of water are soluble in most rock-forming silicates, most significantly quartz, and that this may affect their yield strength. In quartz, water is particularly important because of its control on the plasticity of this mineral (Sibson 1977), reducing yield and promoting plastic flow through hydrolitic weakening (Griggs 1967). As little as a few hundred ppm of water are necessary to promote plastic flow in quartz so the factors controlling the solubility and bonding of water in quartz are critical. The relative controls of temperature and pressure on these parameters are as yet uncertain, but preliminary experiments indicate some degree of temperature dependence (M.S. Paterson personal communication 1978). This suggests that for quartzofeldspathic rocks, the shear strength of the rock will decrease with increasing temperatures. Thus low temperatures and presumably low pressures are essential pre-requisites for frictional sliding.

Mechanism for the generation of the melts by frictional sliding

Chemical investigations of pseudotachylyte melts suggest that frictional fusion involves total rather than partial melting (e.g. Scott & Drever 1953, Ermanovics *et al.* 1972, Masch 1973, Sibson 1975). However, the precise mechanism for this is uncertain. Some workers (e.g. Scott & Drever 1953, Sibson 1975) have concluded that the temperature of fusion and composition of the melt is controlled by the individual melting points of the constituent minerals of the parent rock, whilst Phillpotts (1964) has suggested that the initially formed melt is not a minimum melting fraction, but that continuous melting modifies it towards a minimum melt. Sibson (1975) estimated basaltic andesite compositions for the Outer Hebrides Pseudotachylytes and postulated temperatures of fusion of approximately 1100°C, whereas Wallace (1976) estimated temperatures of only 750°C for formation of pseudotachylytes from the Alpine Fault, New Zealand. Furthermore McKenzie & Brune (1972) showed that a temperature rise of 1000°C could be obtained by frictional heating along a fault.

It is argued that estimates of the temperatures of formation of pseudotachylyte melts utilizing experimental data determined under stress-free melting (e.g. Sibson 1975, Wallace 1976) are invalid, since they are based on the unjustified assumption that mineral melting points control fusion during frictional sliding in the same way as in equilibrium melting. However, all work done during frictional fusion cannot be considered purely in terms of frictional heating, as the reduction in grain size and disruption of mineral lattices brought about by frictional sliding considerably increases the susceptibility of the rock to fusion, by increasing the surface area and breaking lattice bonds which would normally be resistant to heat. Micas in particular would be prone to fusion under such conditions because disruption of their lattices during frictional sliding would result in release of large quantities of water which would promote melting in the immediate surroundings. Small, extremely localized domains of melt with large water contents may thus be produced and further melting is promoted because high water contents reduce the temperature of fusion. Such a process will be rapid and self-propagating until fusion of anhydrous minerals reduces the water content of the melt to a sufficient degree that further melting is inhibited. This stage will be reached more rapidly once further addition of water to the system ceases, due to depletion of the hydrous phases.

In the Harry Creek Pseudotachylytes, fusion has been controlled by the fabric of the blastomylonitic parent. The coarser ribbon quartz domains have generally resisted fusion, whereas the alternating finer-grained domains, in which the micas were concentrated, have preferentially fused. Since in banded crystalline rocks the shear strength of layers enriched in ferromagnesian minerals, such as the micas, will be lower than that of layers richer in quartz and feldspar, differential shear failure probably tends to occur in the ferromagnesian enriched domains. Thus a melt less silicic than the parent rock as a whole will develop, which because of its enrichment in water and ferromagnesian components will have a lower viscosity than a minimum melt fraction, and can be more easily injected into the surrounding rocks. Enrichment of water in the melt could also promote hydraulic fracturing, which aided by transient overpressuring of fluid inclusions as suggested by Sibson (1975), would account for the extensive grain and fragment shattering characteristic of many pseudotachylytes. This would obviate the necessity of invoking the fluidization and gas blasting mechanisms of Shand (1916), Reynolds (1954) and Phillpotts (1964), which involve the introduction of large volumes of gas, for which there is no evidence.

The role of biotite in pseudotachylyte generation noted by Scott & Drever (1953) is a function of the high water content and widespread occurrence of this mineral. Release of water from biotite due to disruption of the biotite lattice during frictional sliding promotes and may even initiate melting. Oxidation of Fe^{2+} in the biotite by the reaction:

$$Fe^{2+} + 20H^{-} = Fe^{3+} + H_2 0$$

causes further disruption to the biotite lattice, hastening the preferential loss of Fe indicated by the probe analyses in Table 1; this effect accounts for the iron fluxing described by Scott & Drever (1953) in their Himalayan pseudotachylytes. It is therefore postulated that frictional fusion will be most favoured in medium-to coarse-grained crystalline rocks with high shear strength and significant water contents. Thus the most suitable rock types for pseudotachylyte generation will be quartz-rich rocks with a significant biotite content, the proportion of melt phase produced largely depending on the percentage of biotite in the rock.

The above mechanism for fusion during friction sliding can account for the apparently contradictory compositional data for pseudotachylyte melts obtained by previous workers. Thus, differential melting of biotite (see also Scott & Drever 1953) will produce initial melts of quite mafic composition (e.g. Masch 1973, Sibson 1975), which led to Sibson's concept of total melting, whilst subsequent fusion produces a melt closer to a minimum melt composition (Phillpotts 1964, Wallace 1976). If the parent rock does not contain any hydrous phases, the above fusion mechanism will not apply. Melts derived from such rocks will tend to mirror the composition of the parent, because the absence of hydrous minerals such as the phyllosillicates will preclude the concentration of water into domains occupied by ferromagnesian phases, and so inhibit selective further melting.

In the light of the above reasoning, it is contended that no relationship exists between the composition of the melt and the temperature of fusion, because the composition of the melt will be a function mainly of the composition of the parent rock and the rate of cooling of the melt. The inhomogeneous character of pseudotachylyte melts (Ermanovics *et al.* 1972, Wallace 1976) and the cooling half-life calculations of Sibson (1975) support this reasoning. Finally it is argued that the production of pseudotachylyte melts and the degree of melting realized will be determined less by the magnitude of the temperature rise brought about by frictional heating during fault movements, than by the composition of the parent rocks. Thus quite small temperature rises may generate intense fusion in relatively mica-rich rocks, whereas large temperature rises may produce little or no melt in more anhydrous rocks.

The depth of formation of pseudotachylytes

Although Francis (1972) and Sibson (1975) have presented detailed analyses of stress-slip relationships indicating that pseudotachylytes are developed at high levels in the crust, some workers (e.g. Cardwell *et al.* 1979) still dispute this. Francis (1972) calculated that depths of as little as 1km and sliding rates of only 5 cm/s^{-1} were sufficient for frictional fusion to take place, whilst Sibson (1975, 1977) has argued that the depth of mylonite formation ($\simeq$ 10–15 km) could be taken as the lower limit for pseudotachylyte generation. Analyses of the depths of formation of pseudotachylyte melts in the Himalayas and Eastern Alps (Masch 1979) and on the Alpine Fault in New Zealand (Wallace 1976) support the conclusions of Francis and Sibson.

Perhaps the most conclusive evidence for a high crustal level of formation for pseudotachylytes is the presence of glass or the evidence for its pre-existence in many pseudotachylytes. Cooling of a melt has an exponential function, which is rate-dependent on the ambient temperature of its surroundings. Therefore it follows that the rapid chilling of a melt necessary for glass formation will be restricted to near surface environments, where the ambient temperature of the surrounding rocks is low. Although other factors will also partly govern whether cooling is sufficiently rapid for glass to form, in general the probability of glass formation will decrease with increasing depths in the crust. Certainly, ambient temperatures of 400°C proposed for pseudotachylyte generation by Cardwell *et al.* (1978) would prohibit formation of glass, and the lower limit for glass formation would appear to be set by the depth of formation of microlite-bearing pseudotachylytes. Sibson (1975) has estimated depths of 4–5 km (i.e. $T < 150°C$) for microlitic pseudotachylytes from the Outer Hebrides Thrust Zone. For the Harry Creek Pseudotachylytes depths of the order of 2–4 km are estimated based on the absence in the matrices of these rocks of microlites or of vesicles, for which a depth limit of 2 km has been implied (Burnham & Jahns 1962, Moore 1965).

Relationship of pseudotachylytes to mylonites

The association of pseudotachylytes with mylonites is a common feature of many pseudotachylyte occurrences and their contemporaneity has been implied by many workers (e.g. Scott & Drever 1953, Sibson 1975, 1977, Wallace 1976). Sibson (1977) subdivided fault rocks into mylonite series rocks with a strong *L–S* shape fabric, and those with random shape fabrics, and related both categories to deformational environments. He correlated random shape fabrics (including pseudotachylytes) with elastico-frictional (*EF*) deformation mechanisms which predominate in the upper levels of the crust where shear displacement mainly takes place by intermittent seismic failure. Strong *L–S* shape fabrics on the other hand, were correlated with quasi-plastic (*QP*) deformation mechanisms, which predominate at depths below the onset of the greenschist facies where crystal plasticity becomes an important deformation mechanism. Sibson (1977) estimated the transition zone between the two regimes to occur in the depth range 10–15 km.

On the basis of Sibson's (1977) model, mylonites and pseudotachylytes should form at different levels in the crust and glassy pseudotachylytes in particular should not be associated with mylonites if they formed contemporaneously. However, Sibson (in press) has also suggests that random-fabric fault rocks, including pseudotachylyte can sometimes form within the *QP* regime as a result of transient seismic faulting. Sibson cites shape fabric in pseudotachylyte veins (e.g. Sibson 1977, plate 2) as evidence for renewed ductile deformation after pseudotachylyte formation. However, the deformation experiments of Tullis & Yund (1977) indicate that brittle-ductile behaviour is governed primarily by temperature, so that even at very shallow depths plastic deformation in quartz may take place at temperatures greater than 300–400°C. It is thus possible that shape fabrics in pseudotachylytes do not indicate formation in the *QP* regime, but reflect deformation during the cooling of hot pseudotachylyte melts produced by frictional heating in the *EF* regime.

The pseudotachylytes in the present study unequivocally postdate the mylonite series rocks with which they are associated in the field, and in all other instances where an unequivocal relationship can be established (e.g. Sibson 1977, plate 2), the pseudotachylytes postdate the associated mylonites. This is contrary to the theoretical expectation that pseudotachylyte formation would be favoured by conditions at the onset of movements in the fault zone before the effective normal stress is reduced by hydration along the fault (Francis 1972, Sibson 1975). However, pseudotachylyte melts generated at this time would probably be obliterated by subsequent shearing. It is thus argued that pseudotachylytes associated with mylonite series rocks always postdate the latter, generally forming during a later date reactivation of the fault zone subsequent to exhumation of the mylonite series rocks to a higher level in the crust. Pseudotachylytes formed by the reactivation of a ductile shear zone in the *EF* regime may do so by two mechanisms (R.H. Sibson personal communication 1979). In one setting progressive displacements on a reverse fault may raise mylonites to a level where brittle failure occurs within them (e.g. the Alpine Fault, New Zealand, Sibson *et al.* in press). Alternatively, pseudotachylytes may form where a fault zone, not necessarily with any vertical displacement across it, is progressively exhumed and then reactivated in the brittle mode, (e.g. the Ikertoq Shear Zone, West Greenland, Grocott 1977). However, it is also possible that some pseudotachylytes (*sensu lato*) may form in the *QP* regime subsequent to cessation of aseismic shear. This could result from replacement of aseismic shear mechanisms by seismic movements towards the end of deformation in a ductile fault zone, in response to strain hardening brought on by falling temperatures as the production of frictional heat from aseismic shear waned.

CONCLUSIONS

In the light of the above arguments, the time relationship of the Harry Creek Pseudotachylytes to their associated mylonite series rocks can be deduced. Microstructural evidence indicates that the Harry Creek Pseudotachylytes either postdate the Alice Springs Orogeny or formed during the late stages of that event subsequent to development of the parent blastomylonites. Evidence from the Harry Creek area indicates that the Alice Springs Orogeny has a complex history consisting of two deformations with an intervening static period. Reactivation of the Harry Creek Deformed Zone and development of mylonite series rocks is correlated with the first deformation, whilst NW–SE faults (e.g. the Bald Hill Fault) which cross-cut the E-W shear zones of the Arunta Block are correlated with the later deformation. Mineral assemblages imply that progressive uplift was associated with the Alice Springs Orogeny, with *P–T* conditions of the order of 5.5 kb and 600°C estimated for the early stages of the event and approximately 3.5 kb and 400°C for the closing stages, i.e. well within the *QP* regime of Sibson (1977). Because the presence of glass in the Harry Creek Pseudotachylytes implies depth of formation of less than 5 km, they must therefore post-date the Alice Springs Orogeny.

Marjoribanks & Black (1974) have also postulated uplift for the southern part of the Arunta Block during or immediately after the Alice Springs Orogeny. Furthermore, there is strong evidence for rapid erosion and denudation associated with the Alice Springs Orogeny. Accumulation of about 3500 m of molasse-type sediments took place at this time in the Pertnjara Group in the Amadeus Basin, immediately to the south of the Arunta Block (Jones 1970, 1972). Age data also support progressive uplift at this time. A wide spread of

K/Ar and $^{40}Ar/^{39}Ar$ age dates ranging from about 500–320 Ma has been recorded for the Alice Springs Orogeny (e.g. Stewart 1971, Armstrong & Stewart 1975, Woodford *et al.* 1975, Iyer *et al.* 1976, Allen & Stubbs in press). Allen & Stubbs postulate that the close of the Alice Springs Orogeny took place at about 400–370 Ma and suggest that the younger ages may reflect variable closure of different K/Ar systems associated with the continued uplift and denudation of the Arunta Block immediately subsequent to this event.

The Harry Creek Pseudotachylytes are thus considered to have formed subsequently to this phase of uplift and denudation after the Harry Creek area had been exhumed. Shear stresses accumulating during the uplift stage are postulated to have brought about reactivation of some of the steep displacement surfaces in the Harry Creek Deformed Zone, thereby initiating brittle failure in the weaker more ferromagnesian-rich domains of the blastomylonitic parent rocks and leading to generation of the Harry Creek Pseudotachylytes. Strain hardening in the parent rocks may have been promoted by the uplift through a process of exsolution of lattice-held water from quartz in response to the decrease in its solubility with failing temperature and / or pressure. Uplift of as much as 8 km in as little as 40 Ma may have been associated with the formation of the Harry Creek Pseudotachylytes.

The present investigation of the origin of the Harry Creek Pseudotachylytes thus supports the conclusions of Francis (1972) and Sibson (1975, 1977, 1979) that pseudotachylytes are generated at high levels in the crust. In the main, pseudotachylytes appear to be generated by reactivation of pre-existing ductile fault zones subsequent to their exhumation to higher levels in the crust.

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