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Field Relationships and Tectonic History of the Hinckley Gabbro Felsic to Mafic Granulites and Granitoids, West Hinckley Range and Champ de Mars Areas, Tomkinson Ranges , Musgrave Block, WA. Record 1992/33.

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MINERALS AND LAND USE PROGRAM
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A contribution to the NGMA Musgrave Project
Minerals and Land Use Program

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SUMMARY

This record summarizes structural and petrological investigations of parts of the mid-Proterozoic Musgrave Block, central Australia, a terrain dominated by the layered mafic-ultramafic Giles Complex, felsic granulites and granitoids. Field work was undertaken over a period of four weeks in July and August, 1991, working from a field base at the Wingellina (Irrunytju) Aboriginal Community, Western Australia. Detailed geological mapping of the Champ de Mars area and the west Hinckley Range was conducted using 1:20 000 colour aerial photographs, with the aim of constraining geological relationships between the Hinckley Gabbro, Michael Hills Gabbro, recrystallized gabbro and derivative mafic granulites and country rocks including felsic granulites and felsic orthogneiss bodies.

Well-layered felsic and mafic granulites, which include numerous thin and discontinuous metasedimentary horizons, comprise the oldest rocks in the area, yielding Rb-Sr whole-rock ages of 1564+/-12 and 1327+/-7 Ma (Gray, 1971, 1977; Gray and Compston, 1978). These dates have been confirmed by preliminary U-Pb zircon dating using the Australian National University's SHRIMP ion-microprobe (S. Sun, pers. comm. 1992). The granulites preserve evidence of two deformation events, D1 and D2, that accompanied granulite facies metamorphism (P about 7 kbar, T above 750^{o}C; Ballhaus and Berry, 1991), and include pre-S1 mafic orthogneiss and post-S1, pre-S2 felsic orthogneiss. D2 resulted in mesoscopic to macroscopic isoclinal reclined F2 folds with an axial planar foliation, S2, that is the pervasive gneissosity in the felsic-mafic granulites. Large mafic to ultramafic intrusions comprising the Hinckley Gabbro and Michael Hills Gabbro cut S2 in the felsic-mafic granulites, but are themselves intruded by regionally extensive microgranitoid and K-feldspar megacrystic granitoid dykes and stocks. Bodies of rapakivi granite, charnockite and mafic inclusion-rich granite occur near contacts between gabbro and the granitoids; these rock types show gradational relationships with K-feldspar megacrystic granitoid bodies distal to the contact. Type A mafic dykes intrude all of the above rock types, and are post-dated by a third deformation event, D3, which resulted in a system of steep, southeast-trending mylonites that contain an S3 foliation and a well-developed down-dip stretching lineation. Whereas the Type A mafic dykes show marginal to complete recrystallization to granulite facies S3 assemblages, in

most places the layered intrusions of the Giles Complex remained unaffected by D3. However, in the west Hinckley Range, the Hinckley Gabbro was extensively intruded by granite dykes and D3 was associated with the recrystallization of gabbro to mafic granulite. Coarse-grained Type B mafic dykes, and aphanitic Type C mafic dykes intrude most rock types and cut S3, but are themselves deformed by steep east-trending D4 ultramylonites that preserve evidence of southeast-directed deformation and amphibolite facies recrystallization. D4 ultramylonites with either normal or reverse movement are observed; these zones form the boundaries of some gabbroic bodies, and are cut by steep north-trending D5 ultramylonites that preserve southwest-directed deformation at similar metamorphic conditions to D4. Individual D4 and D5 shear zones involved maximum displacements of a few hundred metres. Prominent east-trending zones of D6 pseudotachylite and ultramylonite, which are superposed on earlier structures (Glikson and Mernagh, 1990), cut all the above fabrics and preserve evidence of north-directed thrusting. These zones probably involved considerable displacement and are interpreted to be the expression of the Petermann Orogeny in the Tomkinson Ranges. East-trending, muscovite+biotite-bearing D7 retrograde shear zones form broad "crush" zones that are poorly exposed due to recessive weathering.

The mapping results and interpreted chronology of geological events are discussed with reference to the regional geology and tectonic synthesis of the Musgrave Block.

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Appendix has been omitted from the hardcopy of Record 1992/33.

I. INTRODUCTION

Granulite facies gneisses comprising the Musgrave Block form a latitudinally-trending gravity high with a strike extent of over 700 km, straddling the South Australian-Northern Territory border and extending to Western Australia. The areas investigated in this report form part of Tomkinson Ranges within the COOPER 1:250,000 mapsheet (Daniels, 1971)(Fig. 1). Large layered mafic to ultramafic lopoliths and sills, collectively termed Giles Complex, occur within the granulite terrain, have attracted considerable geological interest (Nesbitt and Kleeman, 1964; Nesbitt and Talbot, 1966; Nesbitt et al., 1970; Goode and Krieg, 1967; Ballhaus and Glikson, 1990; Ballhaus and Berry, 1991). However, although described in early work (Nesbitt et al., 1970; Goode,1978; Moore and Goode, 1978), the temporal and spatial relationships of the Giles Complex with surrounding high-grade gneisses in Western Australia require further studies.

This report summarizes observations made in two areas, the Champ de Mars area and the west Hinckley Range, within the Tomkinson Ranges, south and southwest of Wingellina, Western Australia (Fig. 1). Four weeks were spent mapping during July and August, 1991, in collaboration with a BMR field party involving A.Y. Glikson and A.J. Stewart. These areas were selected in order to elucidate the relationships between the Hinckley Gabbro and associated felsic igneous and metamorphic units, and establish their tectonic history. Field observations are compared with the published literature, and follow up petrographic work is still continuing. Field data were directly marked on transparent overlays of 1:20,000 colour aerial photographs and compiled to maps included as Figs 2, 3, 6, 8 and 10. Locality reference numbers as used during mapping are of the form: X (Run number); Y (photo frame number); and, Z (Locality). All sample localities and sites of geological significance discussed in this report are denoted according to this scheme and located on Fig. 2 and 8; where several samples were collected from the same locality they were successively labelled A,B.C...

Permits are required for travel in the Tomkinson Ranges, which lie within the Central Australian Aboriginal Reserves. Surface access is via dirt and gravel roads from Giles Meteorological Station to the north, Curtin Springs via Amata to the east, and Warburton to the west. New tracks are constantly being made by Aboriginal communities in the area, making most published maps unreliable. Most areas are accessible to cross country travel, with sparse bloodwood and corkwood trees on open, flat plains between hills rising 100 to 150m above the plains, the main impediment in places being high sand dunes.

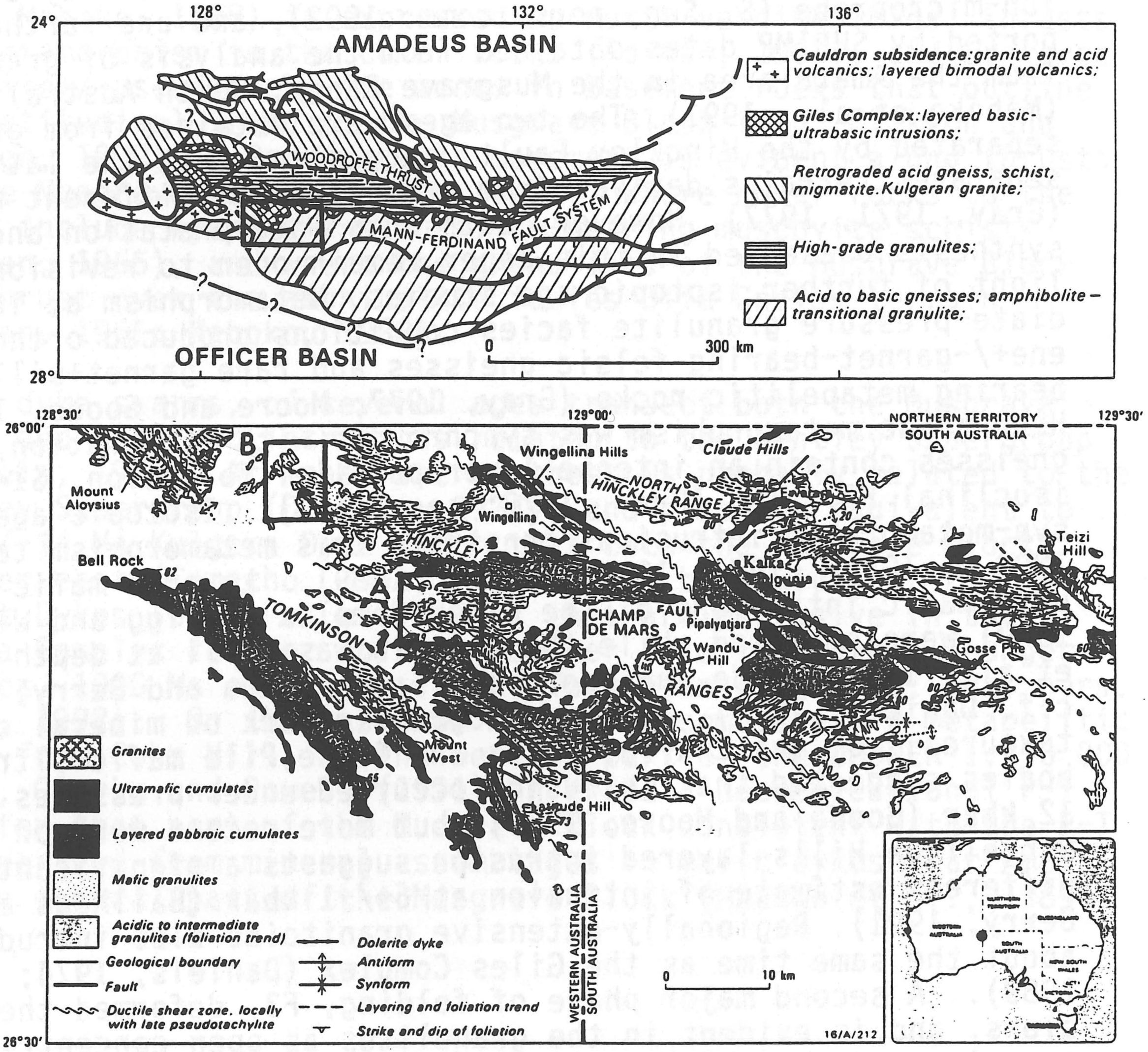

Fig. 1 - Geological sketch map of the Tomkinson Ranges, showing the two areas studied in detail: area A - Champ de Mars; area B - westernmost Hinckley Range

II. REGIONAL GEOLOGY

Much of the high-grade terrain is dominated by orthogneiss and charnockite and by banded felsic to mafic granulites interpreted as derived from volcanic and/or sedimentary precursors (Gray, 1971, 1977; Daniels, 1974; Moore and Goode, 1978). Two whole rock Rb-Sr ages interpreted as protolith ages of the felsic granulites in the Tomkinson Ranges are 1564+/-12 and 1327+/-7 Ma (Gray, 1971, 1977). These ages are confirmed by preliminary U-Pb zircon dating using the Australian National University's SHRIMP ion-microprobe (S. Sun, pers. comm. 1992), and are further supported by SHRIMP dates obtained from the analysis of granulites from the Amata area in the Musgrave Range, South Australia (Maboko et al., 1991). The two ages were obtained from granulites separated by the Hinckley Fault, suggesting that the latter separates terrains derived from protoliths of different ages (Gray, 1971, 1977). However, both this interpretation and the synthesis presented in this paper remain open to revision in the light of further isotopic age studies. Metamorphism at intermediate-pressure granulite facies conditions produced orthopyroxene+/-garnet-bearing felsic gneisses and rare garnet+sillimanite-bearing metapelitic rocks (Gray, 1977; Moore and Goode, 1978). High-grade metamorphism was synchronous with deformation, and all gneisses contain an intense layer-parallel foliation, S1-2, and isoclinal F2 folds (Gray, 1978; see below). Isotopic ages of the syn-metamorphic intrusions constrain this metamorphism to about 1200 Ma (Gray, 1971, 1978; Maboko, 1989). Layered mafic and ultramafic intrusions of the Giles Complex (Sprigg and Wilson, 1959) were emplaced while the terrain was still at depth (Nesbitt et al., 1970; Goode and Moore, 1975; Ballhaus and Berry, 1991; c.f. Daniels, 1974). Early petrographic work on mineral corona textures from the Ewarra, Kalka and Gosse Pile mafic-ultramafic bodies suggested that intrusion occurred under pressures of 10 to 12 kbar (Goode and Moore, 1975), but more recent work on the Wingellina Hills layered intrusion suggests a significantly different estimate of intrusion at 6+/-1 kbar (Ballhaus and Berry, 1991). Regionally-extensive granitoids also intruded at about the same time as the Giles Complex (Daniels, 1974; Maboko, 1989). A second major phase of folding, F3, deformed the intrusions, and is evident in the granulites as open concentric folds superimposed on S1-2 (F2 of Nesbitt et al., 1970; Gray, 1971; see below).

Areally-restricted quartzites and quartz-mica schist, of unknown age and with no formal name, unconformably overlie the Musgrave Block (Daniels, 1974), but appear conformable with the overlying ca. 1080 Ma-old Bentley Supergroup (Daniels, 1974; Forman, 1965; Gray, 1971) -- a thick series of felsic and mafic volcanics and sediments (Daniels, 1974). Cauldron subsidence structures and ca. 1040 Ma granitic intrusions (Gray, 1971) associated with the volcanic series transect the granulites (Daniels, 1974). An upper unit of the Bentley Supergroup, the Townsend Quartzite, has been correlated by Daniels (1974) with the Dean Quartzite of the Petermann Ranges, which has been correlated by Forman (1965) with the areally-extensive Heavitree Quartzite at the base of the late Proterozoic to Palaeozoic Amadeus Basin. These correlations are the subject of confirmation by further mapping (Trendall and Cope, 1975). The mid-Cambrian Petermann Orogeny (Forman and Shaw, 1973; Maboko, 1988) is expressed by north-verging folds, thrusts and metamorphism in the cover rocks (Forman, 1965), and by large mylonite+/-pseudotachylite zones in basement rocks that outline the latitudinal trend of the Musgrave Block (e.g. Glikson and Mernagh, 1990). Considerable movement is evident along thrusts in the Musgrave Ranges (Major, 1973), where cover rocks to the north include kyanite+/-staurolite-bearing muscovite schists (Forman, 1965), and where the granulites of the Musgrave Block are thrust over the amphibolite facies Olia Gneiss terrain (Forman, 1965; Maboko, 1988).

Major dyke swarms, of several ages transect both the Musgrave Block and granitic intrusions related to the Bentley Supergroup (Daniels, 1974). At least one of these is probably related to the Bentley Supergroup (Daniels, 1974), and possibly equivalent to 1054+/-14 Ma Kulgera Dyke Swarm that cuts the Musgrave Block further east (Camacho, 1991). Both could be equivalent to the Stuart Dykes (Black et al., 1980) that are pervasive in the Arunta Complex farther north. Younger doleritic dykes younger than ca. 1000 Ma old occur in the Tomkinson Ranges (S. Sun, pers. comm., 1992). On the basis of mineral assemblages in metapelitic rocks from Cohn Hill, in the western part of the COOPER 1:250 000 sheet, Clarke and Powell (1991) inferred a decompressional P-T path for that part of the Musgrave Block consistent with the P-T path derived from mineral assemblages in mafic dykes near Amata in the central part of the Musgrave Block (Maboko et al., 1989).

III. GEOLOGY OF THE CHAMP DE MARS AREA

The Champ de Mars terrain has been selected for detailed mapping since it constitutes a felsic igneous/metamorphic core complex between the Hinckley Gabbro and the Michael Gabbro and spans a wide lithological range, including felsic and mafic granulites, micrograntes, K-feldpar megacrystic granite and rapakivi granite (Fig. 1). The contacts between the large layered mafic intrusions and the felsic complex are widely modified by post-intrusion deformation, however, the area allows the construction of a sequence of geological events in the Tomkinson Ranges. The structural history developed for the area is summarized in Table 1, and the geology portrayed in Fig. 3 and schematically represented in Fig. 11.

III.1 Field relationships

The oldest rocks in area are well-layered felsic and mafic granulites that preserve evidence of one or two deformation events. Daniels (1974) divided these rocks into two types: (1) granulites that are characterized by lithological variations on a metre to centimetre scale reflecting primary sedimentary layering; and (2) poorly banded felsic granulites, which include charnockitic gneisses inferred to comprise orthogneiss. Principal locations for the well-banded variety in Western Australia include Mt Aloysius (Fig. 1) and the area between Winburn Rocks and Lightning Rocks (western part of COOPER); these rocks were interpreted to unconformably overlie the poorly-banded variety (Daniels, 1974, p. 34). In South Australia well banded granulites dominate the terrain between North Hinckley range, Ewarara and Teizi soak. A migmatitic variety of the poorly banded felsic granulites, including minor amounts of quartzite, was mapped in the Champ de Mars area by Daniels (1974). Minor mafic granulites are interlayered with the felsic granulites on a centimetre scale, with the mafic granulites having recorded identical deformation histories to the felsic granulites. Daniels (1974) inferred that these mafic rocks were genetically related to the Giles Complex, but the rocks are imprinted by tectonic fabrics which predate the large gabbroic intrusions.

Mafic rocks of the Hinckley Gabbro and Michael Hills Gabbro intrude the layered felsic-mafic granulites, but primary contacts in the Champ de Mars area have been disrupted by later deformation. No contact metamorphic effects that can be attributed to intrusion of basic magma were recognized in this area, but well exposed intrusive contacts of the Giles Complex occur along the southern margin of the Mt Davies intrusion and the northen margin of the Kalka intrusion (Nesbitt et al., 1970; A.Y. Glikson and A.J. Stewart, pers. comm., 1991). Regionally-extensive K-feldspar megacrystic granite and microgranite dykes and stocks intrude the felsic-mafic granulites and, in places, intrude mafic to ultramafic rocks of the Giles Complex (TR27-074-30). Large xenoliths of felsic-mafic granulites occur in both types of granitoid (e.g. TR28-141-4), and stocks of K-feldspar megacrystic granitoids show gradational variations into microgranite, so the two rocks were mapped as a single unit. Less common felsic intrusions, including a younger generation of charnockite (TR27-074-26; TR28-141-31), and rapakivi granite (Fig. 4a; TR28-141-26), containing abundant mafic inclusions occur along and near the southern margin of the Hinckley Gabbro (TR27-073-7, 9). In places, the rapakivi granite is gradational into the more common K-feldspar megacrystic granite (TR28-141-23, 24). Dykes of charnockite and rapakivi granite also intrude the Hinckley Gabbro (TR27-074-30, TR27-073-9). Possible mechanisms to explain these observations involve: (1) limited stoping and minor assimilation of the Hinckley Gabbro during intrusion of the felsic granitoids; or (2) if the gabbroic body was incompletely crystallized at the time of the felsic intrusions, mixing of the two magma types.

The felsic-mafic granulites, K-feldspar megacrystic granite and the Hinckley Gabbro and Michael Hills Gabbro are intruded by mafic dyke swarms of several generations. Dyke swarms of two distinct ages (Type A and Type C) can be recognized in the Champ de Mars area, and an additional dyke swarm (Type B) of intermediate age is inferred for the area mapped in the west Hinckley Range. Type A dykes are dominantly northwest-trending in the Champ de Mars area (TR24-141-18), but north-trending (TR28-143-1) and northeast-trending (TR27-074-29) Type A dykes occur. The dominant trend of the dyke swarm is due to post-intrusion deformation: Type A dykes were folded during the D3 deformation (TR28-141-6), and, in most places, are aligned with the southeast-trending S3 foliation (see below). Thus, the present orientation of the Type A dyke swarm has little to do with the original regional stresses during dyke intrusion. Type A dykes show marginal to complete recrystallization of primary igneous textures to granulite facies S3 mineral assemblages (Figs 4b, 4c).

The D3 phase affected all rock types described above, with the exception of Type B and C dykes, but the intensity of recrystallization during this deformation is highly variable. Different rock types show different intensities of S3 development: most of the Hinckley Gabbro was unaffected by the event, whereas most felsic orthogneisses were pervasively recrystallized during D3. As discussed below, the intensity of recrystallization related to

S3 development can also vary on a mesoscopic scale within the one rock type. Throughout most of the Champ de Mars area, the S2 gneissosity in the felsic-mafic granulites has been tightly to isoclinally folded by F3 folds (Fig. 4d; TR28-141-3) and aligned with a steeply dipping southeast-trending S3 foliation that is well-developed in felsic orthogneisses.

In the Champ de Mars area, Type C mafic dykes cut S3 foliation. Type C dykes are fine-grained to aphanitic dolerite intrusions (TR28-143-3), dominantly northwest-trending and northeast-trending, and commonly contain minor pyrite (Stewart and Glikson, 1991). All rock types, including Type C dykes, are cut by mylonites and ultramylonites (Fig. 5a) of several ages. The earliest recognized shear zone event, D4, formed east-trending to southeast-trending ultramylonite zones, such as occur along the southern boundary of the Hinckley Gabbro (TR28-141-23). The maximum displacement involved in these zones is probably only a few hundred metres (see Fig. 5a), since similar or related rock types occur on either side of individual shear zones. In detail, the ultramylonite zones have a variable geometry and sense of movement, but D4 seems to have involved southeast-directed transport (see below). D4 ultramylonite zones are offset by north-trending D5 ultramylonite zones (TR27-074-24) that suggest southwest-directed transport. None of the observed D4 or D5 ultramylonite zones are accompanied by pseudotachylite.

Broad east-trending D6 ultramylonite+pseudotachylite zones cut all rock types, and form prominent fault zones that run for tens of kilometres, as mapped out by earlier workers (Thomson et al., 1962; Nesbitt et al., 1970; Goode, 1978). These zones are likely to represent the local expression of the Petermann Orogeny (Forman, 1965), which thrust the Musgrave Block northwards over late Proterozoic sediments of the Amadeus Basin and resulted in the Woodroffe thrust zone mapped to the north of the Tomkinson Ranges (A.J. Stewart, pers. comm., 1991). Pervasive D6 recrystallization occurs in zones more than 500 m wide where deformation has affected felsic rocks, or as broad (over 150m) zones of pseudotachylite veining where the shear zone cuts gabbroic rocks (Glikson and Mernagh, 1990). Poorly-exposed muscovite-rich and/or biotite-rich, east-trending D7 retrograde shear zones are interpreted in terms of the last deformation event in the area. These zones are very different in character to the mica-poor D4-6 ultramylonites.

III.2 Lithological assemblages

Layered felsic and mafic granulites

These gneisses are petrologically monotonous, comprising variations in the proportions of their constituents. Where plagioclase dominates over mafic minerals, the rock was mapped as a felsic granulite, and where mafic minerals dominate over leucocratic minerals the rock was mapped as a mafic granulite. Felsic granulites predominate in the Champ de Mars area, and no early charnockite units were mapped. A typical felsic granulite comprises orthopyroxene, clinopyroxene, plagioclase, quartz, biotite and opaques with or without K-feldspar or hornblende. Mafic minerals range in modal abundance from less than 5% to more than 40%, and orthopyroxene is usually More abundant than clinopyroxene. Most mafic granulites are similar; clinopyroxene is usually present in greater abundance than orthopyroxene and K-feldspar is absent. Large, zoned and simply twinned plagioclase grains of relic igneous origin are common in mafic granulite layers, suggesting that many were derived from recrystallized gabbroic rock.

As outlined above, the granulites show a pervasive S1 gneissosity that is commonly defined (e.g. TR27-073-12) by alternating mesosome comprising fine-grained clinopyroxene (?some pigeonite), hypersthene, plagioclase, biotite, quartz and opaques and leucosome comprising coarse-grained orthopyroxene, clinopyroxene, plagioclase, K-feldspar, quartz and opaques. The leucosomes are rich in quartz, contain large K-feldpar grains that are simply twinned, and orthopyroxene in greater abundance than clinopyroxene. The compositions of the mesosome and leucosome units militate against derivation of the latter from the former by insitu closed-system partial melting, favouring instead injection of allochtonous material.

Only one garnet-bearing felsic granulite was found within the area mapped (TR28-142-15A). It comprises a coarse-grained S3 plagioclase, quartz and K-feldspar fabric, with post-S3 symplectites of garnet and biotite, with or without hornblende, pseudomorphing a pre-existing mineral, most probably orthopyroxene. The locality is adjacent to a D4 ultramylonite, and the recrystallization is interpreted to be a consequence of the D4 event.

The Hinckley Gabbro and Michael Hills Gabbro

No attempt was made to study the Hinckley and Michael Hills layered intrusions in any detail during this work, since previous projects have focussed on petrological features of these bodies (e.g. Ballhaus and Glikson, 1990; Ballhaus and Berry, 1991). The Michael Hills Gabbro forms the southern margin to, and continues well outside, the area mapped in detail. This intrusion has been interpreted as being more than 6,500 m thick, and crops out over an area of 260 km^2 that straddles the Western Australia-South Australia border (Daniels, 1974). Well-developed igneous banding is observed on all scales, and in much of the Michael Hills Gabbro this layering still preserves shallow dips that have resulted in benches approximately 16 m high. Units of pyroxenite are common, especially in the western and southern parts of the intrusion (A.Y. Glikson, pers. comm., 1991). Along the northern margin of the Michael Hills Gabbro in the Champ de Mars area, primary igneous banding on a macroscopic scale is truncated by a large retrograde shear zone (Fig. 3), showing marginal recrystallization of the gabbro into amphibolite (TR28-143-16). Some retrogression of the gabbro has occurred within 200 m of the shear zone. Elsewhere south of this fault the Michael Hills Gabbro is extensively recrystallized along its northern margin to mafic granulite in conjunction with the intrusion of granitic veins which predate the faulting (A.Y. Glikson, pers. comm., 1991). The petrology of gabbroic rocks (minimally affected by later deformation) from the Michael Hills Gabbro is described in some detail by Daniels (1974).

No detailed work has been conducted by the author on the Hinckley Gabbro, which forms the spine of the Hinckley Range. The gabbroic intrusion is interpreted as having been approximately 2,700 m thick (Nesbitt and Talbot, 1966), and much of it shows little obvious igneous banding (Daniels, 1974). The contact between the gabbro and the felsic rocks of the Champ de Mars area is commonly marked by a D4 ultramylonite (see below; TR28-141-23). Dykes and stocks of rapakivi granite, charnockite and felsic granitoids with abundant mafic inclusions (TR27-074-26) occur along this contact, as discussed further below.

Granitoids

Stocks and dykes of K-feldspar megacrystic and microgranite dykes are widespread in the Champ de Mars area, and pervasively intrude, and contain xenoliths of, the felsic granulites (TR28-141-3). In the west Hinckley Range, the granitoids intrude (TR25-126-21, 22) and contain xenoliths of (TR25-126-16) the

Hinckley Gabbro and derivative mafic granulites (see below). Stocks of K-feldspar megacrystic granitoid are intruded by dykes of microgranite, and stocks of microgranite are intruded by dykes of K-feldspar megacrystic granitoid. These lithologies contain xenoliths of each other, gradations between the two end-members are observed, and the rocks appear to be contemporaneous. Outcrops of the different granitoids could not be differentiated on the scale mapped. Both types of granitoids were pervasively recrystallized during D3, and they typically comprise K-feldspar and subordinate plagioclase megacrysts enveloped by a mylonitic S3 foliation comprising K-feldspar, plagioclase, quartz and opaques with or without garnet and biotite. In some samples (TR28-141-17), garnet+biotite symplectites pseudomorph a pre-existing mineral, probably orthopyroxene, in zones of intense S3 recrystallization. Immediately south of Walpa-Puka Rockhole (TR28-141-9), K-feldspar megacrystic granitoid is pervasively sheeted by 2-5 cm wide aplitic veins that are now parallel to S3.

Most of the felsic granitoids comprise K-feldspar, plagioclase and quartz. Biotite is present in only a few localities (TR28-141-9, 10), but where biotite-bearing the orthogneiss has been extensively recrystallized during late mylonite-forming events.

Granitoids along the southern margin of the Hinckley Gabbro

The southern contact of the Hinckley Gabbro includes small dykes and stocks of charnockite that contain abundant mafic xenoliths (TR27-074-26) which in places intrude the Hinckley Gabbro (TR27-073-9). Large othopyroxene grains (1 cm diameter) in the charnockite are rimmed by clinopyroxene, and coarse-grained plagioclase and hornblende symplectites occur with mafic rims (TR27-074-26, 33B). Large K-feldspar grains, which are pale green with a greasy texture, are rimmed by plagioclase. Sample TR27-074-33B is a charnockite comprising large igneous clinopyroxene, orthopyroxene and perthite grains in a fine-grained recrystallized matrix of quartz, microcline, plagioclase, hornblende and ilmenite. Horblende partially pseudomorphs pyroxene grains and encloses ilmenite, and coarse-grained symplectites of well-formed hornblende, plagioclase and clinopyroxene (3 cm diameter) are inferred to be after large igneous clinopyroxene grains. Angular to partially resorbed xenoliths of mafic rock occur, in various concentrations. Gabbroic rocks near the charnockite are intruded by abundant feldspathic stringers and may contain K-feldspar megacrysts. They later comprise plagioclase and K-feldspar megacrysts (2-3 cm in diameter) surrounded by fine-grained plagioclase, quartz, orthopyroxene, clinopyroxene, biotite and opaque minerals. These charnockitic rocks postdate the D1-2 events, and are unrelated to the charnockitic gneisses that occur interlayered with the layered felsic-mafic granulites elsewhere.

Dykes and stocks of rapakivi granite (Fig. 4a) occur with the charnockite and intrude the gabbro in places (TR27-074-30). The bodies may be offshoots of larger rapakivi granite stocks which may occur in depth (TR28-141-26). In these stocks, zones rich in plagioclase-mantled K-feldspars occur in a host with limited mantled feldspar, or amongst zones of simple K-feldspar megacrystic granitoid. Zones of microgranite also occur. Gradational relationships are observed between these zones on scales of ten to one hundred metres. The stocks of rapakivi granite could be distinguished from stocks of K-feldspar megacrystic and microgranite on the basis of outcrop features.

An unusual igneous body of intermediate to mafic composition occurs within a zone of extensive rapakivi granite development (TR28-141-27, 31). This rock shows a coarse-grained sub-ophitic texture defined by randomly oriented meshing plagioclase laths (60%), with interstitial orthopyroxene (15%), clinopyroxene (5%), biotite (15%), ilmenite and minor hornblende. It contains xenoliths of more mafic rock and includes zones of charnockite (TR28-141-25). It does not show features of the D1-2 events, and is interpreted to be genetically related to the charnockites and rapakivi granites that occur marginal to the Hinckley Gabbro. The intermediate heterogeneous igneous rocks along the margin of the gabbro are best interpreted in terms of the intrusion of felsic magma into, and contamination by, the gabbro. The end-member felsic magma produced K-feldspar megacrystic granite or microgranite where uncontaminated, and rapakivi granite and charnockite where contaminated by mafic material.

Mafic dykes type A

Cutting all the rocks described above are steeply-dipping mafic dykes that have a granular texture and consist of orthopyroxene, clinopyroxene, plagioclase and opaques with or without hornblende or biotite. The cores of the dykes (TR28-146-12; Figs 4b, 4c) commonly preserve a coarse-grained subophitic texture comprising randomly oriented, zoned and simply twinned plagioclase laths with interstitial aggregates of orthopyoxene and clinopyroxene commonly rimmed by biotite. Whereas there is no penetrative foliation in the cores of such dykes, a recrystallized mylonitic S3 foliation (Fig. 4c; TR28-146-12) comprising clinopyroxene, orthopyroxene, plagioclase, biotite, quartz and opaques occurs along their margins. Dykes that intrude the felsic granitoids commonly show recrystallization to amphibolite; they comprise (e.g. TR28-141-5) S3 green-brown hornblende, plagioclase and ilmenite with or without quartz. Where the dykes cut gabbro, they appear to have been protected from recrystallization associated with D3 and primary igneous features are well preserved (TR28-143-17). These differences arise in part from the dry nature of the gabbroic host rocks as compared to the granitoids. The dykes define tight to isoclinal F3 folds (TR28-141-6) and are now mostly aligned with the southeast-trending S3. The dykes cut igneous layering in the Michael Hills Gabbro (TR28-143-17) and rapakivi granite that intrudes the Hinckley Gabbro (TR-28-141-24), thus clearly postdating the Giles Complex.

Mafic dykes type C

Northwest-trending and northeast-trending dolerite dykes cut S3 but are themselves cut by D4-7 shear zones. These dykes are fine-grained to aphanitic and show minimal effects of recrystallization outside the shear zones. They are very fresh in outcrop and in place contain pyrite. Sample TR28-143-9 is from a dyke partially recrystallized during D4; it comprises zones of porphyroclastic pyroxene and plagioclase with a fine-grained sub-ophitic texture, enveloped by S4 quartz, epidote and calcite. These dykes are probably equivalent to dolerite dykes that cut all rocks below the late Proterozoic Townsend Quartzite (Daniels, 1974) and were possibly comagmatic with mafic volcanics of the the Bentley Supergroup.

III.3 Structural geology

Metasedimentary gneisses, orthogneisses and dykes in the Champ de Mars area record evidence of seven phases of deformation, D1-7. In particular, attempts were made to correlate the effects of D1-3 between the outcrops of felsic granulites and orthogneisses and gabbroic rocks of the Hinckley Gabbro, rather than discuss the data in terms of separate deformation schemes for felsic and gabbroic rocks (e.g. Pharaoh, 1990). The first two phases of deformation, D1-2, resulted in the pervasive gneissic layering in felsic-mafic granulites, and pre-dated intrusion of the Giles Complex and granitoid stocks and dykes. D3 postdates the intrusion of these bodies, and resulted in the near-vertical southeast-trending S3 foliation that can be observed throughout much of the Tomkinson Ranges. Two phases of ultramylonitization, D4 and D5, preceded the Petermann Orogeny (D6) that is represented by large ultramylonite and/or pseudotachylite zones. Muscovite-bearing D7 retrograde shear zones are interpreted as preserving evidence of the last deformation event. The relationships between the various shear zones are summarized in Fig. 6.

D1 event

Evidence for the earliest tectonic event recorded in the western Musgrave Block is preserved in the felsic and mafic granulites (Daniels, 1974), which contain a penetrative S1 gneissosity that is deformed by isoclinal F2 folds (Fig. 5b). The S1 gneissosity is defined by feldspar-rich leucocratic segregations, and alternations in the proportion of mafic versus felsic minerals. These segregations are commonly 0.5 to 2 cm in thickness, and laterally continuous for several metres. Significant boudinage of these thin bands is not observed. Little kinematic information can be obtained concerning the nature of D1, due to the intensity of recrystallization during D2: with the exception of F2 hinges, S1 has been everywhere rotated into parallelism with S2. At only one locality in the west Hinckley Range could isoclinal F1 folds be confidently identified (see below). Elsewhere, small, rootless intrafolial folds, now aligned within S2 could be interpreted as F1 folds: in thin section examination of many such folds, only one gneissosity that is axial planar to the fold can be identified, but the lack of hydrous minerals in the rocks means that interpretations are ambiguous. S1 represents recrystallization at the peak of metamorphism. Nowhere does S1 contain a linear component to the foliation. Nesbitt et al. (1970) and Moore and Goode (1978) did not recognize S1 and their F1 is equivalent to the F2 folds described below. S1 as defined in this report is equivalent to the $S1_F$ event of Pharaoh (1991).

D2 event

The D2 event is characterized by mesoscopic to macroscopic, tight to isoclinal F2 folds with an axial surface, S2, defined mostly by the transposition of the S1 gneissosity. Where unaffected by subsequent deformation, the F2 folds have east to east-southeast trending axes and were reclined with an S2 foliation dipping shallowly (15 to 30^{o}) to the east. This is observed in the west Hinckley Range (TR24-142-11), but is obscured by overprinting by D3 in the Champ de Mars area. A pervasive S2-S1 intersection lineation, L2, is defined by ubiquitous intrafolial F2 folds in outcrops of the felsic-mafic granulites (Fig. 5c). In the limbs of mesoscopic F2 folds there are no blebs or trains of minerals defining an L2 lineation within S2, so the lineation does not represent a mineral or stretching lineation.

In thin section, the S1-2 foliations can be distinguished on textural grounds from later fabrics. The S1-2 assemblages comprise granoblastic, interlocking coarse-grained minerals, whereas S3 is a fine-grained mylonitic foliation, typically with quartz ribbons enveloping residual S1-2 mineral grains.

The absence of any stretching lineation within S2 implies that D2 involved mostly pure shear, with only a small component of rotational strain. An absence of continuous marker horizons in the felsic-mafic granulites precludes an interpretation of whether the overall D2 strain involved crustal shortening or extension. However, the form of S2 in areas not affected by D3 implies that the flattening-style D2 strain accompanied the development of either a shallowly-dipping reclined terrain or a recumbent terrain. This suggests that the axis of principal compression was close to vertical, which could most simply be explained by the weight of rocks overlying a terrain at granulite facies near the base of a continental crust of stable thickness. This style of deformation, apparent for both S1 and S2, does not easily fit with models of deformation resulting from continental collision, since such models usually invoke deformation dominated by simple shear (e.g. Escher and Waterson, 1974; LeFort, 1975; Shackleton and Ries, 1984).

D3 event

The D3 deformation is characterized by upright to reclined, tight to isoclinal mesoscopic F3 folds (Fig. 4d) with a steeply dipping, southeast-trending mylonitic S3 axial surface. F3 folds are observed with amplitude and wavelength on a scale between metres and tens of metres; the absence of suitable marker horizons prevented the interpretation of any macroscopic D2 features. F3 folds are mostly isoclinal, but tight folding of S1-2 is observed in places within the felsic granulites (TR28-141-3). The S3 axial plane is defined by the recrystallization of earlier fabrics into a mylonitic foliation. It is easily distinguished from S1-2 by the presence of a steeply dipping, southwest-trending L3 mineral and stretching lineation within S3. The intensity of recrystallization during D3 is variable on a centimetre to metre scale, but most of the microgranitoids and K-feldspar megacrystic granitoids contain a pervasive S3. Commonly S1-2 in the felsic-mafic granulites has been rotated into sub-parallelism with S3, but zones where S3-L3 fabrics dominate also occur and in places S3 foliation cuts through D2 folds in the granulites (Stewart and Glikson, 1991). The effects of D3 on the Hinckley Gabbro and Michael Hills Gabbro are principally reflected by large-scale upright folds and flextures which predate the mylonitic shear zones. Penetrative deformation is commonly difficult to detect in the massive gabbro.

The S3 foliation dips mostly to the south and L3 plunges mostly to the southwest, but asymmetric movement criteria such as C-S planes (Berth et al., 1979), pressure shadows on porphyroclasts and F3 fold asymmetry gave no consistent sense of displacement. Thus, D3 can only be inferred as involving a southwest-trending axis of compression that resulted in recrystallization under conditions of dominantly simple shear.

D4 event

Rock outcrops in the Champ de Mars area are dissected by a series of overprinting ultramylonite, mylonite and retrograde shear zones (Fig. 6). The earliest ultramylonites form northeast-trending to southeast-trending D4 shear zones (TR28-141-14) that dip steeply northeast and steeply southwest, respectively. A steep, down dip L4 mineral and stretching lineation, trending between 120^{o} and 160^{o} is present in the S4 mylonitic foliation. The D4 zones comprise ten to one hundred metre wide zones of intense recrystallization, with much of the southern margin to the Hinckley Gabbro being defined by a large D4 ultramylonite (TR28-141-23). Mafic dykes provide convenient markers to estimate the throw along individual zones: on the basis of the relationship between S4-L4 and dyke displacement (Fig. 6), the throw of these zones varies between a few metres and a hundred metres or so. No major dislocations are inferred.

The D4 ultramylonites principally contain a well-developed C-planar fabric (after Berth et al., 1979) most commonly defined by alternations in the proportions of quartz and feldspar, with lesser hornblende, biotite, orthopyroxene, clinopyroxene, and ilmenite. The observation of occasional C-S fabrics (after Berth et al., 1979), deflection of the shear zone fabric around porphyroclasts, asymmetric porphyroclasts with recrystallized tails, and any offset of mafic dykes were used to obtain a sense of shear within individual zones that is marked on the map (Fig. 6). The pattern of D4 shear zones is complex, with both north and south-dipping shear zones showing both normal and reverse movement. However, the larger D4 zones dip north and involve a reverse sense of movement, with most smaller zones also dipping north and involving a reverse sense of movement. The inferred transport direction for D4 is thus northwest over southeast (see Table 1).

D5 event

The southern margin to the Hinckley Gabbro in the Champ de Mars area (a D4 ultramylonite) has a stepped nature, which is defined by the margin being consistently displaced by north-trending D5 mylonite and ultramylonite zones that show an apparent dextral sense of shear (Fig. 6; TR27-074-27; TR28-141-23). These D5 shear zones dip steeply to the east and have an L5 mineral and stretching lineation that plunges obliquely with a trend between 025^{o} and 040^{o}. The apparent dextral shear of between fifty and two hundred metres translates into a true southwest-directed reverse throw of a few hundred metres for these D5 zones. As for D4, no major dislocations are inferred. The consistent offset of D4 ultramylonites by D5 shear zones, together the difference in trend of L4 (160^{o}) and L5 (040^{o}), suggests that the two deformation events are distinct.

With the exception of geometry, the D5 ultramylonite zones show similar fabrics to the D4 ultramylonites described above. The D5 shear zones indicate recrystallization under greenschist to amphibolite facies conditions: in sample TR28-143-2A a C-planar foliation comprises quartz, plagioclase, green hornblende/tremolite, zoisite, sphene and calcite. Another D5 shear zone in the vicinity of Walpa-Puka Rockhole changes along strike from a fifty metre-wide quartz-feldspar ultramylonite zone (TR-074-27) into a broad biotite-rich shear zone that contains abundant quartz veins (TR28-141-9). The patchy nature of retrogression along these D5 zones suggest that there was limited introduction of fluids along the zones.

Timing of the D6 and D7 events

Wide (over 500 m), east-trending pseudotachylite-rich ultramylonite zones reflect the latitudinal trend of the Musgrave Block (Forman, 1965). Where these zone cut gabbroic rock, spectacular approximately 200 m wide zones of pseudotachylite-rich rock are observed. Pseudotachylite in these zones shows no clear relationship to any ultramylonite (Glikson and Mernagh, 1990). Where the zones cut felsic orthogneiss or granulite rocks, pseudotachylite occurs less abundantly than in mafic hosts and pseudotachylite shows clear relationships to narrow ultramylonite zones. Ultramylonites in these pseudotachylite zones are poor in hydrous minerals.

Immediately south of Walpa-Puka Rockhole, east-trending, muscovite-quartz-feldspar+/-biotite retrograde shear zones offset the north-trending D5 ultramylonites with a consistent apparent sinistral sense of shear (TR28-141-10,11). A large east-trending retrograde schist zone also forms the northern margin to the Michael Hills Gabbro in the western part of the mapped area, but is poorly exposed. No field relationship was observed to suggest the relative age of the pseudotachylite-bearing ultramylonites with these retrograde shear zones, but their characteristics suggest that they are distinct events. Deformation that resulted in the pseudotachylite zones is interpreted as D6, and the retrograde shear zones are inferred to be evidence of D7.

D6 - the Petermann Orogeny

The Champ de Mars fault (Fig. 6) is one of only two D6 shear zones observed in the area mapped. Where it cuts felsic host rocks (TR28-143-7), all D1-5 fabrics are completely recrystallized by an east-trending, steeply south-dipping quartz+feldspar mylonite to ultramylonite S6 foliation over a distance of several hundred metres (across strike) into the footwall of the pseudotachylite zone within the gabbro. An intense L6 mineral and stretching lineation plunges steeply down-dip and trends approximately due south. Excluding geometry, ultramylonite assemblages and fabrics are similar to those described above for the D4 event, but there are additional quartz-K-feldspar-epidote ultramylonites that are inferred to be produced from recrystallized pegmatite. The main pseudotachylite-bearing ultramylonite zone appears to be south dipping and involved north-directed thrusting (TR28-143-7), but there is no clear pattern of movement sense in the broad recrystallized footwall (TR28-143-9): fabrics that imply normal and reverse movement alternate. These features of the Champ de Mars fault are similar to those reported from north-directed faults such as the Woodrofe thrust (e.g. Bell, 1978) in the central Musgrave Block, produced during the mid-Cambrian Petermann Orogeny (Forman and Shaw, 1973; Maboko, 1988).

D7 event - retrograde shear zones

The D7 shear zones south of Walpa-Puka Rockhole (TR28-141-10,11, Fig. 2) are north dipping and preserve a reverse movement sense. A wide belt of well foliated amphibolite forms the northern margin to the Michael Hills Gabbro; the amphibolite truncates igneous layering in the gabbro on a macroscopic scale (TR28-143-18) and is interpreted as D7 shear zone. Deformation during D7 appears to have reactivated some pre-existing shear zones. In places along the southern margin of the Hinckley Gabbro, muscovite-rich shear zones retrogress the mostly anhydrous D4 ultramylonite fabric (TR27-073-9). Muscovite defines an L5 mineral and stretching lineation, that plunges to the northwest.

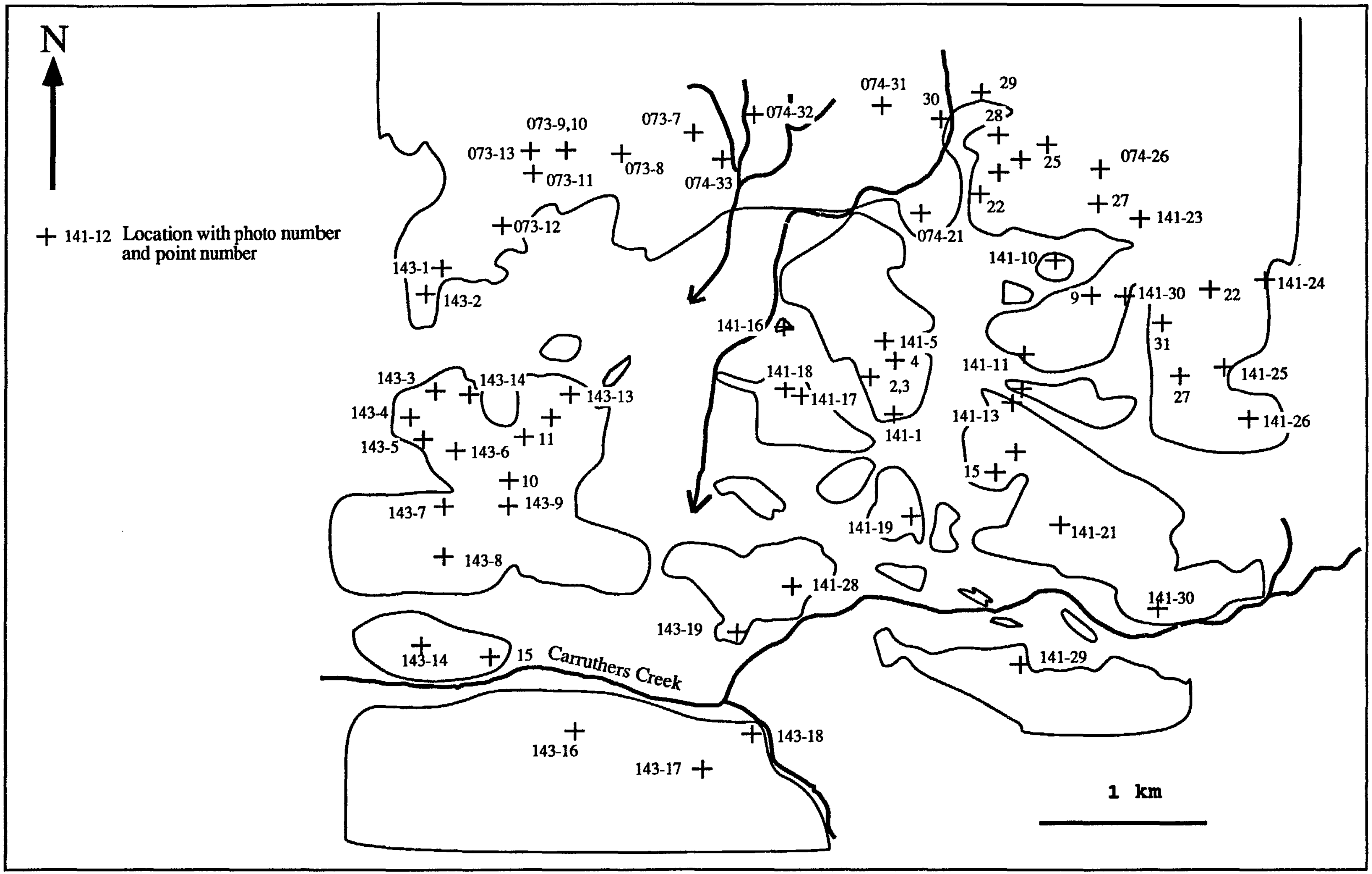

Fig. 2 - Reference and sample location points for the Champ de Mars area (frame A in Fig. 1).

Figure 2

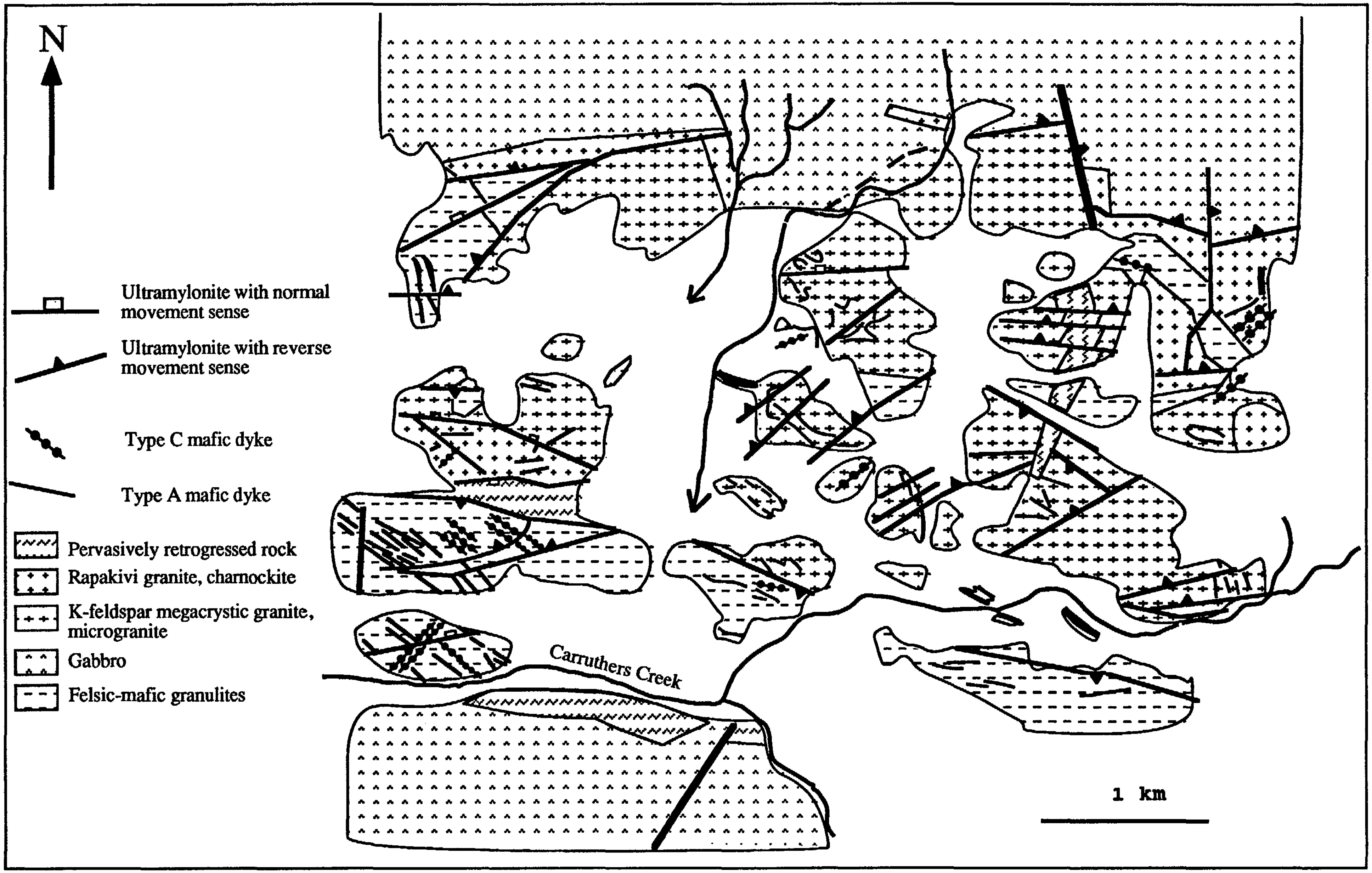

Figure 3

Fig. 3 - A geological map of the Champ de Mars area (frame A in Fig. 1)

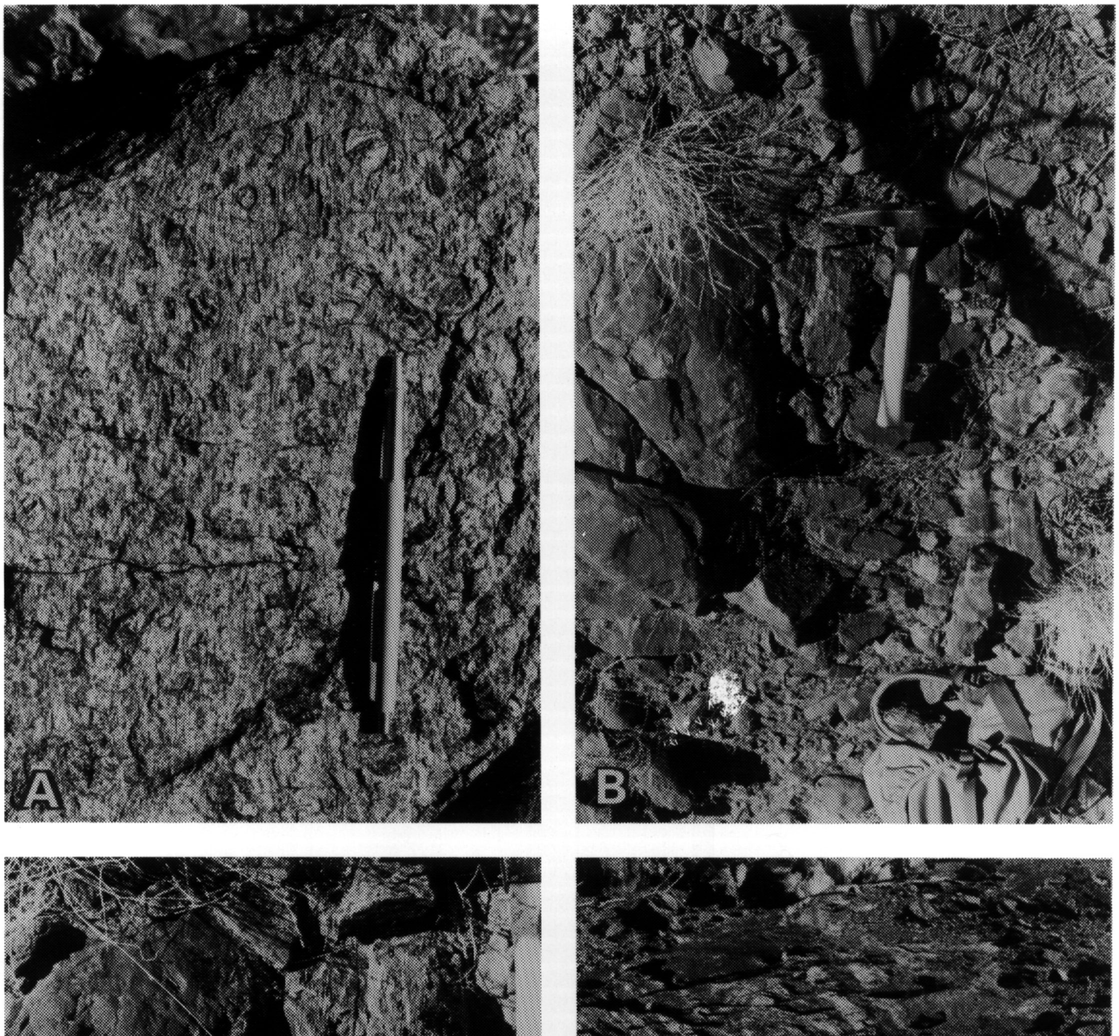

Fig. 4

A –Rapakivi granite with pervasive S3 foliation. Plagioclase forms dark rims around large K-feldspar megacrysts (TR27–74–26);
B –Type A mafic dyke (left of the hammer handle) intruding mafic-felsic granulites (right of the hammer handle). The margin of the dyke has a pervasive S3 foliation, absent at the centre of the dyke.
C –A close-up view of the margin of the dyke shown in Fig. 4b.
D –An isoclinal F3 fold in felsic-mafic granulites (TR27–141–1)

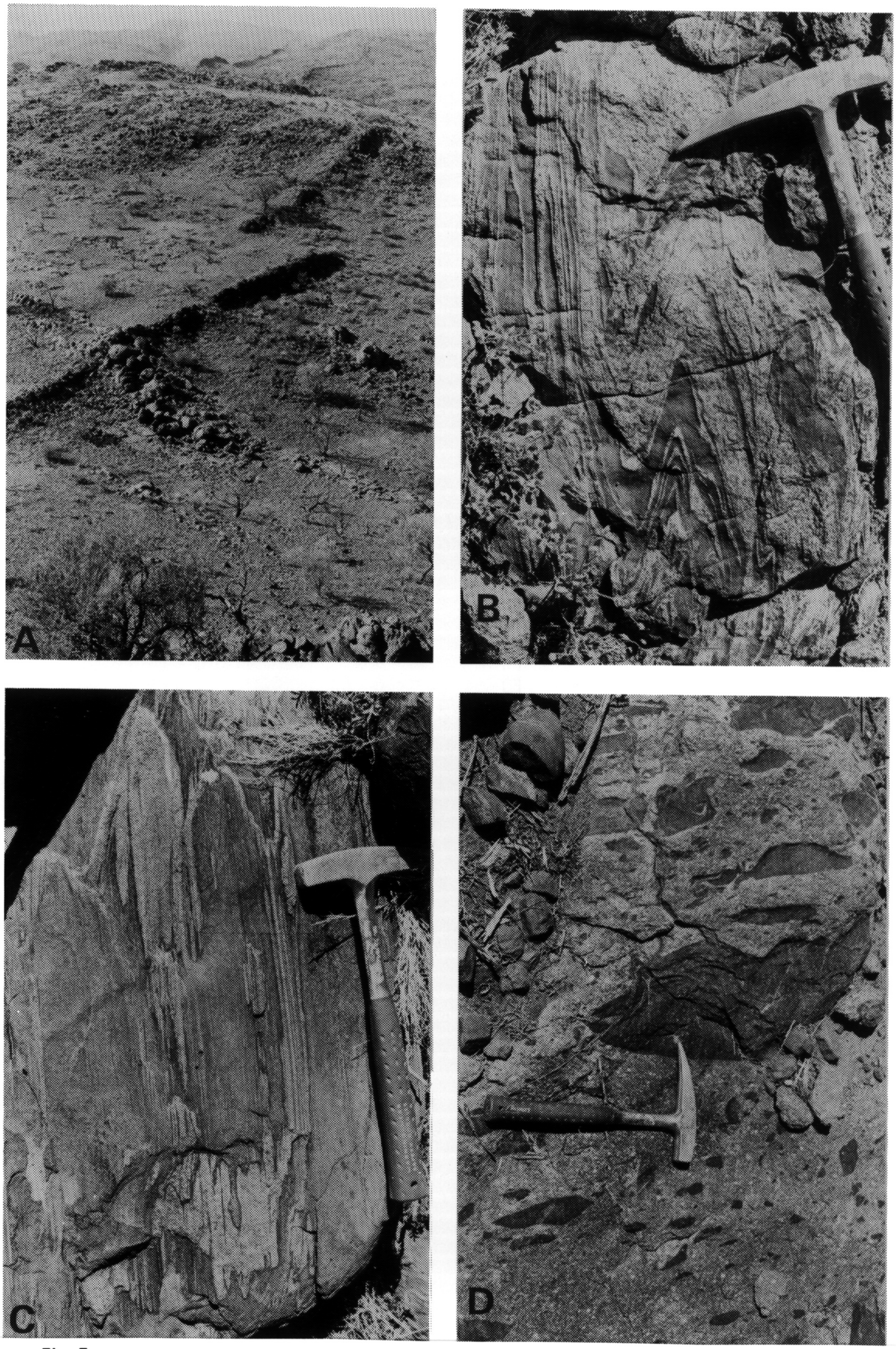

Fig. 5

A –A type B mafic dyke cutting a megacrystic granite dyke (in the foreground). The mafic dyke is offset by a D4 ultramylonite (in the background).

B –An isoclinal F2 fold in layered felsic-mafic granulites (TR27–141–1).

C –Pervasive L2 intersection lineation in layered felsic-mafic granulites (TR27–73–11).

D –A megacrystic felsic dyke with xenoliths of gabbro and recrystallized gabbro (TR25–126–16)

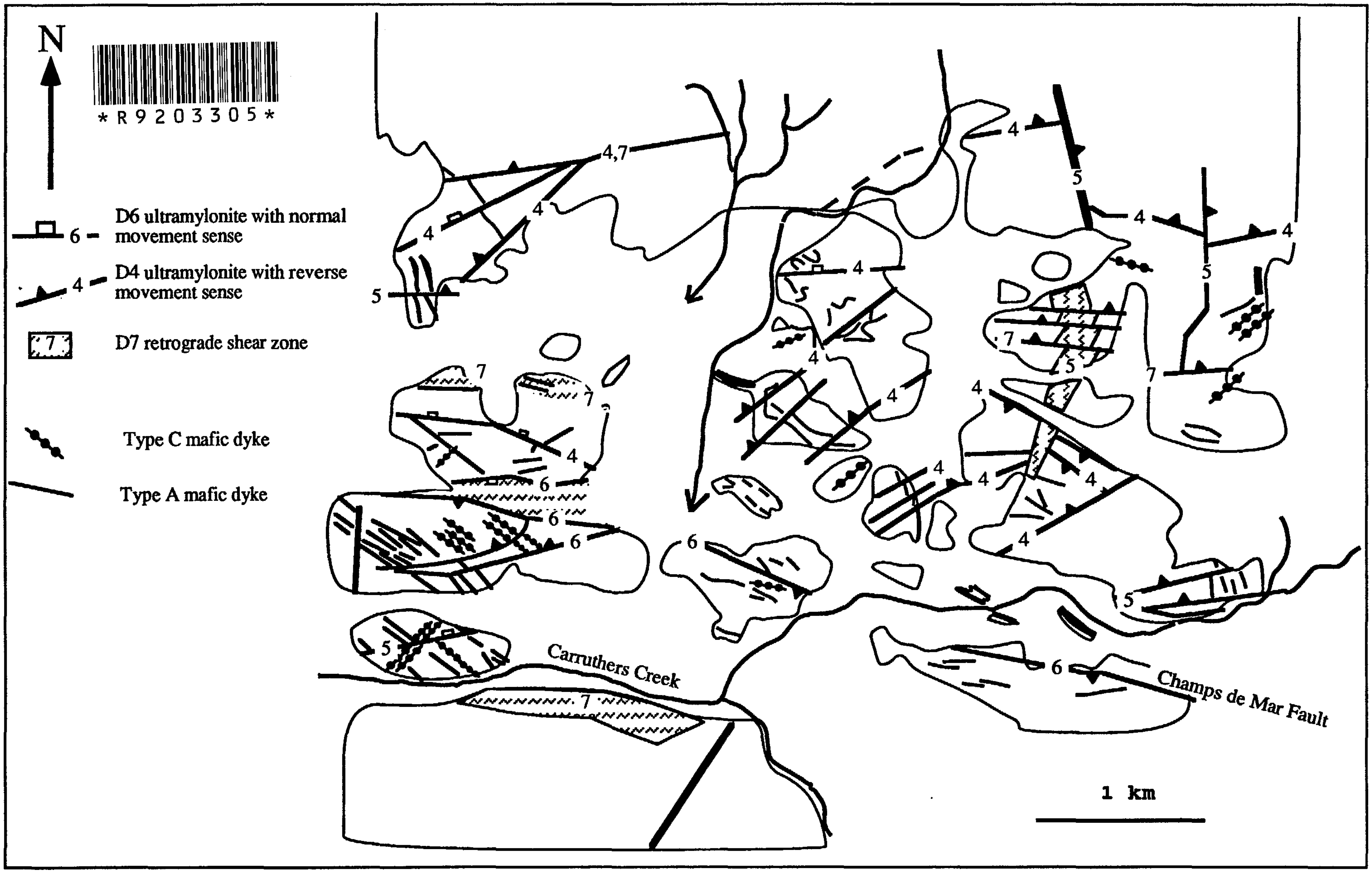

Fig. 6 - Summary of the relationships between dykes and shear zones in the Champ de Mars area (frame A in Fig. 1).

Figure 6

IV. GEOLOGY OF THE WESTERNMOST HINCKLEY RANGE

The westernmost part of the Hinckley Range was selected for mapping because it contained good exposures of what Daniels (1974) interpreted as being a contaminated, marginal phase to the Hinckley Gabbro; these rocks are mostly mafic granulites. The Hinckley Gabbro forms the spine of the west-trending Hinckley Range, and is extensively recrystallized into mafic granulites in which relics of gabbro abound. To the northwest of its westernmost extremity the Hinckley Gabbro is in contact with layered felsic-mafic granulites, and to the south it is flanked by felsic granulites and granitoids (Fig. 1). Immediately to the west of the Hinckley Range are the Charnockite Flats, where exposures of well-layered felsic-mafic granulites occur (Daniels, 1974). The aim of the mapping was to investigate the field relationships between the gabbro, mafic granulites, layered felsic-mafic granulites and granitic veins, concentrating on the mafic granulites that Daniels (1974) mapped as contaminated gabbro. As indicated below, these rocks are recrystallized gabbro and to avoid confusion with the older layered felsic-mafic granulites, they will be referred to as mafic granulites.

The structural history inferred for the west Hinckley area is identical to that described above for the Champ de Mars area. Sample localities are shown in Fig. 7 and the geology summarized in Fig. 8.

IV.1 Field relationships

The oldest rocks are well-layered felsic-mafic granulites cropping out in the Charnockite Flats area (TR24-142-8), which predate all other rock units and preserve evidence of two deformation events, D1-2. Mafic granulites interlayered with felsic granulite in this area are distinguished from the mafic granulite (recrystallized gabbro) that occurs in the westermost Hinckley Range; the former predates intrusion of the Hinckley Gabbro and contains S1 and S2 foliations, whereas the latter includes relict gabbro and contains only S3 foliation. Charnockitic gneiss and small amounts of metasedimentary rocks are interlayered with the felsic-mafic granulites. Pods of charnockitic gneiss in the area may cut S1, and are thereby interpreted to have intruded between D1 and D2. As in the Champ de Mars area, K-feldspar megacrystic and microgranitoid stocks and dykes intrude these felsic-mafic granulites (TR24-142-23, TR24-142-17).

Mafic rocks comprising the Hinckley Gabbro intrude the layered felsic-mafic granulites, and a primary intrusive contact is inferred at the western end of the Hinckley Range (TR24-141-3). Daniels (1974) regarded mafic granulites of the western Hinckley Range as a "contaminated gabbro" facies. The mafic granulites contain residual pods of gabbro and are intensely foliated by S3 fabric (TR24-141-9, TR25-126-13, 24). The gabbro pods are mostly undeformed, retain coarse-grained igneous textures easily recognized in hand specimen, and occur on a range of scales. Pods 100 m or more in diameter have a distinctive, flat expression on the colour aerial photographs due to a vegetation anomaly involving spinifex and or bluebush (TR24-142-24). Numerous gabbro relics have been photo-interpreted and confirmed by field checking (Fig. 8). Gabbro pods up to one metre in diameter occur as isolated bouldery outcrops within the heterogeneous felsic veined mafic granulite which form smoother outcrops (TR25-126-15). The small scale of these relics and their gradational relations with the surrounding mafic granulites complicate their systematic mapping.

Whereas intrusion of granitoid into the Hinckley Gabbro is confined to the margins in the Champ de Mars area, in the west Hinckley Range abundant dykes and stocks of K-feldspar megacrystic granitoid and microgranite cut mafic granulite and residual pods of gabbro on all scales (TR25-126-24; Fig. 8). Large dykes of granitoid (over 5 m across strike) are readily distinguished on aerial photographs due to their light colour, but numerous smaller dykes occur on outcrop scale and veins on hand-specimen scale. Many granitoid bodies show gradational contact with the surrounding heterogeneous rock. Common angular xenoliths of foliated amphibolite in weakly deformed granitoid are interpreted to be recrystallized gabbro (TR25-126-16; Fig. 5d). The intensely S3 foliated granite-veined mafic granulite envelopes bodies of gabbro and amphibolite, and has a banded, streaky expression on the colour aerial photographs due to its intensely S3 foliated nature. Compositional variations occur on the 1-100 m scale.

At the western end of the Hinckley Range, pods of gabbro and mafic granulite (recrystallized gabbro) are tectonically interleaved with older layered felsic-mafic granulites. Where gabbroic relics are absent, the distinction between granite-veined gabbro-derived mafic granulite on the one hand and the older banded mafic-felsic granulites on the other hand is extremely difficult. Occurrences of thin, laterally-persistent feldspar-rich and pyroxene-rich S1 gneissic layers gives outcrops of the layered felsic-mafic granulites a flaggy appearance that the mafic granulite (recrystallized gabbro) lacks. This flaggy habit is moderated by the presence of F2 folds, which commonly have amplitudes of 10 to 30 cm. The layered felsic-mafic granulites are compositionally monotonous with thin laterally continuous feldspathic segregations; the mafic granulite (recrystallized gabbro) is compositionally heterogeneous with discontinuous, vein-like feldspathic segregations. Whereas the pervasive S1-2 foliation in the layered felsic-mafic granulites contains no mineral lineation, the mafic granulite (recrystallized gabbro) always contains a pervasive L3-S3 fabric. Where the diagnostic significance of the above features may be ambiguous, and many outcrops are difficult to assign, the occurrence of residual gabbro pods offers a reliable criterion for identification of the younger generation mafic granulite.

Recrystallized Type A mafic dykes are less common than in the Champ de Mars area, but are observed intruding K-feldspar megacrystic granitoid (TR24-142-26). S3 defines the structural grain to geology in the west Hinckley Range; it is cut by large (over 2 m wide) coarse-grained northwest-trending Type B dykes and smaller northeast-trending fine-grained to aphanitic Type C dykes. Numerous east-trending to northeast-trending D4 ultramylonites form prominent shear zones that show a consistent southeast-directed thrust movement (TR25-126-17).

IV.2 Lithological assemblages

Layered felsic-mafic granulites

In the Charnockite Flats area, gneisses include two-pyroxene mafic granulites and interlayered felsic granulite. Granulites with a well developed banding appear migmatitic in parts of the area (TR24-142-11,12). They comprise fine-grained, pervasively S1-foliated mesosome comprising orthopyroxene, clinopyroxene (possibly some pigeonite), biotite, plagioclase quartz and opaques, alternating with coarse-grained, poorly foliated leucosomes comprising orthopyroxene, clinopyroxene, plagioclase, K-feldspar, quartz and opaques (TR24-142-11). In places, the mesosome occurs as boudins or xenoliths within the leucosome, with S1 truncated at the margins of the mesosome (TR24-142-11A). The leucosomes are rich in quartz and K-feldspar, poor in clinopyroxene and are compositionally incompatible with partial melting of the mesosome. Leucosomes may occur as larger bodies, locally cross-cutting, within the layered felsic-mafic granulites and are interpreted as offshoots of the nearby charnockitic gneiss (TR24-142-13), noting that the latter also lack the S1 gneissosity. The layer-parallel disposition of the charnockites may be explained by deformation during D2. Minor quartzite and amphibolite (TR24-142-24) occur within the felsic-mafic granulites, indicating metasedimentary precursors to part of the layered granulite sequence, as inferred by Daniels (1974) for the well banded largely felsic granulites of Mount Aloysius (Gray, 1977; Stewart and Glikson, 1991) (Fig. 1), with which the Charnockite Flats layered felsic-mafic granulites are correlated.

The Hinckley Gabbro

Bodies of coarse-grained gabbro are widespread within mafic granulite (recrystallized gabbro) in the west Hinckley Range (Fig. 8), preserving igneous textures, including primary igneous layering. Where S3 is not well developed, these bodies commonly retain an ophitic texture defined by coarse-grained (over 2 mm), zoned and simply twinned, inter-digitating plagioclase grains, with subordinate fine-grained (0.1 mm diameter) pyroxene (TR24-141-15). In most places the contacts of the gabbro bodies have been extensively modified by later deformation, but a primary intrusive contact is inferred near the westernmost margin of the Hinckley Range (TR24-141-3). Northwest of the contact are banded felsic/mafic granulite with thin, discontinuous horizons of quartzite, intruded by granitoid dykes (Fig. 8). Southeast of the mapped gabbro contact, over a distance of about 100 m, isolated angular fragments of felsic and mafic granulite 30 cm to 3 m across occur within undefomed gabbro. Foliations within the fragments are truncated by sharp contacts with the gabbro host, or by extensively recrystallized margins to the fragments. Felsic stringers attached to the fragments cut surrounding gabbroic rock.

The above features are interpreted in terms of the fragments being xenoliths of felsic-mafic granulite within the gabbroic intrusion. Recrystallization and partial melting of the xenoliths could have been related to heat conduction from, and contact effects of, the gabbro magma, accounting for the felsic stringers and recrystallized margins. These features are less likely to have arisen during D3 recrystallization of gabbro and granite veins, in view of the angular nature of the fragments and the truncation of structural fabrics. The gabbro shows minimal recrystallization, in contrast to the extensive recrystallization and gradational relations which characterize the mafic granulites (recrystallized gabbro) elsewhere. The field relationships between the gabbro, mafic granulites and granite veins systems have been interpreted by Daniels (1974) in terms of contamination of the gabbroic magmas by felsic wall rocks (see below).

Near their margins the gabboic bodies are cut by K-feldspar-rich veins and stringers (Figs 9a, 9b) that are surrounded by a narrow zone of alteration/recrystallization. This alteration involves hydration of the gabbro and recrystallization to a two pyroxene-bearing mafic granulite, with or without hornblende. Sample TR25-126-25A is an undeformed granite vein intruding gabbro that preserves an igneous fabric. The granite vein comprises quartz and microcline (with myrmekite). Piokiloblastic plates of orthopyroxene and clinopyroxene, together with interdigitating plagioclase laths preserve the igneous fabric in the surrounding gabbro. However, aggregates of hornblende, ilmenite (with minor hematite exsolution) and secondary orthopyroxene pseudomorph some clinopyroxene grains, and grains of biotite and hornblende occur, showing no orientation and partially pseudomorphing some pyroxene grains. The size and density of the feldspathic stringers increase toward the margin of the gabbro (Fig. 9c) until the only mafic rock that can be recognized is a recrystallized secondary mafic granulite containing an intense S3 foliation.

Granitoid intrusions

Only one large felsic granitoid stock occurs in the area mapped in detail (TR24-142-23). This granitoid intrudes felsic-mafic granulites at Charnockite Flats: it is megacrystic with K-feldspar and shows features identical to stocks in the Champ de Mars area. Rocks in the west Hinckley Range are pervasively intruded by K-feldspar megacrystic and microgranite dykes, that vary in width from a few centimetres to more than fifty metres. In places (TR25-126-29), several large dykes have coalesced to form small granitoid stocks. The dykes were all pervasively recrystallized during D3, and most are now aligned with the southeast-trending S3. One sample (TR24-141-22D) of microgranitoid comprises S3 quartz, antiperthite, perthite, orthopyroxene and ilmenite with minor biotite. This agrees with the occurrence of altered orthopyroxene in Champ de Mars granitoids.

Rrecrystallized gabbro/mafic granulite

Mafic granulite (recrystallized gabbro) penetratively cut by felsic stringers (Figs 9c, 9d) is the dominant rock type in the western Hinckley Range. The stringers vary from a centimetre or less across to granitoid dykes more than 50 m wide, and are usually intensely recrystallized by S3. Where thin felsic stringers occur in a mafic host, a discontinuous S3 gneissic layering is developed by alternations of mafic and felsic rock (Figs 9c, 9d). In areas minimally affected by recrystallization during D3, gabbro is cut by undeformed K-feldspar+quartz-rich stringers (Figs 9a, 9b), or mixtures of felsic and mafic rock are observed with unusual textures. Such areas of low D3 strain are enveloped by mafic granulite (recrystallized gabbro), and there is a gradational variation from one rock type to the other. The mafic granulite (recrystallized gabbro; e.g. TR24-141-15B) commonly comprise a fine-grained (0.5 mm) recrystallized assemblage of hypersthene, clinopyroxene plagioclase, biotite, opaques and quartz. These minerals define a mylonitic S3 foliation (Fig. 9e) that envelopes coarse-grained (2mm diameter) orthopyroxene and clinopyroxene grains that have rutile and opaque minerals aligned in cleavage traces; these minerals, together with large simply twinned plagioclase grains, are interpreted as residual relict igneous grains. The mafic granulite (recrystallized gabbro) is more fine-grained than the layered felsic-mafic granulites, and generally does not have a well-developed gneissic layering. It also shows gradational contacts with large granitoid dykes, and inclusions of mafic granulite and amphibolite occur in pervasively foliated granite dykes (Fig. 5d).

These observations are best explained by the recrystallization of gabbroic rock that was pervasively infiltrated and veined by granite dykes and stringers prior to D3 (cf. Daniels, 1974). Although the mafic granulite (recrystallized gabbro) is grossly heterogeneous on a metre to tens of metres scale (due to local variations in the density of felsic veins or the intensity of S3), the mapped units are homogeneous on a 100 m scale. With few exceptions, the material infiltrating the gabbro consists of K-feldspar megacrystic granite or microgranite dykes. Daniels (1974) interpreted the origin of the felsic-veined mafic granulite as involving the contamination of gabbroic magma by partial assimilation of felsic country rock. However, such a model is in conflict with evidence indicating intrusion of granitic veins into brittle fractured gabbro, with occurrence of angular gabbro fragments in the granite and with the generally good distinction between gabbro and felsic veins. By contrast, granitic magmas intruding the gabbro may be locally contaminated with basic material (see below).

Mafic dykes

Mafic dykes identical to those identified as Type A and Type C in the Champ de Mars area are observed in the west Hinckley Range. Type C dykes in the west Hinckley Range are mostly northeast-trending. Coarse-grained northeast-trending mafic dykes with a clear ophitic texture in hand specimen cut S3 but are displaced by D4 ultramylonites (Fig. 5a). Type B dykes are wide (approximately 3-5 m across) and fresh in outcrop, with interlocking plagioclase laths up to 1 cm in length, and may be recrystallized along dyke margins. They are texturally distinct from the distinctly post-metamorphic fine-grained to aphanitic Type C dykes, which are also usually much narrower (1-2 m wide).

IV.3 Structural geology

D1-2 interference structures

The Charnockite Flats area includes the only recognizable macroscopic marker horizons observed within the mafic-felsic granulites in the westernmost Hinckley Range. With the exception of a charnockite unit, all the rocks are very well layered and a pervasive S1 gneissosity is deformed by common isoclinal F2 folds that plunge shallowly toward between 110^{o} - 130^{o}. At locality TR24-142-20, S2 dips 15^{o} toward 065^{o}, with F2-L2 plunging 15^{o} toward 105^{o}. Type 2 mesoscopic F1-F2 fold interference patterns (after Ramsay, 1962) are recognized at one locality (TR24-142-10). Intrafolial isoclinal F1 folds are refolded by tight to isoclinal F2 folds. The interference pattern can be identified as involving F1-F2 where this pattern is locally cut by a post-D2 pre-D3 microgranite dyke. A pervasive L2 intersection lineation is marked by the isoclinal F2 hinges that transpose S1 into S2.

The structure of the main eastern hill in the Charnockite Flats area (Fig. 8) is a macroscopic, reclined F2 antiform, with S1 tracing around the U-shaped hill. The western and southern flanks of the hill are unusual because they have not been significantly affected by D3, and S2 dips shallowly to the east. Although the northeastern flank of the hill has been disrupted by later deformation, the major F2 structure is defined by the following units. The core of a macroscopic antiform is marked by a massive charnockite (TR24-142-13), which lacks the S1 gneissosity that is pervasive in surrounding granulites. The charnockite could be a post-S1 intrusive, but due to the intensity of recrystallization during D2 any grossly transgressive contacts would have been destroyed. However, enclosing the charnockite are intermediate to mafic granulites (TR24-142-12) that have a banded migmatitic appearance. As outlined above, these "migmatites" represent two rock types with the leucosomes explained as apophyses and stringers intruded from the charnockite body. Intrusion is constrained to be between D1 and D2. This "migmatitic" unit is enclosed by banded mafic granulite (TR24-142-11).

The absence of the intense S1 gneissosity in this charnockite gives the rocks a massive outcrop habit. Daniels (1974, p.34) has suggested that the banded granulites rest unconformably on the massive granulites. However, this is not confirmed and the massive granulites are regarded as intrusives which postdate the banded granulites and D1. Further resolution of these relationships requires isotopic data.

D3 event

A southeast-trending mylonitic S3 fabric pervades the basic granulites and granitic veins of the west Hinckley Range, and is defined by tight to isoclinal F3 folding of the granite veins and stringers and by a granoblastic texture of two-pyroxene S3 assemblages in the mafic granulite. With rare exceptions, the larger granite dykes also contain a pervasive S3. However, whereas intense D3 foliation and S3-L3 mylonites to ultramylonites are widespread, no consistent sense of displacement was recognized.

D4 and D5 events

Large, east-northeast-trending D4 ultramylonite zones, with a consistent apparent sinistral sense of shear, cut the West Hinckley Range (Fig. 10). The shear zones dip to the northwest, have a steep down-dip mineral and stretching lineation and record a reverse sense of shear (TR25-126-17). They imply southeast-directed movement for D4, consistent with the movement direction inferred for the Champ de Mars area. In granitic rocks and granulites, the D4 shear zones are marked by wide (25-50 m) zones of intense recrystallization that can be recognized on the aerial photograph. However, when the zone is traced into gabbro or gabbro-derived mafic granulite, the width of the shear zone reduces dramatically and may be impossible to trace. Strain is partitioned into significantly smaller zones in the more competent mafic rocks. Several of the shear zones show significant drag-related re-orientation of S1-3, such that S1 and S2 in layered felsic-mafic granulites (TR24-140-7) and S3 in mafic granulite (recrystallized gabbro) and related lithologies (TR24-141-6, 7) are elongated parallel to S4. East-trending D5 shear zones cut D4 ultramylonites in the southern part of the Charnockite Flats area (TR24-142-9, 16). Retrogression of the surrounding felsic-mafic granulites accompanied formation of these shear zones, which contain (TR24-142-9A, 9B) S5 chlorite, sericite and calcite pseudomorphing original plagioclase and pyroxene.

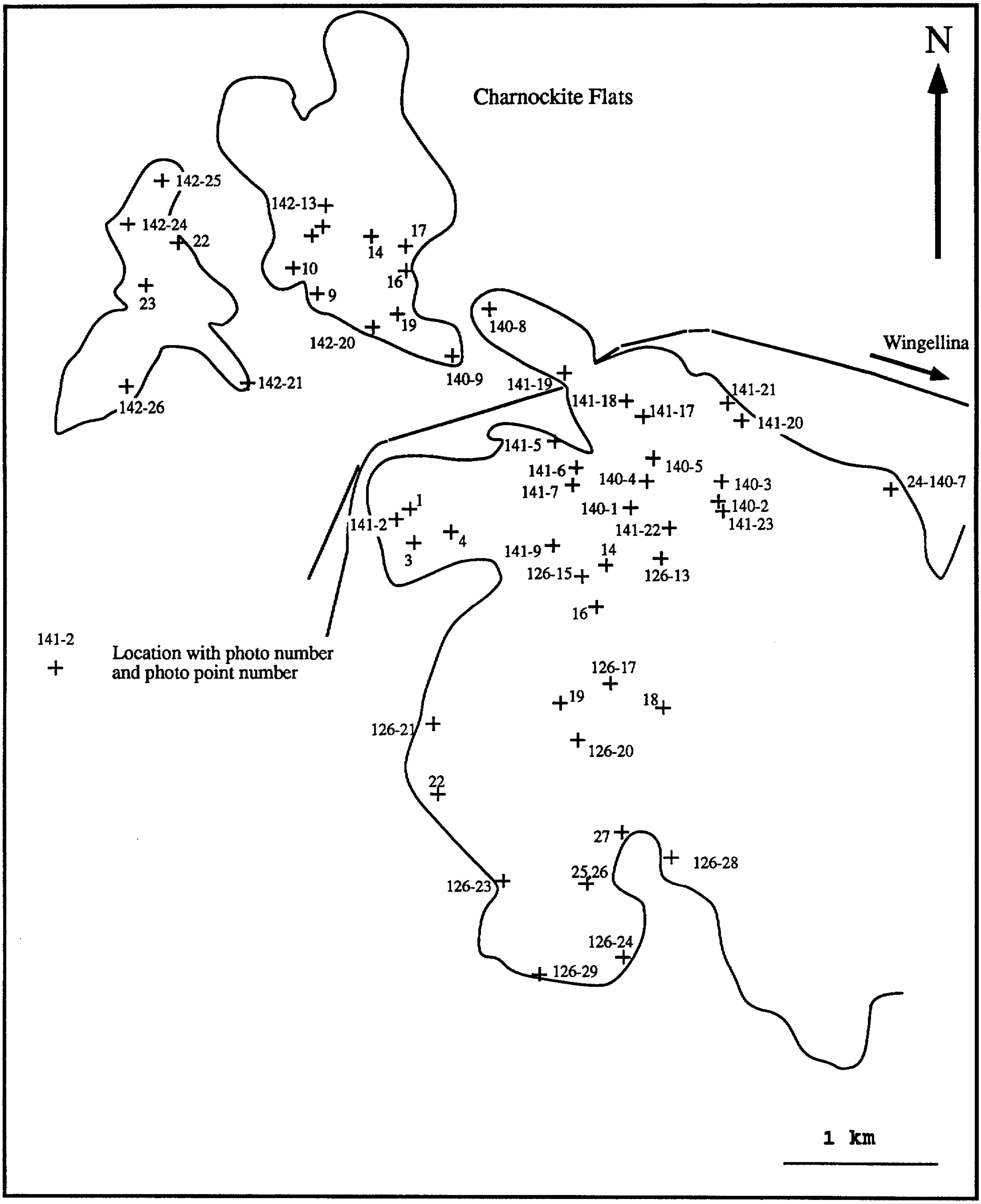

Fig. 7 - Reference and sample locations points for the western most Hinckley Range study area (frame B in Fig. 1).

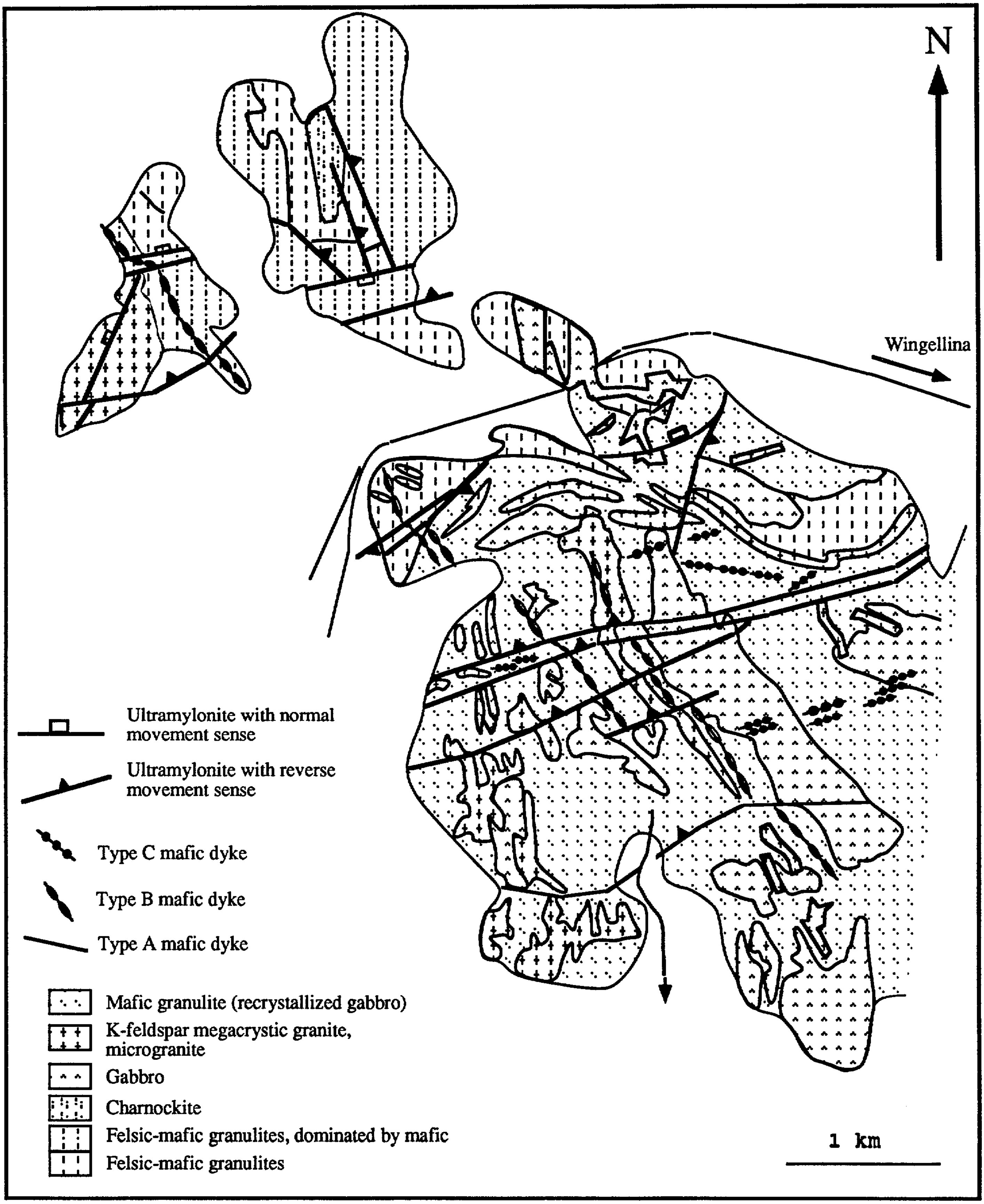

Fig. 8 - Geological map of a study area in the westernmost Hinckley Range (frame B in Fig. 1).

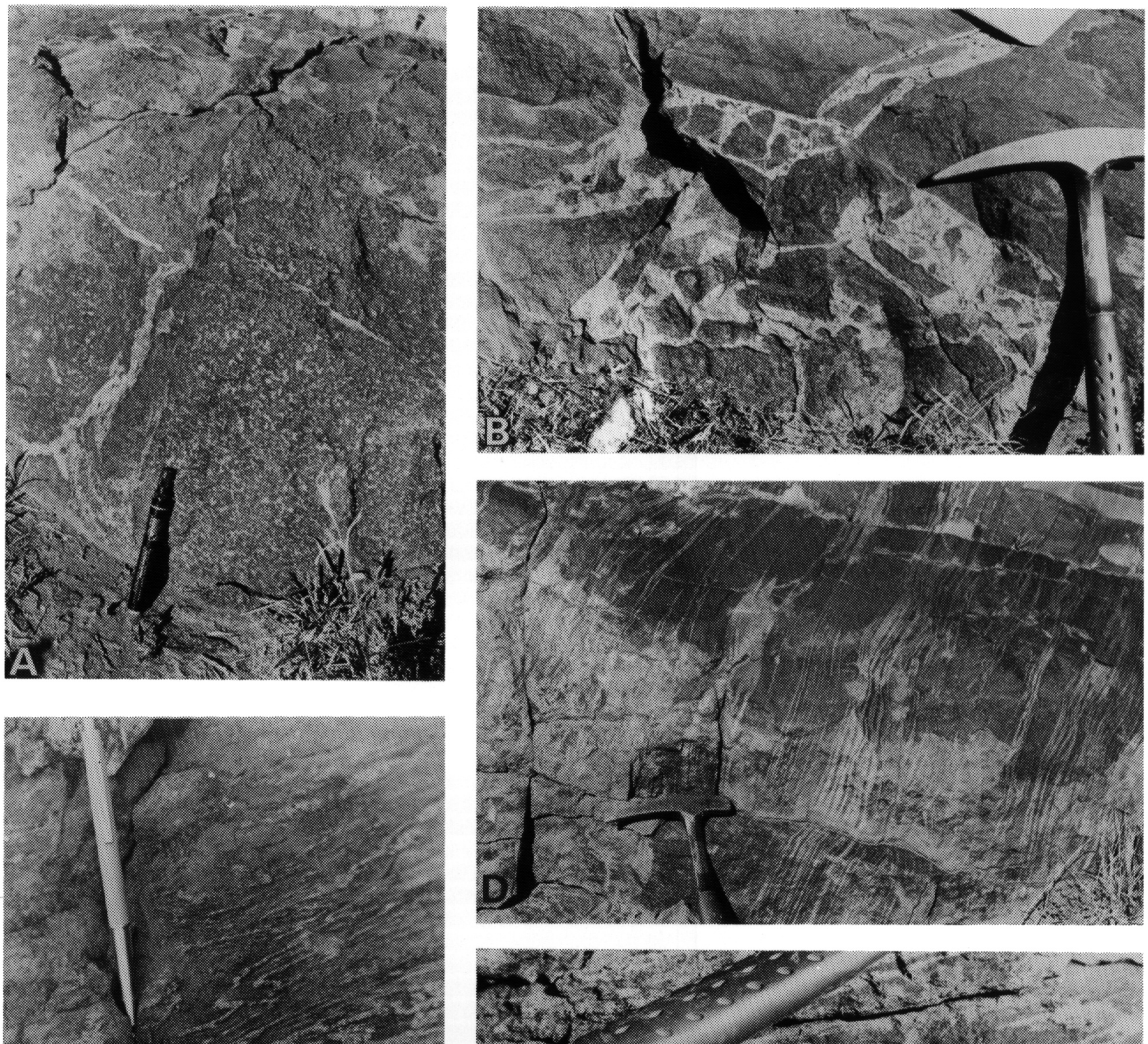

Fig. 9

A –Gabbro cut by granitic veins (TR25–126–20).
B –Gabbro cut by granitic veins (TR25–126–25).
C –Mafic granulite (recrystallized gabbro) with well developed S3 fabric defined by discontinuous granitic stringers (TR25–126–17).
DE-A close-up view of S3 fabric in mafic granulite (recrystalled gabbro) showing the discontinuous nature of the feldspathic stringers that define S3 (TR25–126–17).

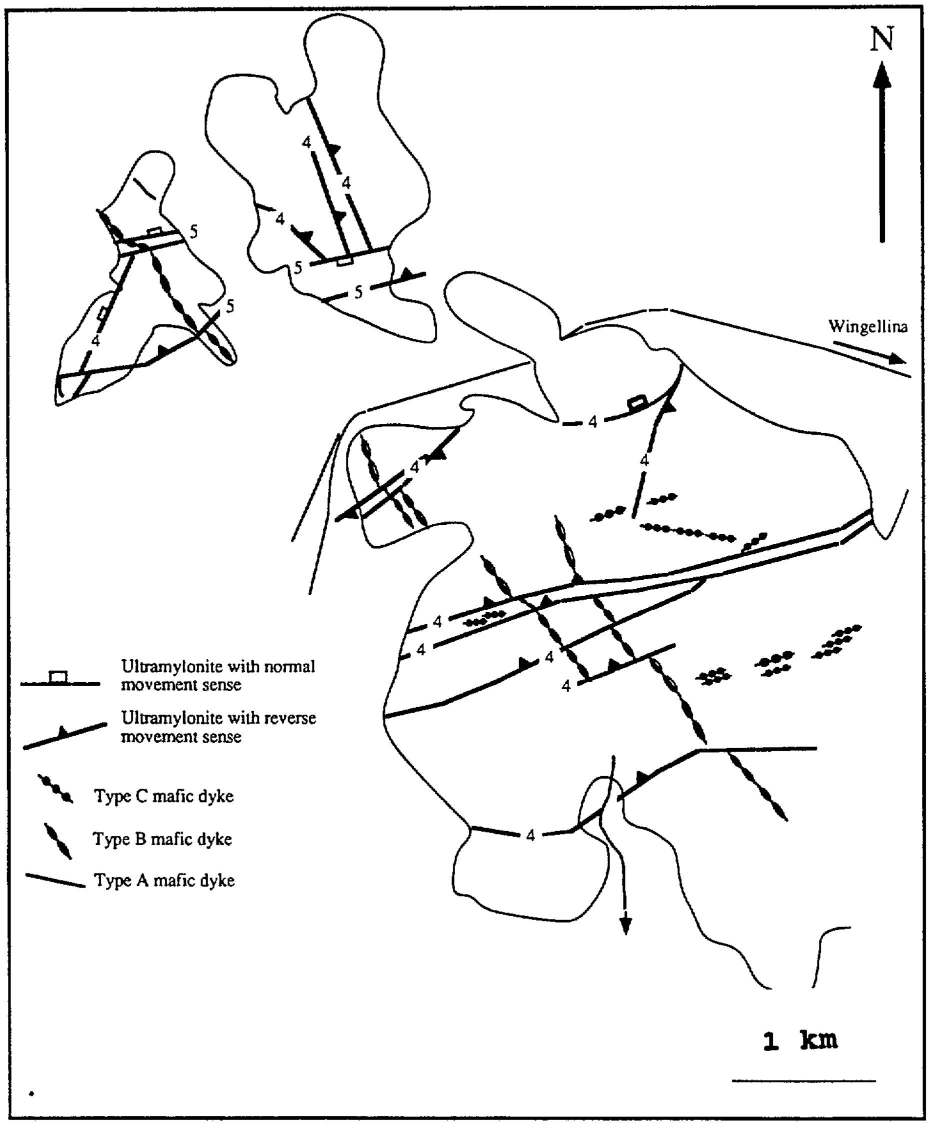

Fig. 10 - A summary of the relationships between dykes and shear zones in the western Hinckley Range study area (frame B in Fig. 1).

V. SYNTHESIS

The current concept on the relationships between the main geological units and tectonic elements in the two test areas is portrayed in a block diagram (Fig. 11) and in Table 1. Well-layered felsic-mafic granulites, which include discontinuous quartzite and garnet+sillimanite-bearing metapelitic horizons, comprise the oldest rocks in Champ de Mars area and west Hinckley Range. Similar rocks in the Tomkinson Ranges have given whole-rock Rb-Sr ages of 1564+/-12 and 1327+/-7 Ma, interpreted as protolith ages of the gneisses (Gray 1971, 1977). These ages are confirmed by preliminary U-Pb dating of zircons using the SHRIMP at ANU (S-S. Sun, pers. comm., 1992). The layered granulites preserve evidence of two deformation events, D1 and D2, contemporaneous with granulite facies metamorphism. Peak metamorphism, marked by the formation of S1, is estimated as involving pressures a little over 7 kbar, on the basis of revised estimates for intrusion of the Giles Complex (Ballhaus and Berry, 1991). Such pressures are supported by the absence of reported occurrences of orthopyroxene+sillimanite, which would be expected in metapelitic rocks at higher pressures (e.g. Hensen, 1971; Norman and Clarke, 1990). Detailed microprobe work on appropriate samples is presently being undertaken by the author in order to test this interpretation. The zoning profiles in garnet within metapelitic assemblages at Cohn Hill, westernmost Musgrave Block (Clarke and Powell, 1991), suggests a minimum temperature of 750^{o}.

In the Champ de Mars area and west Hinckley Range, the common occurrence of large, simply twinned and zoned feldspar grains in the layered felsic-mafic granulites suggests that many of these rocks could be derived from pre-D1 gabbroic sills and/or dykes and felsic intrusions. Some felsic granulites, including charnockitic gneiss, cut S1 but are intersected by S2, suggesting intrusion between D1 and D2. Although any grossly discordant intrusive contacts were destroyed by recrystallization during D2, injection of K-feldspar+quartz-rich stringers and veins of felsic granulite into mafic granulites occurred on all scales. The montonous nature of some of the layered felsic-mafic granulites suggests that these rocks may have been derived from igneous precursors (see also Daniels, 1974).

D2 resulted in mesoscopic to macroscopic isoclinal reclined F2 folds with an axial planar foliation, S2, which is the pervasive gneissosity in the felsic-mafic granulites. S2 can be correlated with the regional S1 gneissosity of Nesbitt et al. (1970) and Moore and Goode (1978), who did not define S1 as designated in this report. S1 is equivalent to the S1F described by Pharaoh

(1991; Table 1). D2 involved mostly pure shear, with only a small component of rotational strain, and resulted in shallowly-dipping or recumbent structures. The principal axis of compression during D2 was close to vertical, accounted for by the weight of overlying rock column near the base of continental crust of stable thickness (see Wells, 1978). This style of deformation, apparent for both S1 and S2, typical of high grade metamorphic terrains, does not easily fit with models of deformation associated with continental collision.

The emplacement of large mafic to ultramafic layered intrusions, comprising the Hinckley and Michael Hills Gabbros, post-dated D2, since undeformed gabbro truncates the S2 foliation of layered felsic-mafic granulites. Emplacement of the gabbroic magmas occurred under elevated pressures, as indicated by replacement of olivine by orthopyroxene on the liquidus, by unusually high proportion of Tschermaks molecule in magmatic pyroxenes, and the subsolidus breakdown of olivine and plagioclase to spinel/pyroxene symplectites (Nesbitt et al., 1970; Moore, 1971; Goode and Moore, 1975; Ballhaus and Berry, 1991; cf. Daniels, 1974). The lack of chilled margins and the gradational relationships between the layered intrusions and country rocks suggests that the latter were still at temperatures well above the stable continental geotherm. The most recent work suggests that intrusion occurred whilst the terrain was at depths equivalent to 6+/-1 kbar, and that these rocks cooled under such pressures (Ballhaus and Berry, 1991).

Areally-extensive granitoids, including microgranitoid and K-feldspar megacrystic granitoid dykes and stocks, intrude both the layered felsic-mafic granulites and the Hinckley Gabbro. Bodies of rapakivi granite, charnockite and mafic inclusion-rich granite are observed near contacts between gabbro and the granitoids. These rocks show gradational relationships with granitoid bodies distal from the contact, and are interpreted to have involved contamination of the felsic magma by partial assimilation of gabbroic material.

Recrystallized Type A mafic dykes cut all of the above rock types, including the felsic components, and therefore cannot represent feeders of the main phase of Giles Complex, but they are affected by mylonitic S3 foliation. Although these dykes are extensively recrystallized, relic igneous plagsioclase phenocrysts may be retained (J.W. Sheraton, pers. comm., 1992). The D3 event resulted in an impersistent, steep southeast-trending S3 foliation with a well-developed down-dip stretching lineation. Type A mafic dykes show marginal to complete recrystallization to granulite facies mylonitic S3 assemblages. In general, due to its massive and dry nature, large parts of the Giles Complex gabbro is little affected by D3 fabrics. In the west Hinckley Range, the Hinckley Gabbro is extensively intruded by granite dykes and D3 resulted in recrystallization of gabbro to mafic granulite.

On the basis of the above features, granulite facies condition-sprevailed at the time of D3 in the west Hinckley Range. Pressure conditions during D3 can be qualitatively inferred from corona textures in metapelitic gneisses from Cohn Hill in the western part of COOPER 1:250 000 sheet. At this locality, S3-related spinel plus cordierite coronas to garnet suggest that D3 occurred under pressures of 4-5 kbars (Clarke and Powell, 1990). Similar corona textures involving garnet, sillimanite and spinel are observed in metapelitic gneisses surrounding Ewarara and Gosse Pile in the Tomkinson Ranges (Moore, 1969), suggesting that similar pressure estimates are appropriate for D3 assemblages in this area. Thus, decompression of the granulites of the Musgrave Block from peak pressures of 7 kbar during D1-2 and during the emplacement of the Giles Complex (Ballhaus and Berry, 1991) to pressures of 4-5 kbar during D3 is inferred. Since spinel-bearing assemblages require elevated temperatures of at least 700^{o} (see Clarke and Powell, 1991), a near-isothermal uplift is implied. This trend contrasts with the isobaric cooling of the Giles Complex suggested by Ballhaus and Berry (1991), and it is suggested that the uplift has therefore postdated emplacement of the Giles Complex. Further work is required to refine estimates of P and T for the various events of recrystallization.

In contrast to Type A dykes, which are affected by D3, Coarse-grained Type B mafic dykes and aphanitic Type C mafic dykes postdate S3. It is possible Type B dykes are comagmatic with the Bentley Supergroup, which rests unconformably on the granulite-gneiss terrain west of the Hinckley Range (Daniels, 1974), whereas Type-C dykes postdate metamorphism and are ≈1000 Myr old (S. Sun, pers. comm., 1992). Both dyke swarms are deformed by steep east-trending D4 ultramylonites that preserve evidence of south-east-directed deformation. D4 ultramylonites with either normal or reverse movement are observed; these zones form the boundaries of the Hinckley Gabbro, and are cut by steep north-trending D5 ultramylonites that preserve southwest-directed deformation. D4 and D5 ultramylonite zones contain mineral assemblages that imply greenschist to amphibolite facies conditions, suggesting that the terrain had cooled considerably between the D3 and D4 events. Individual D4 and D5 zones in the Champ de Mars area and west Hinckley Range involved maximum displacements of several hundred metres, and significant uplift and/or significant dissection of the terrain did not occur along these shear zones.

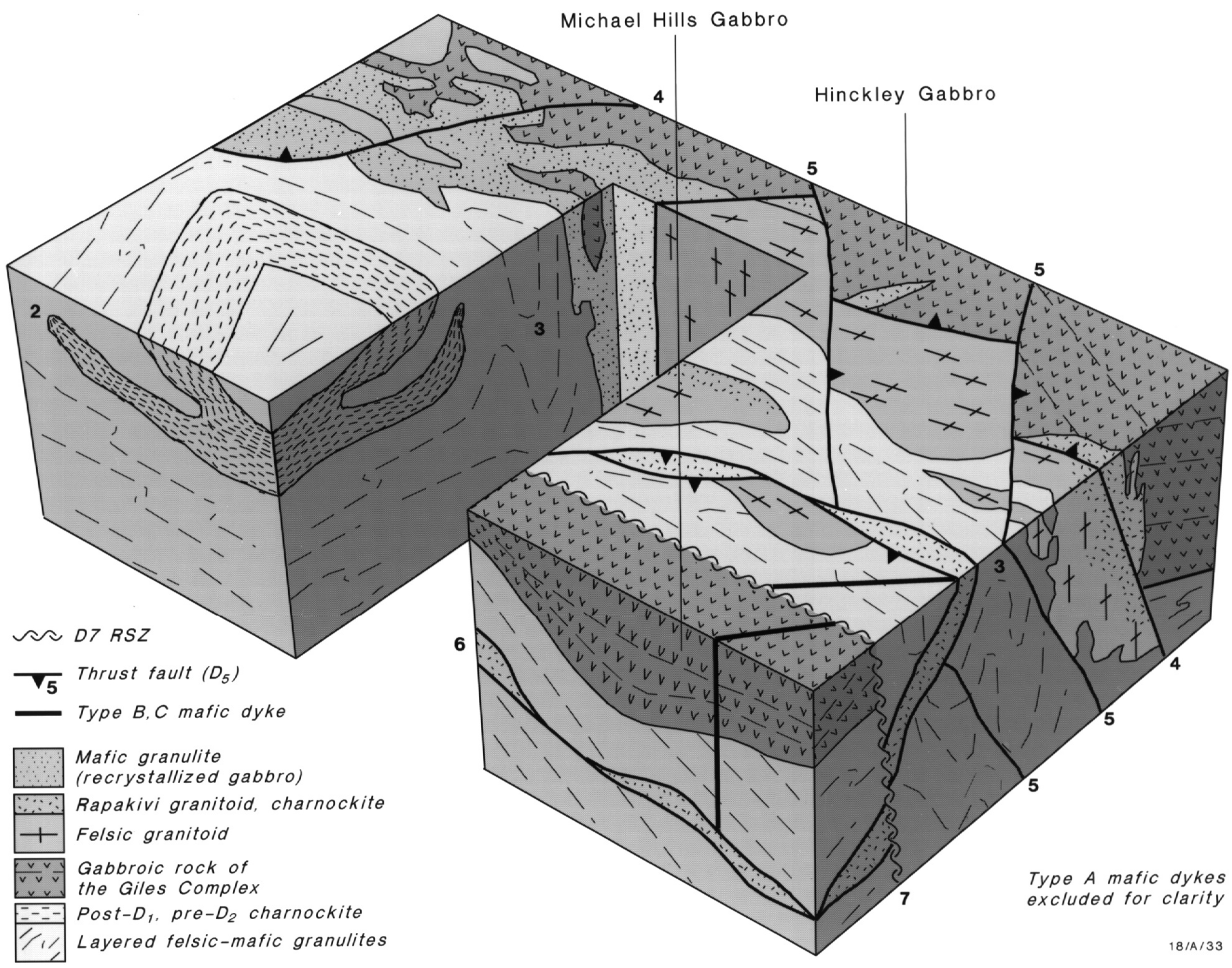

Fig. 11 - A block diagram portraying the field relationships between geological units and structural elements in the Champ de Mars and westernmost Hinckley areas.

Table 1: Tectonic history of the Champ de Mars area and westernmost Hinckley Range area

Regional Events	Age (Ma)	This record		metamorphic conditions	Previous work	
					Pharaoh 1990	Nesbitt *et al.* (1970)
D_7		Retrograde shear zones	east-trending	musc+bt "crush" zones		
D_6	mid-Cambrian[2]	Petermann Orogeny	overthrusting to the north ultramylonite+pseudotachylite			Hinkley Fault
D_5		ultramylonites	overthrusting to the southwest	greenschist facies		
D_4		ultramylonites	overthrusting to the southeast	amphibolite facies		
Mafic intrusion	<1000[3]	Type C mafic dykes	aphanitic			Type D mafic dykes
Tollu Volcanics and	1080±140[1]					
Mafic intrusion	1054±14[4]	Type B mafic dykes	coarse-grained plagioclase laths ? feeders of the Bentley Group			Type C mafic dykes
D_3		upright tight to isoclinal F_3	SE-trending, steep S_3	granulite facies P~4-5 kbar, T>700°C	F_{2F}, F_{1M}	F_2
Mafic intrusion		Type A mafic dykes				Type A mafic dykes
Felsic intrusion	1185[3]	Megacrystic granitoids Microgranite, rapakivi granite				
Mafic intrusion		Michael Hills, Hinckley gabbros		6±1 kbar	Emplacement of Giles Complex	
D_2	1189±9[1]	reclined isoclinal F_2 folds	shallowly dipping S_2, pervasive L_{2i}	granulite facies	F_{1F}	F_1
Felsic intrusion		charnockite				
D_1		pervasive gneissosity in felsic/mafic granulites		granulite facies P~7kbar, T>750°C	?early gneissose fabric	?Early fabric
Mafic intrusion		Mafic granulites with igneous relics				
?Felsic Intrusion		Dominant pre-D_1 orthogneisses				
	1327±12[1] 1564±12[1]	protolith of paragneisses				Felsic volcanic and sedimentary protoliths

[1] Rb-Sr whole rock, Gray (1971, 1977); [2] U-Pb on zircons, Maboko (1989); [3] U-Pb on zircons, S-S. Sun (pers. comm., 1992); [4] Rb-Sr whole rock , A. Camacho (pers.comm. 1991).

Prominent east-trending zones of D6 pseudotachylite and ultramylonite cut all the above fabrics and preserve evidence of north-directed thrusting - a principal example being the Champ de Mars fault. These zones are interpreted to be the expression of the Cambrian Petermann Orogeny in the Tomkinson Ranges. They are probably contemporaneous with the Woodroffe thrust zone, along which the granulite facies terrain overthrusts amphibolite facies gneisses of the Olia Chain, and with northward-directed thrust faults in the Petermann Ranges at the margin of the late Proterozoi-Palaeozoic Amadeus Basin (Forman, 1965; Collerson et al., 1972; Forman and Shaw, 1973; Bell, 1978; Maboko, 1988; Glikson et al., 1990). East-trending, muscovite+biotite-bearing D7 retrograde shear zones form broad "crush" zones, representing some of the latest structures in the Tomkinson Ranges. Some of the youngest events in the Musgrave Block are represented by cross-cutting pseudotachylite breccia-vein networks (Glikson and Mernagh, 1990), interpreted in terms of friction melting along faults and other discontinuities in response to earthquake effects at brittle middle to upper crustal levels in post-uplift times.

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