Mafic dykes in the Williams–Wandering area, Western Australia

by

J. D. Lewis

Abstract

A small area of the Late Proterozoic Boyagin dyke swarm, 150 km south-southeast of Perth, has been mapped in detail. The area also includes part of the 600 km long Binneringie Dyke, and an associated hybridized dyke, both members of the early Proterozoic Widgiemooltha dyke swarm. The Boyagin swarm consists of dolerite dykes, generally between 10 m and 30 m thick, in two sets trending northwest and west-northwest, and a minor east northeast set. In the vicinity of the Binneringie Dyke, the direction of the dyke swarm was deflected anti-clockwise about 20°. The pattern of the Boyagin dyke swarm is interpreted as reflecting intrusion along a conjugate set of Riedel shears associated with a sinistral wrench zone that was reactivated in the final phase of the Pinjarra Orogen. Major northwest-trending lineaments which terminate the Binneringie Dyke are interpreted as similar Riedel shears formed during an earlier ductile phase of orogenesis, at the time of the formation of the proto-Darling Fault.

Thirty chemical analyses are presented, to characterize the dyke swarms. The Binneringie Dyke is calc-alkaline basaltic andesite, and the Boyagin dyke swarm is quartz tholeiitic in composition.

KEYWORDS: Dyke swarms, chemical anayses, Pinjara Orogen, Western Australia

Introduction

A prominent feature of the western part of the Yilgarn Craton is the presence of a number of dense swarms of basaltic to gabbroic dykes of Late Proterozoic to Phanerozoic age (Fig. 1). The dykes occupy a zone about 200 km wide, bounded on the west by the trace of the Darling Fault and extending in a north–south direction for about 1000 km. The general trend of the dykes is northwest over most of the zone, and the swarm has been named the Boyagin dyke swarm by Myers (1990). In the northwest part of the Yilgarn Craton, the swarm is intersected by the Muggamurra dyke swarm, which trends northeast; in the south it is intersected by the Gnowangerup dyke swarm, which trends roughly east.

In addition to these dense swarms of narrow dykes, there is also a widespread, but less numerous, swarm of large east-northeasterly trending dykes which traverse the whole of the craton. These dykes, of Early Proterozoic age, form the Widgiemooltha dyke swarm, the 'Widgiemooltha Dyke Suite' of Sofoulis (1966).

Whereas the dykes of the western swarms can rarely be traced for more than a few kilometres, individual members of the Widgiemooltha dyke swarm can be followed, in outcrop or magnetically, for up to 600 km. Many basic dykes are noted on the 1:250 000 scale geological maps but, except for the large easterly trending dykes in the Eastern Goldfields (where they have been prospected for base metals and platinum) little notice has been taken of them. The principal causes of the neglect are the enormous extent of the dyke swarms, the poor exposure over most of the area, the uniformity of composition, and the presumed lack of economic mineral potential. This paper examines in some detail a relatively well-exposed part of the Boyagin dyke swarm about 150 km south-southeast of Perth, in the vicinity of Williams.

The Williams–Wandering area was chosen following an examination of the regional mapping on a scale of 1:250 000 (Wilde and Lowe, 1980; Wilde and Walker, 1982). In particular, the 1:100 000-scale maps, CROSSMAN and DARKAN, promised both numerous dykes and a variety of dyke directions. The area lies east of the Tertiary laterite sheet which blankets much of the Darling Range, and most of it has been cleared for agriculture, with the result that the trace of major dykes is not obscured by dense forest cover or scrub vegetation.

Previous investigations

Until recently, little work had been done on the basic dykes of the southwest of Western Australia. Prider (1945) summarized studies of a number of small areas along the Darling Scarp; and in later years, honours students of the University of Western Australia have mapped the scarp near Perth in great detail. To the east of Perth, in the vicinity of Meckering, Lewis (1970) described the

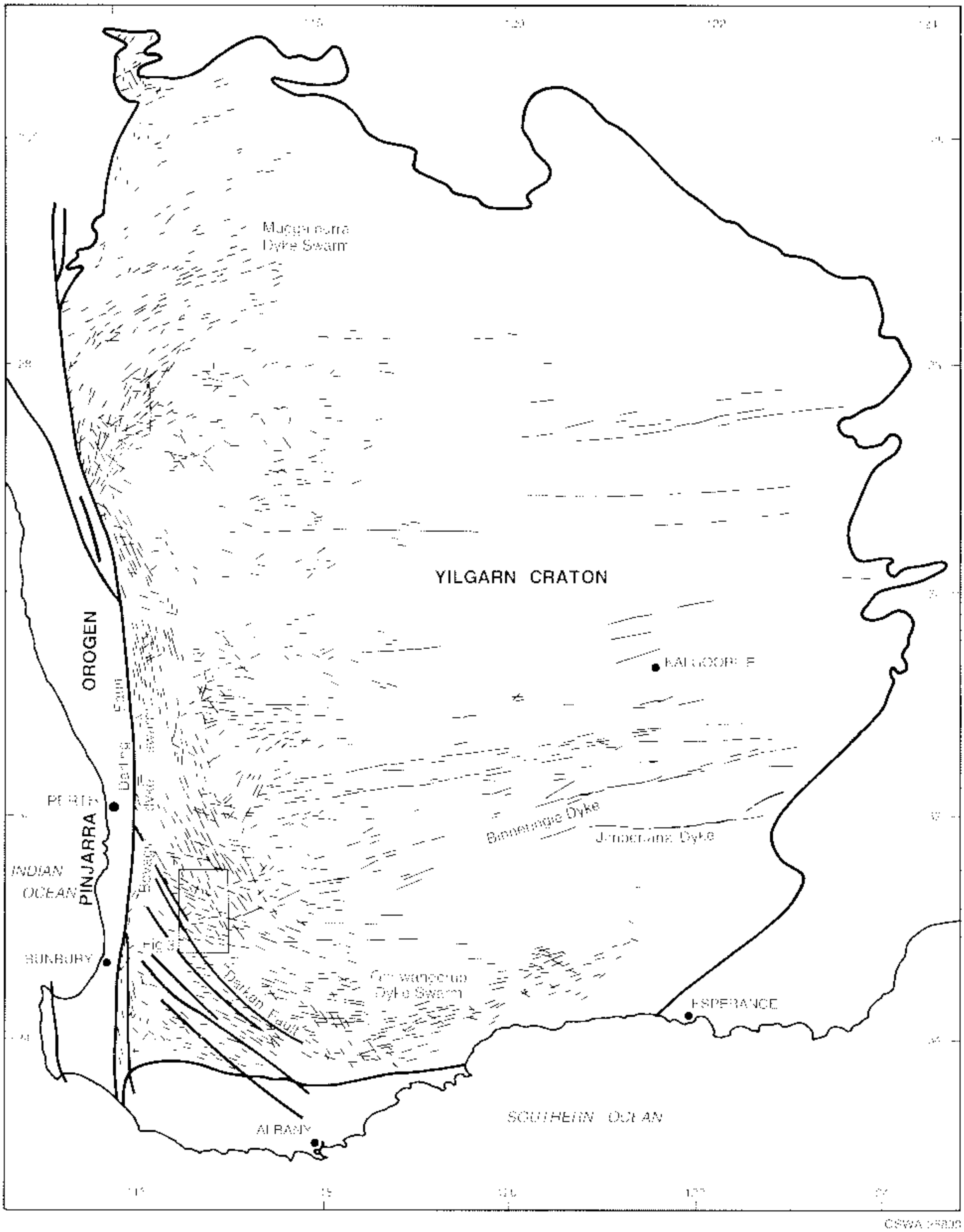

Figure 1. Mafic dyke swarms of the Yilgarn Craton (after Myers, 1990)

petrography and chemistry of a small number of basic dykes contaminated by numerous granitic xenoliths. The palaeomagnetism of basic dykes in the Perth region has been investigated by Giddings (1976), who concluded that five ages of dyke intrusion, ranging from 2500 Ma to 700 Ma, could be distinguished.

The availability of airborne magnetic surveys over the whole of the Yilgarn Craton in recent years has led to a renewed interest in the dyke swarms. Tucker and Boyd (1987) have shown that grey-scaled pixel maps produced from total magnetic intensity data can be used to detect the larger basic dykes in the southwest of Western Australia — particularly the large westerly trending dykes, which are shown to extend to the western margin of the craton. Individual dykes of the Widgiemooltha swarm — particularly the Jimberlana Dyke (Campbell, 1968, 1977; Campbell et al., 1970; Mazzuchelli and Robins, 1973; McClay and Campbell, 1976) and the Binneringie Dyke (McCall and Peers, 1971) — have received considerable attention; but there is no general account of the dyke swarm or of individual dykes outside the Eastern Goldfields Province of the Yilgarn Craton. Isles and Cooke (1990) distinguished six dyke suites in the Eastern Goldfields, and discussed their spatial relationship to pre-existing gold deposits. The only general accounts of all mafic dyke swarms of the Yilgarn are found in Parker et al. (1987), which provides only a short summary of each dyke swarm; and in Hallberg (1987), which reviews past work and provides some chemical data.

Regional geology

That part of the western margin of the Yilgarn Craton intruded by mafic dyke swarms is broadly coincident with the Western Gneiss Terrane of Gee et al. (1981). The terrane consists of repeatedly deformed and metamorphosed ortho- and paragneisses of a variety of ages, intruded by granites which have also been deformed. Enclosed greenstone belts are small and discontinuous, particularly when compared with their abundance in the remainder of the craton. The age of much of the gneiss is more than 3.0 Ga. Cores of detrital zircon from orthoquartzites have been dated at 3.31 Ga, and metamorphic overgrowths at 3.18 Ga (Nieuwland and Compston, 1981). Younger gneisses and deformed granites have Sm–Nd model ages between 3.11 and 2.74 Ga (Fletcher et al., 1983).

Undeformed granites, which intrude the gneiss, underlie large areas in the south of the Western Gneiss Terrane and have been dated by the Rb–Sr isochron method at 2.7–2.5 Ga (Libby and de Laeter, 1979), an age similar to the widespread granite intrusions throughout the remainder of the craton. Zircons from sediments and felsic volcanics of the Saddleback Greenstone Belt, a small greenstone belt enclosed by the granite, give a similar age of 2.65 Ga (Wilde and Pidgeon, 1986).

The Williams–Wandering area is underlain by a variety of granites which form part of the Darling Range Batholith (Wilde and Low, 1980); the largest (2.7–2.5 Ga) intruded the southern part of the Western Gneiss Terrane. The batholith is mostly undeformed, but encloses remnants of older migmatite and gneiss.

To the west, the Yilgarn Craton is terminated by the Darling Fault, a major normal fault that was active during Palaeozoic and Mesozoic times. During that time, up to 6 km of sedimentary rocks were deposited in the Perth Basin (Playford et al., 1976). Beneath the basin lies the largely unknown Pinjarra Orogen (Myers, 1990) of Proterozoic age. The intrusion of the basic dyke swarms in the neighbouring Archaean Yilgarn Craton is probably related to the final post-orogenic phase of development of the Pinjarra Orogen.

The basic dykes

Widgiemooltha dyke swarm

Two major parallel dykes of the Widgiemooltha dyke swarm are present in the Williams area. The Binneringie Dyke, which passes close to the town, extends a further 600 km eastwards to Norseman and beyond. A second dyke, parallel to the Binneringie Dyke and 6 km south of Williams, is confined to DARKAN (1:100 000) and is characterized by abundant granitic xenoliths. Both of the dykes are generally well exposed in the vicinity of Williams, although parts of the outcrop are capped by laterite.

Aeromagnetic data indicate that the Binneringie Dyke occupies a single, continuous fracture, and that it has a positive magnetic anomaly east of Narrogin and a negative anomaly to the west (Tucker and Boyd, 1987). In the field, however, the dyke is discontinuous in outcrop and occupies a series of parallel fractures over a total width of up to 3 km (Fig. 2). East of Wickepin, the dyke forms a positive physiographic feature, particularly in the Wedenin Hills northeast of Kulin where the dyke is at least 300 m wide and forms a ridge about 30 m high. At Walters Hill, 15 km east of Wickepin, the dyke occupies the summit ridge but is largely obscured by laterite. Elsewhere the Binneringie Dyke occurs as low ridges of boulders and small outcrops and is generally 150–200 m wide.

Between Wickepin and Narrogin, the dyke occupies at least four fractures, which step northward as the dyke continues to the west. Here the dyke commonly forms a distinct negative topographic feature, up to 300 m wide, mostly soil covered, but with a few small outcrops and scattered boulders. In the Williams area, and to its western termination south of Meridian Hill, the Binneringie Dyke again forms a strong positive feature. Individual segments of the dyke are up to 4 km long and 400 m wide, and are well exposed in narrow ridges up to 60 m high.

Throughout most of its length, the Binneringie Dyke occupies straight, parallel-sided, vertical fractures; but, in the Williams area and to the west, the dyke pinches, swells, and branches into short apophyses, and its trace is sinuous. In this section, the dyke appears to be a passive intrusion into the granite. For most of its length, the Binneringie

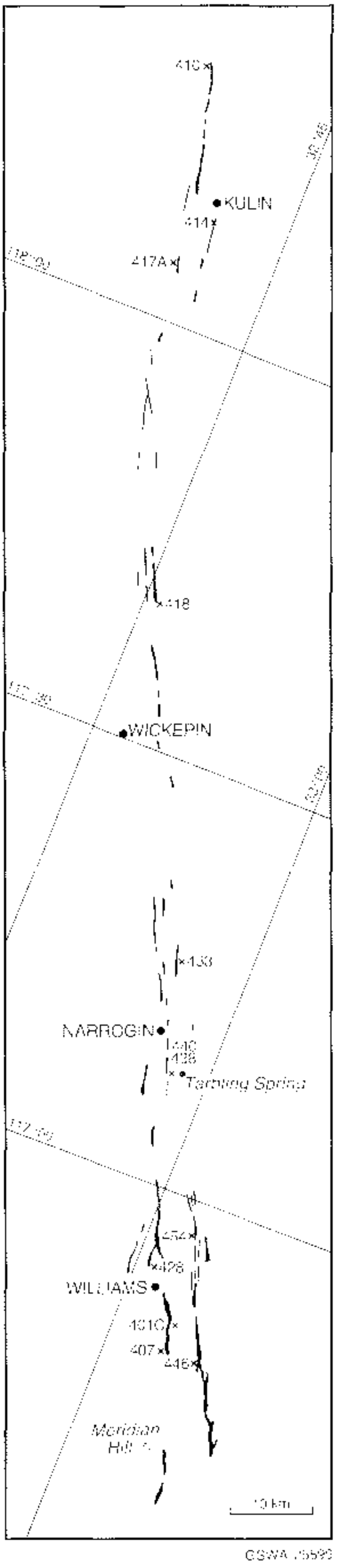

Figure 2. The Binneringie Dyke between Kulin and Williams, showing the location of analysed samples. See Table 1 for sample numbers

Dyke is a single intrusive phase of coarse-grained gabbro, similar in each of the separated outcrops. However, about 5 km north of Williams, a 75 m-wide dyke, similar in overall composition and parallel to the main dyke, dips 70°S and shows prominent banding on a 2–10 cm scale. Possible cross-bedding can be seen in parts. Similar features were described by McCall and Peers (1971) from the eastern end of the Binneringie Dyke, where the banding is believed to result from the combined effects of convection currents within the magma and progressive crystallization inwards from the dyke footwall.

Pods and veins, often several metres long and up to a metre across, of medium grained, pink, aplitic rock are found throughout the length of the main dyke. There is no evidence of granitic xenoliths in the dyke; the pods are probably segregations of the final melt fraction.

At three locations in this area the Binneringie Dyke is a multiple dyke. At Tarbling Spring, southwest of Narrogin, a coarse dolerite dyke about 200 m wide forms a low ridge to the north of the main dyke and separated from it by a narrow screen of granite up to 50 m wide. A similar pattern is present 5 km southwest of Williams, where a gabbroic dyke, to the south of the main dyke, shows a well-developed chilled margin against an incomplete screen of granite pods each about 50 m long by 10 m wide. Farther southwest, near Meridian Hill, a doleritic phase is present on the northern side of the dyke; this may be a second intrusion or a wide, chilled margin of the main dyke.

South of Williams, a second member of the Widgiemooltha dyke swarm, here named the Binneringie Dyke South, is characterized by abundant granitic xenoliths. This dyke is complex, and occupies a narrow zone of fractures 30 km long, trending 070°, and parallel to the main Binneringie Dyke. Magnetic pixel maps of Tucker and Boyd (1987) show a faint negative anomaly continuing the same trend for a further 40 km west-southwest; but for much of this distance, the anomaly is coincident with a major water supply pipeline. It is probable that the dyke terminates close to the westernmost outcrop; and almost certainly, neither the northern or southern Binneringie dykes extend west of the major northwesterly trending magnetic lineament of the Darkan Fault.

The Binneringie Dyke South is relatively rectilinear, and for most of its length, occupies a single fracture, or two fractures separated by a screen of granite several hundred metres wide. The dykes are generally 200–300 m wide; but where a single dyke is present, it may be up to 500 m wide. Where the dyke is crossed by the Albany Highway 6 km south of Williams, and continuing to its eastern termination, the Binneringie Dyke South is commonly made up of a number of parallel dykes, each about 30–50 m wide and together occupying a zone up to 1 km wide. Throughout its length, the dyke is notable for the presence of abundant xenocrysts of plagioclase and quartz, granitic xenoliths up to 10 cm across and, rarely, larger xenoliths up to 1 m across. It is probable that the dyke intrudes a contemporaneous fault zone.

Petrography

The Binneringie Dyke: Throughout its length, the Binneringie Dyke is fairly uniform, coarse-grained quartz gabbro, varying only in alteration products and the proportion of interstitial granophyric intergrowth. Essentially, the rock consists of prisms of anhedral to subhedral plagioclase 2–5 mm long – zoned from cores of labradorite (An[illegible]) to narrow rims of oligoclase (An[illegible]) and abundant anhedral to subhedral augite aggregates 1–3 mm across. Ilmenite, and pseudomorphs after orthopyroxene, are common and rarely occurring grains of pigeonite are enclosed by augite. Late-stage crystallization has produced small amounts of olive-brown hornblende and biotite, and ubiquitous interstitial patches of granophyre and quartz. Accessory perthite, apatite, and a variety of secondary minerals, are also present, and baddeleyite is a rare occurrence in some samples.

Most samples are partly altered: plagioclase is commonly saussuritized or sericitized, and augite may be schillerized and partly replaced by secondary amphiboles or chlorite. A few extensively epidotized specimens contain large interstitial masses of clinozoisite and prehnite.

The most prominent late-stage interstitial phase is a granophyre consisting of quartz and perthite or, less commonly, poorly twinned albite. Quartz and perthite may also form discrete, well formed crystals. The proportion of granophyric material varies. West of Narrogin, the proportion is 5–10%, and the rock is a normal quartz gabbro; east of Narrogin, the proportion of granophyre increases to between 15 and 25% of the rock and forms an irregular granophyre network throughout the rock. The abundance of granophyre in some specimens produces the appearance of a hybrid rock with patches of gabbroic textured plagioclase, augite, and ilmenite in a 'sea' of granophyre, quartz, and perthite.

The granophyre has formed from the accumulation of a final 'granitic' residuum in the central and upper parts of the intrusion. Where this residuum completely separated from the crystallizing magma, it formed aplitic pods of perthite, oligoclase, quartz, and small amounts of hornblende. There are no partly resorbed xenocrysts of quartz or plagioclase to suggest an origin from assimilated granitic xenoliths. In the western part of the dyke, the residuum either did not separate or it migrated to a portion of the dyke now lost by erosion. It is possible that, in the western portion of the dyke, a deeper cross section has been exposed by uplift and erosion relative to the eastern section. The magnetic signature of the dyke also changes, from positive in the eastern section to negative in the western section.

The Binneringie Dyke South: The southern, xenolith bearing member of the Widgiemooltha dyke swarm is a medium-grained hybrid rock containing, in varying proportions, xenocrysts of plagioclase and quartz and xenoliths of granite. The xenolithic material has been partly remelted, and its relationship to the surrounding granites cannot be determined; but no rock types other than granite have been found as xenoliths. Incorporation of the low-temperature melt fraction from the xenoliths, and the complete assimilation of smaller fragments, has given rise to the hybrid nature of the bulk rock.

In thin section, the rock has a doleritic appearance. It contains abundant laths of altered plagioclase up to 1 mm long, anhedral grains of augite about 0.2 mm across, and acicular augite up to 2 mm long. Prismatic orthopyroxene up to 1 mm long is pseudomorphed by chlorite and actinolite, or serpentine. Also present are small patches of interstitial quartz, and abundant interstitial cloudy feldspathic material that constitutes up to 40% of the rock and proves to be extremely fine-grained intergrowths of quartz and feldspar.

Xenocrysts of plagioclase and quartz, up to 2 mm across, make up 10–15% of the rock. The plagioclase is rounded, strongly saussuritized, and contains abundant melt-channels along cleavages; the quartz is embayed and commonly fringed by small diopsidic augite crystals; both were derived from the disaggregation of granitic rocks. Granitic xenoliths within the magma show all stages of melting and disaggregation.

The Boyagin dyke swarm

The dykes of the Boyagin swarm were mapped by airphoto interpretation, and briefly checked in the field for accuracy and rock sampling. Only isolated and dissected remnants of laterite are present in the Williams Wandering area. Outcrop is more commonly obscured by a thin residual sandy soil. Few dykes present a continuous outcrop through the Tertiary laterite or Quaternary soil. A number of easterly trending gabbroic dykes, particularly in the Williams area, are moderately well exposed for a kilometre or more; but most dolerite dykes are exposed for only a few metres, or are found only as cobbles and boulders in the soil. On airphotos, however, many dykes show up as dark lineaments in the soil, and can be easily plotted. A field check showed only rare examples of cultural features, e.g. fence lines, being mistaken for dykes. A number of dykes were present only as dark, lateritized ridges. The final dyke pattern, slightly simplified, is presented in Figure 3.

All dykes checked in the field were essentially vertical, and very rarely less than 10 m wide. However, in a number of areas, it was evident that many smaller dykes, which did not show up as photo lineaments, were present; these ranged from less than 1 m, to as much as 10 or 15 m wide. With the exception of the Binneringie Dyke and its associates, the dykes plotted on Figure 3 range from about 10 to 50 m in width, but rare examples reach 100 metres. Figure 3 probably represents 80% of the dykes in this size range. Most omissions are closer to 10 m than 20 m wide, but it is difficult to estimate the proportion of the total dyke swarm omitted. For the dykes plotted on Figure 3, the average thickness is between 15 and 20 m. Dykes less than 10 m thick, and not plotted on Figure 3, probably represent at least an additional 40%, but many would be thin and impersistent.

As presented in Figure 3, the 2400 mafic dykes plotted in the Williams Wandering area form a pattern only in limited areas where one dyke trend is predominant. When

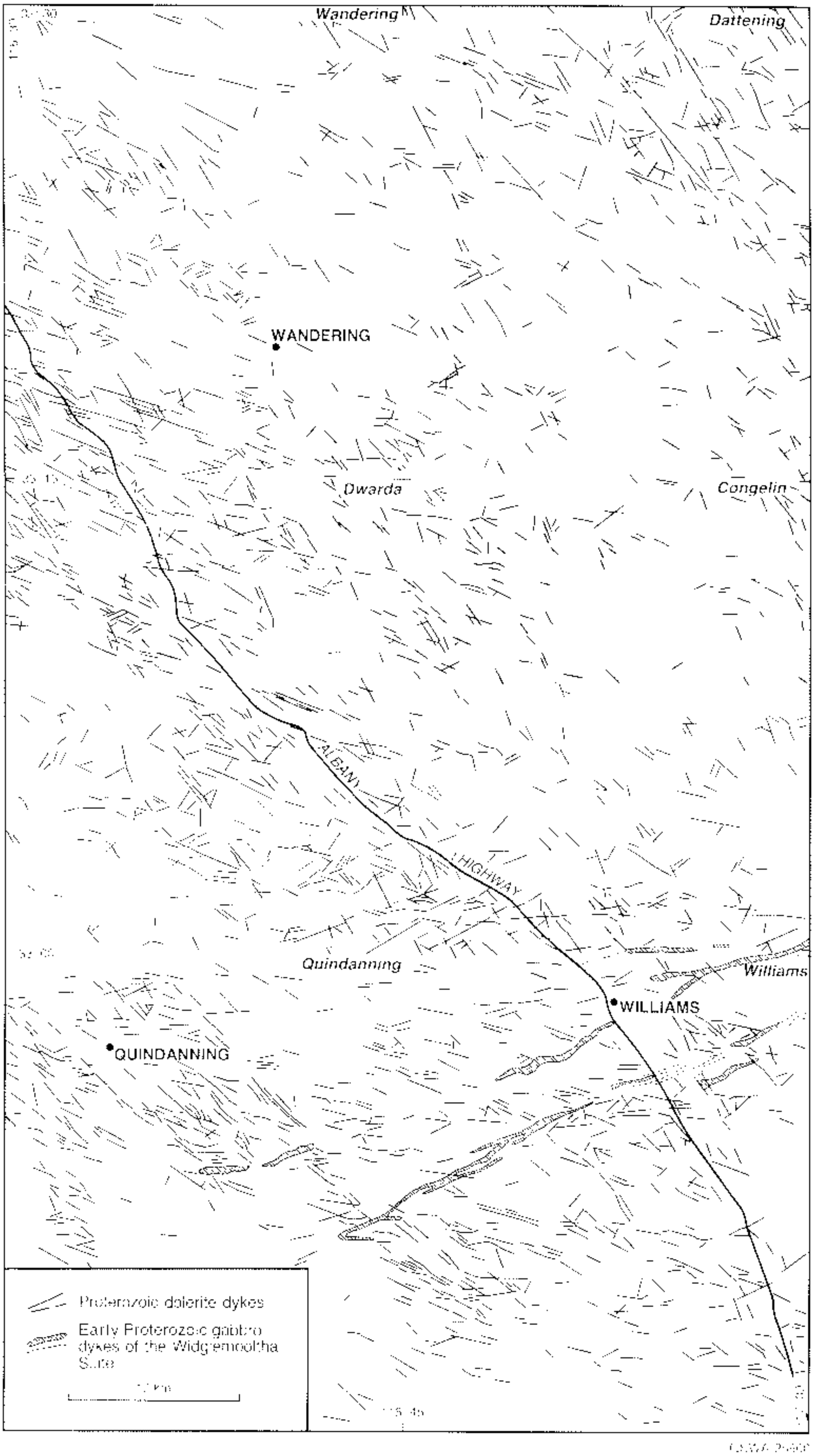

Figure 3. Mafic dykes in the Williams–Wandering area

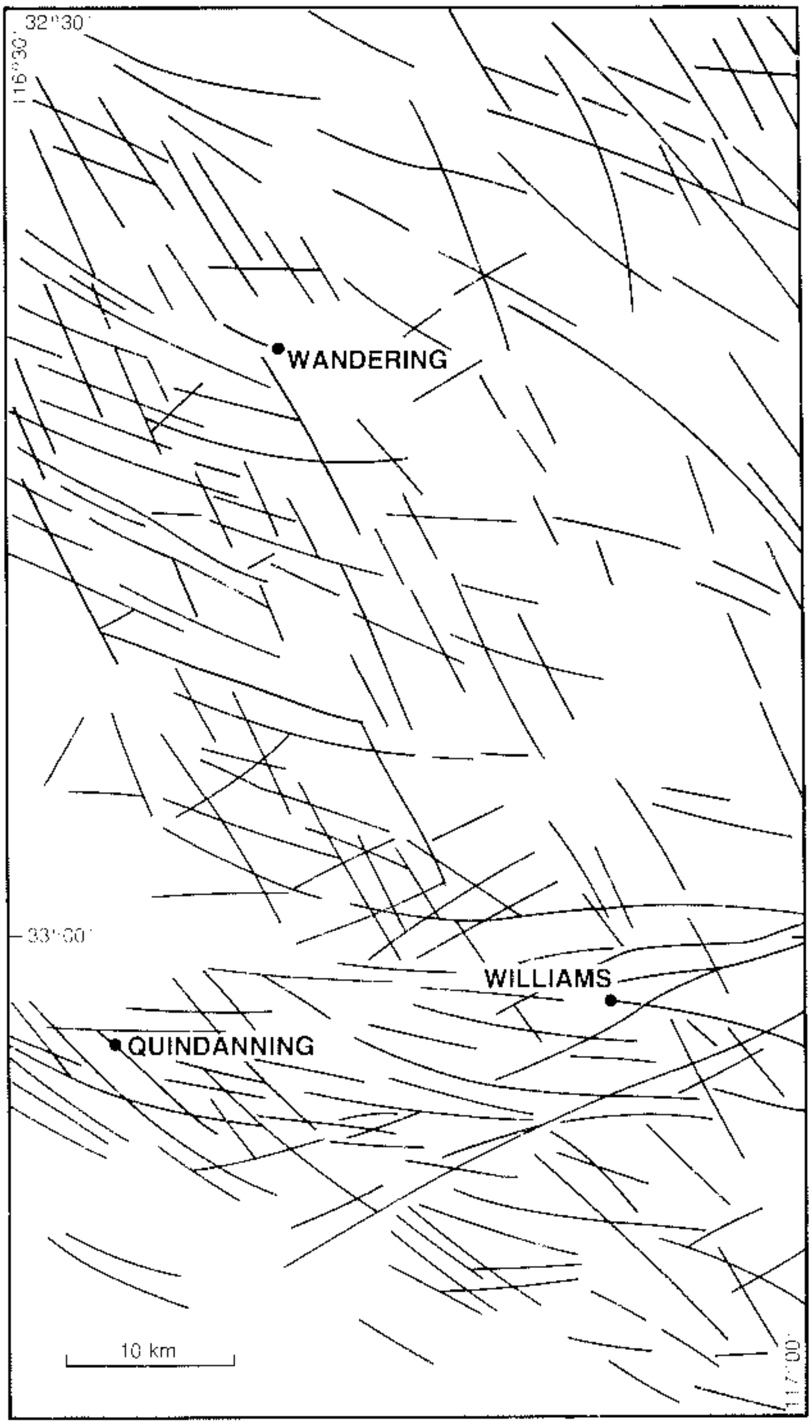

Figure 4. Generalized fracture pattern in the Williams–Wandering area

simplified as a generalized fracture pattern (Fig. 4), or plotted on a rose diagram (Fig. 5), it is evident that the dykes follow a limited number of trends and form distinct dyke sets which intersect each other. North of Williams two trends predominate: northwest (310–330°), and west northwest (290°) dykes. A less prominent trend (070°) is also evident in some areas. In the Williams area, a number of large westerly (260–270°) trending dykes are present. The Binneringie Dyke, trending 070°, traverses the Williams area, but is not included in the rose diagrams of Figure 5.

Throughout the western and southern parts of the mapped area, dykes trending 270–290° form the most prominent swarm. Only in the Datenning and Congelin areas do dykes trending northwest outnumber those trending west northwest (Fig. 3). In the Wandering and Dwarda areas the dykes most commonly trend between

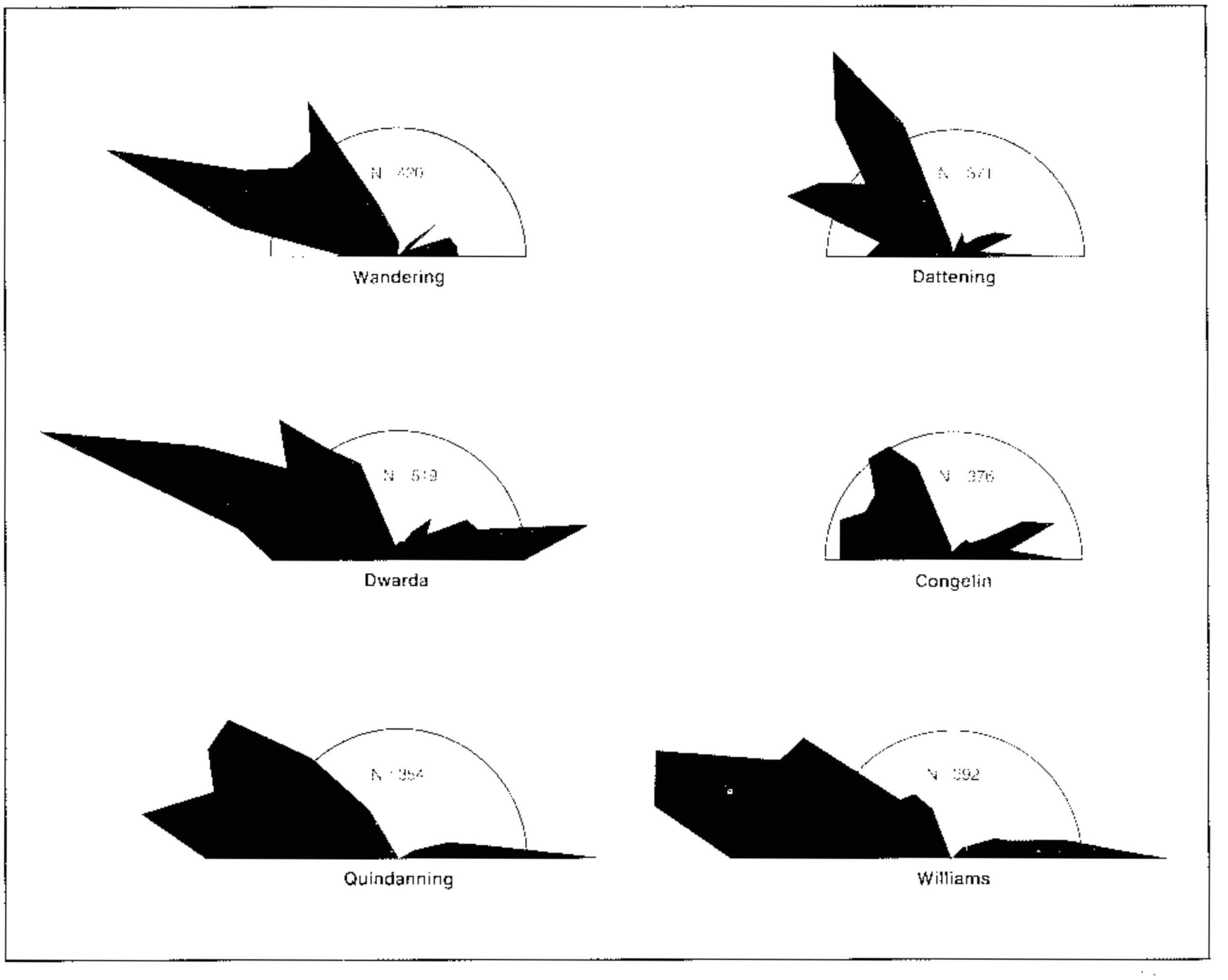

Figure 5. **Rose diagrams of dyke direction and length for each 1:50 000 map sheet in the Williams–Wandering area (radius of circle = 20 km)**

280 and 300°, but in the Quindanning and Williams areas there is also a strong 260–270° trend (Fig. 5). It appears that, in the southern parts of the region, the general trend of the dykes swings slightly from west-northwest to west; but from Figure 4 it is evident that they form a single dyke set.

The west-northwesterly trending dykes are of coarse-grained dolerite, and some show distinct chilled basaltic marginal zones. They range up to 100 m across, but are mostly about 30 m wide and occupy rectilinear or gently curving fractures. A number of dykes can be traced for up to 3 km, but exposures are generally poor. A common feature of the dykes is a prominent, raised, marginal zone of granite, generally a metre or so high and a few metres wide, with the dyke itself only poorly exposed. A few of the larger dykes in the Williams area occupy the crests of granite ridges that can be as much as 20 m high. In general, the presence of upstanding hornfelsed granitic margins appears to be a function of the width of the dyke, although not all large dykes have noticeable contact aureoles.

A second major dyke set, evident from Figures 4 and 5, trends approximately northwest. In the north of the mapped area, the most prominent dyke direction is 330°; but this progressively swings round to 310° in the Williams and Quindanning areas. The dykes are basaltic to doleritic in texture, between 10 and 20 m wide, and traceable on airphotos for less than 1 km. Groups of related dykes arranged en echelon may be traced for several kilometres, particularly in the Dattening area; many smaller dykes are not detectable on airphotos. Exposure of the dykes is poor; outcrops are rarely more than 100 m long and commonly consist only of scattered boulders. The few dykes which form strong positive features on the landscape are usually thoroughly lateritized.

A small number of dykes, particularly in the Congelin area, trend between 060 and 070°, and suggest a distinct east-northeasterly trending set. These are narrow, doleritic dykes, petrographically distinct from the Binneringie Dyke, which has a similar trend; they probably occupy fractures conjugate to the west-northwesterly and northwesterly trending dykes.

The relative ages of the northwesterly and west-northwesterly trending dyke swarms is difficult to determine, as few examples of dykes intersecting each other were found in the field. From airphoto interpretation, and the few examples found in outcrop, the two dyke sets appear to be contemporaneous.

Petrography

The petrography of the Boyagin dyke swarm is fairly uniform; the dykes range from coarse grained quartz dolerite to basalt. The principal minerals are plagioclase laths up to 3 mm long, prismatic to anhedral interstitial augite up to 2 mm across, small amounts of ilmenite, and varying proportions of interstitial quartz and granophyric intergrowth. In a few dykes, interstitial grains and cores of pigeonite are prominent. A small amount of late-stage olive-brown hornblende is commonly present, but biotite occurs rarely. Accessory apatite is common; zircon and baddelyite were rarely noted. A few dykes display ophitic or sub-ophitic texture, and the chilled basaltic marginal facies of many dykes carries abundant small augite phenocrysts.

Plagioclase is commonly zoned, ranging from cores of bytownite (An_{75}) to rims of andesine (An_{35}). Augite is mostly uniform in composition, but a few crystals show rhythmic zoning. Ilmenite varies from small anhedral grains about 0.2 mm across, to large skeletal crystals up to 2 mm across.

The most prominent variation is in the proportion of interstitial quartz and granophyric intergrowth. Most commonly, there is less than 5% of such intergrowth; however, the proportion may rise to about 15% – mostly quartz, but including patches of coarse granophyre. The granophyre is commonly confined to the coarse central part of the dyke; this suggests that it is the result of the late-stage accumulation of a 'granitic' residuum.

Most dykes are extensively altered, although the original textures are preserved. Plagioclase is saussuritized, and in some cases, partly replaced by prehnite. Ilmenite is leucoxenized, and augite has been replaced by actinolite and chlorite. Secondary epidote is common, and there are a few grains of secondary pyrite. A few dykes are completely fresh and preserve both original textures and mineralogy.

Chemistry

Thirty samples from the Binneringie Dyke and Boyagin dyke swarm were analysed for major and trace elements, and are reported in Tables 1–3. The locations of analysed specimens of the Binneringie Dyke are given on Figure 2. Variation diagrams (Fig. 6) show that, chemically, the Binneringie Dyke is easily distinguished from the Boyagin dyke swarm. In particular, the Binneringie Dyke is higher in SiO_2 and lower in MgO, TiO_2, and total FeO, than the later dyke swarm. The trends for ($Na_2O + K_2O$) versus CaO are similar, but the Binneringie Dyke is more alkalic and less calcic than the Boyagin dykes. Although the range of Mg/(Mg + Fe) ratio is similar for both groups of rocks, the MgO content (and hence $FeO–Fe_2O_3$) is consistently higher for the Boyagin dyke swarm. In general, the analyses show that the Binneringie Dyke is a calc-alkaline basaltic andesite, whereas the dykes of the Boyagin swarm are low-K tholeiites.

A plot of the analyses on a variety of triangular tectonomagmatic discrimination diagrams (Fig. 7) confirms the calc-alkaline nature of the Binneringie Dyke, and suggests that the Boyagin dyke swarm has a more primitive oceanic signature. Tectonic implications of these signatures (Pearce and Cann, 1973) suggest that the emplacement of the Binneringie Dyke, and hence the Widgiemooltha dyke swarm, was related to a converging plate margin, while the Boyagin swarm was related to a diverging plate margin. The Binneringie Dyke is reasonably related to the 'orogenic' field of Pearce et al. (1977), but the Boyagin dykes are scattered throughout the 'oceanic' and 'continental' fields (Fig. 7C). However, the discrimination is based on the composition and tectonic setting of young basalts and may not apply in detail to Proterozoic dykes.

The trace-element contents for the two groups of analyses are also significantly different. The Binneringie Dyke is comparatively enriched in Ba, LREE, Rb, Th, and Pb; but contains only half the amount of V and Cu; and has lower values for Cr, Sc, and Zn, than the Boyagin dykes.

Analyses of the Binneringie Dyke (Table 1) show a range of compositions, but no systematic variation along the length of the dyke. The variation probably reflects the proportion of interstitial granophyre present in each specimen. Consistent with the field and petrographic observations, the two samples from west of Williams (Table 1, 401C and 407) show least differentiation and are low in SiO_2 and alkalis, and high in Al_2O_3, MgO, and CaO, compared with the remainder of the samples. The two samples are almost identical in composition, but 401C is from a later dyke, chilled against the main dyke from which sample 407 was collected. Samples 440 and 414 are also relatively undifferentiated, and similar in composition to the Binneringie Dyke west of Williams; sample 440 is from a later dyke separated by a granite screen from the main dyke (sample 438), while sample 414 is from a narrow, doleritic portion of the main dyke, near Kulin.

The western portion of the Binneringie Dyke described here is similar in composition to the 'normal gabbro' described by McCall and Peers (1971) from the eastern end of the dyke, in the Eastern Goldfields. Although the dyke pinches and swells in the Williams area, it does not show the extreme variation in thickness or chemistry reported by McCall and Peers. Throughout the length of the main dyke, there is no evidence that the magma has been modified by high-level assimilation of xenoliths or of a low-melting fraction from the wall rocks. Any

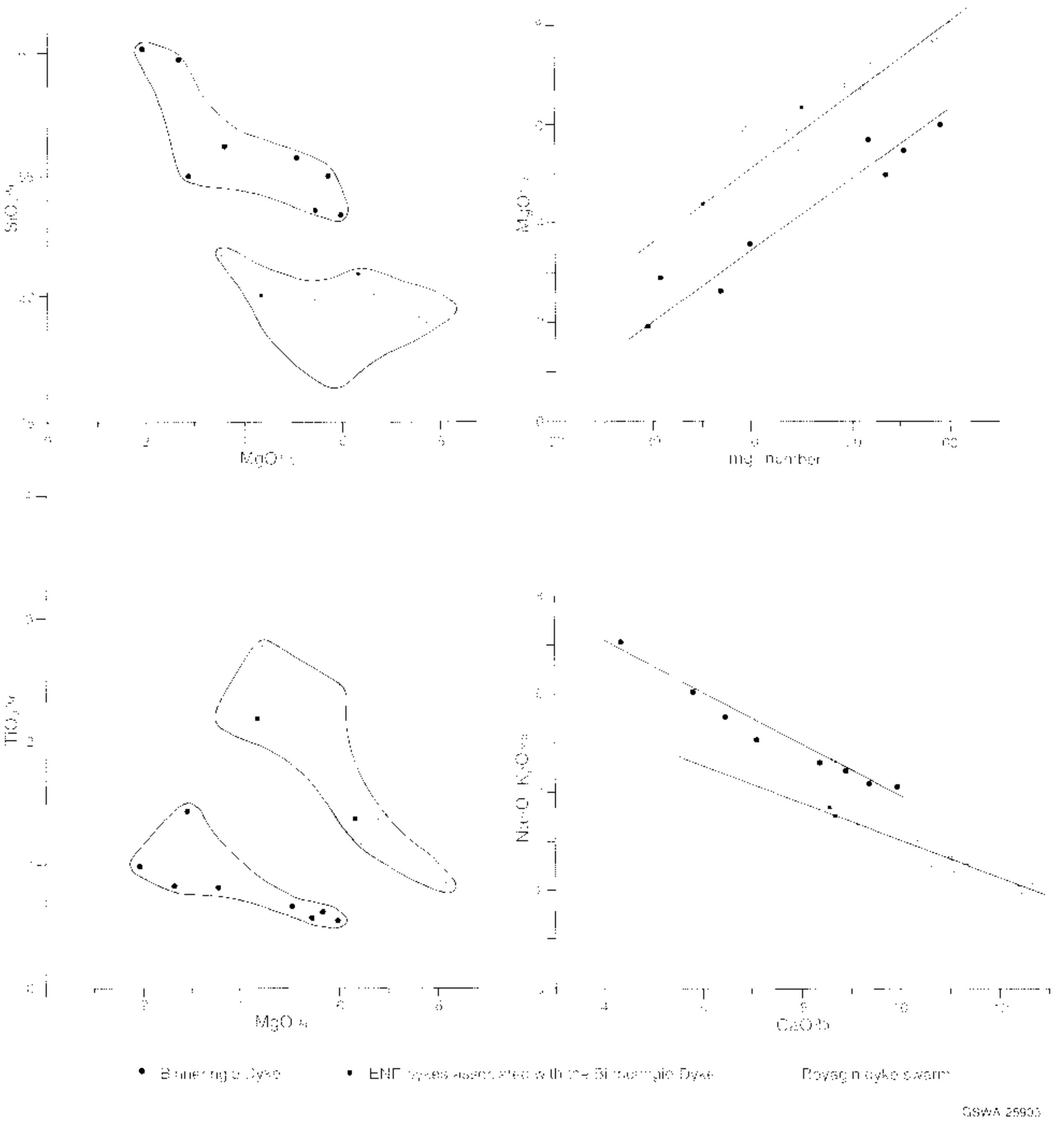

Figure 6. Major-element variation diagrams

modification of an original bashic magma to produce the present basaltic andesite, whether by fractionation or assimilation, must have occurred deep in the crust. However, the magma source, and the mechanism of intrusion for a dyke over 600 km long and of relatively uniform composition, remain problems.

The two analyses of the xenolith rich Binneringie Dyke South (Table 1, samples 446 and 454) are difficult to interpret if the simple model of assimilation of granite, or a low melting point granitic fraction, by calc alkaline magma is assumed. Silica and K_2O are suitably elevated, and CaO depressed, but Al_2O_3 is lower than both basalt and granite, and MgO remains high; among the trace elements, Cr at 300–400 ppm is exceptionally abundant. Although, on field and petrographic evidence, the dyke is probably related to the Binneringie Dyke, the nature of the original magma and its hybridization remains problematic.

Two specimens (Table 1, 428,433), collected as part of the Binneringie Dyke, are chemically dissimilar to the other analyses, and plot with the Boyagin dyke swarm in variation diagrams (Fig. 6). Both are coarse-grained gabbroic rocks which, apart from the paucity of interstitial granophyre, appear similar to the other Binneringie Dyke

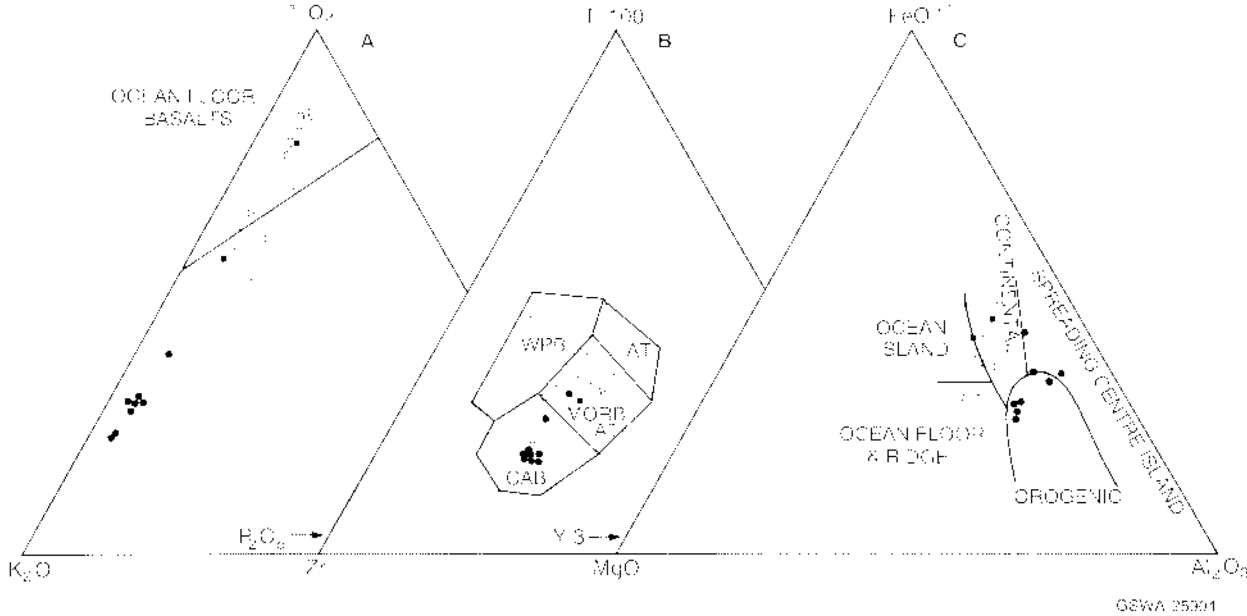

Figure 7. Triangular tectonomagmatic discrimination diagrams. Symbols as in Figure 6. A — after Pearce et al., 1975. B — after Pearce and Cann, 1973. C — after Pearce et al., 1977. (CAB, calc-alkaline basalt; MORB, mid ocean ridge basalt; IAT, island-arc tholeiite; WPB, within plate basalt)

samples. It is probable that the two dykes are east-northeasterly trending members of the Boyagin swarm, and occupy fractures conjugate to the principal west-northwesterly and northwesterly trending fractures. The intrusion of the dykes was possibly influenced by the pre-existing Binneringie Dyke, which follows the same east-northeasterly trend.

The mean compositions of the west-northwesterly and northwesterly trending dykes of the Boyagin dyke swarm are sufficiently similar to indicate that they are co-magmatic (Table 2, column B; Table 3, column C) and of quartz-tholeiite composition. In addition, the two east-northeasterly trending tholeiite dykes associated with the Binneringie Dyke (Table 1, samples 428 and 433) are of similar composition; this is consistent with their being part of the same dyke swarm. On variation diagrams (Figs 6, 7), all the dykes plot together, confirming that they are a single swarm.

Analyses of the northwesterly trending dykes (Table 3) cluster closely around the mean composition, while those of the west-northwesterly trending swarm are more variable in their major-element chemistry. This probably reflects the fact that the northwesterly trending dykes are commonly less than 20 m thick and were not subject to post-emplacement differentiation, whereas the west-northwesterly trending dykes are up to 100 m wide and often show the accumulation of a final granophyric phase in the central parts of the dyke. For example, specimen 476 (Table 2), from the central part of a large east trending dyke, is high in SiO_2 and alkalis but low in CaO and MgO compared with the mean composition; the trace elements are enriched in LREE, Y, and Zr, and depleted in Cr, Ni, and V. In general, the trace element contents of the two groups of dykes are comparable, and the only notable feature is a number of dykes with more than 200 ppm Cu.

All analyses except that for sample 552 (Table 3) are quartz normative, but this dyke is low in SiO_2 and CaO, has a high K_2O content and very high TiO_2, and is olivine normative. However, the trace elements Ba, LREE, Nb, and Sr are high, while Cr and Ni are low when compared with the quartz tholeiites. Petrographically the rock is similar to other members of the dyke swarm, but its chemistry is difficult to interpret.

Discussion

It is evident that members of two independent basic dyke swarms are present in the Williams area: the Binneringie Dyke, a member of the Widgiemooltha dyke swarm, centred on the eastern margin of the Yilgarn Craton; and the numerous basaltic and doleritic dykes of the Boyagin dyke swarm, which have been emplaced along the western margin of the craton. The dyke swarms differ in age, composition, and pattern of intrusion, although the presence of the large Binneringie Dyke appears to have locally influenced the trend of the later Boyagin swarm.

In the Kalgoorlie area, the Widgiemooltha dyke swarm is generally represented by a small number of very large dykes, often more than 200 km long, and up to a kilometre or more wide. The dykes are calc-alkaline, only lightly metamorphosed, and trend in two major directions, east-northeast and east. Aeromagnetic data used by Isles and Cooke (1990) suggest that many more dykes are concealed beneath Quaternary cover. Within this swarm, the

Table 1. Analyses of the Binneringie Dyke and associated dykes

	Binneringie Dyke									Binneringie Dyke South		East northeast-trending dolerite dykes	
Sample number:	*104401C*	*104407*	*104410*	*104411*	*104417A*	*104418*	*104438*	*104440*	*A*	*104446*	*104454*	*104428*	*104433*
Map name:	*Darkan*	*Darkan*	*Kulin*	*Kulin*	*Kulin*	*Yealering*	*Narrogin*	*Narrogin*		*Darkan*	*Darkan*	*Darkan*	*Narrogin*
Grid reference:	*847424*	*823412*	*230910*	*060840*	*603865*	*626744*	*126532*	*126535*		*829378*	*962434*	*911470*	*248573*
						percent							
SiO_2	53.10	53.70	54.90	55.00	56.20	61.10	59.70	55.80	56.23	65.20	66.70	50.90	50.10
TiO_2	0.51	0.57	1.43	0.63	0.82	0.99	0.84	0.67	0.81	0.35	0.32	1.38	2.21
Al_2O_3	15.90	15.50	13.20	14.70	14.40	13.90	14.10	14.70	14.55	12.50	13.00	12.90	13.10
Fe_2O_3	1.54	1.76	3.99	1.43	2.65	3.17	1.92	1.62	2.26	1.26	1.14	3.38	4.00
FeO	5.96	6.22	8.18	6.37	7.19	5.40	6.27	6.33	6.49	2.88	2.61	10.10	10.50
MnO	0.15	0.15	0.19	0.15	0.18	0.15	0.14	0.15	0.16	0.08	0.07	0.25	0.24
MgO	5.98	5.47	2.92	5.72	3.58	1.94	2.65	5.08	4.17	4.24	3.48	6.33	4.36
CaO	9.90	9.36	6.45	8.87	7.10	4.33	5.72	8.34	7.51	3.96	3.40	8.63	8.57
Na_2O	2.95	2.90	3.46	3.02	3.22	3.83	3.49	2.95	3.23	3.08	3.49	2.61	3.28
K_2O	1.20	1.28	2.08	1.44	1.84	3.23	2.60	1.66	1.92	3.06	2.71	0.90	0.41
P_2O_5	0.08	0.08	0.22	0.08	0.15	0.17	0.13	0.10	0.13	0.05	0.06	0.13	0.21
CO_2	0.23	0.11	0.16	0.08	0.06	0.02	0.10	0.09	0.11	0.10	0.11	0.02	0.22
LOI	2.05	2.18	2.42	1.99	2.21	1.90	1.47	2.30	2.06	2.08	2.09	2.00	2.90
Rest	0.26	0.23	0.35	0.27	0.27	0.26	0.29	0.27	0.28	0.30	0.25	0.29	0.34
–O=F,S	0.03	0.02	0.06	0.04	0.03	0.00	0.04	0.04	0.03	0.02	0.01	0.02	0.06
Total	**100.08**	**99.49**	**99.90**	**99.71**	**99.84**	**100.39**	**99.38**	**100.02**	**99.85**	**99.12**	**99.48**	**99.89**	**100.38**
						parts per million							
Ba	353	373	626	371	561	739	629	409	508	714	659	400	90
Ce	31	34	64	41	59	80	66	47	53	50	51	35	24
Cr	114	59	4	163	8	5	7	125	61	406	296	106	31
Cu	92	197	89	86	93	50	57	81	82	36	31	203	125
F	270	172	480	260	413	475	385	270	334	247	229	260	290
Ga	16	16	18	17	18	17	18	16	17	14	15	19	22
La	17	22	28	22	30	40	30	23	26	30	27	17	10
Li	13	10	19	12	11	7	13	15	12	21	15	12	12
Nb	<7	< 7	9	< 7	< 7	8	7	< 7	< 7	< 7	< 7	9	12
Ni	123	105	35	131	50	30	41	96	75	132	95	103	40
Pb	8	12	16	13	17	23	22	15	16	36	22	8	< 1
Rb	47	41	71	51	59	111	89	65	67	116	84	37	13
S	500	300	700	500	300	< 100	500	500	419	200	100	250	1 000
Sc	28	27	29	26	26	18	21	24	25	11	10	34	37
Sn	< 4	< 4	< 4	< 4	< 4	<4	4	< 4	< 4	< 4	< 4	< 4	< 4
Sr	244	247	202	191	222	150	183	182	203	176	185	265	381
Th	6	7	12	10	10	16	15	9	11	16	17	[illegible]	< 2
U	<2	< 2	2	2	< 2	3	4	< 2	2	1	3	2	< 2
V	166	166	269	168	138	155	152	168	173	74	65	323	381
Y	16	15	29	17	26	28	24	19	22	13	13	29	10
Zn	66	72	123	70	97	85	81	75	84	51	43	127	135
Zr	93	101	163	112	153	182	156	119	135	132	137	122	186

Note: A = average of Binneringie Dyke

Table 2. Analyses of the Boyagin dyke swarm (west-northwesterly trending dykes)

Sample number	*104461A*	*104463B*	*104476*	*104477*	*104479A*	*104482*	*104486*	*104489*	*104490D*	
Map name	*Darkan*	*Darkan*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	*B*
Grid reference	*832298*	*965418*	*978845*	*793913*	*678817*	*637655*	*977848*	*550838*	*571806*	
					percent					
SiO_2	46.60	49.70	57.40	49.30	48.90	49.00	51.90	49.10	48.70	50.07
TiO_2	2.45	1.31	1.51	0.92	2.77	1.00	2.18	0.96	1.24	1.59
Al_2O_3	12.10	13.40	17.80	14.30	11.70	13.20	12.30	14.70	13.70	13.12
Fe_2O_3	5.45	3.21	3.15	2.84	3.93	2.87	4.46	2.88	2.96	3.53
FeO	11.30	8.70	8.02	7.01	12.10	8.81	10.70	6.97	9.02	9.12
MnO	0.31	0.22	0.21	0.20	0.29	0.23	0.24	0.18	0.22	0.23
MgO	5.91	6.66	1.78	7.62	4.49	7.74	3.57	7.65	7.20	5.85
CaO	9.09	11.10	5.88	12.40	8.65	12.30	7.26	12.70	11.90	10.15
Na_2O	2.91	2.10	3.60	1.73	2.88	1.88	3.15	1.86	1.89	2.31
K_2O	0.37	0.27	0.97	0.40	0.29	0.11	0.60	0.25	0.12	0.38
P_2O_5	0.19	0.11	0.36	0.08	0.27	0.08	0.35	0.08	0.10	0.18
CO_2	0.15	0.17	0.17	0.10	0.29	0.16	0.12	0.13	0.15	0.16
LOI	3.01	2.08	2.55	2.14	2.78	1.73	3.07	2.52	1.96	2.33
Rest	0.31	0.27	0.41	0.23	0.41	0.23	0.31	0.21	0.26	0.30
-O=F,S	0.05	0.04	0.09	0.02	0.09	0.03	0.05	0.03	0.01	0.05
Total	**100.14**	**99.26**	**98.74**	**99.14**	**99.65**	**99.41**	**99.66**	**100.13**	**99.37**	**99.50**
					parts per million					
Ba	95	77	238	217	107	59	138	77	36	116
Ce	20	12	106	13	36	10	50	13	6	29
Cr	32	143	7	196	58	111	28	175	127	97
Cu	216	209	177	134	135	165	116	138	162	161
F	260	303	970	135	175	160	500	170	188	340
Ga	23	17	27	14	22	17	24	14	15	19
La	6	5	40	6	11	< 5	17	< 5	< 5	11
Li	14	11	12	20	13	< 6	16	9	19	13
Nb	7	< 7	22	< 7	14	< 7	13	< 7	< 7	8
Ni	58	92	14	121	44	105	34	130	107	78
Pb	< 4	< 4	< 4	4	< 4	< 4	5	<4	< 4	< 4
Rb	72	13	27	22	8	3	23	14	6	15
S	700	700	1 000	200	1 500	500	500	500	700	700
Sc	42	11	22	38	37	43	30	36	40	37
Sn	4	< 4	5	< 4	< 4	< 4	6	< 4	< 4	< 4
Sr	166	156	197	147	180	132	160	154	134	158
Th	< 2	< 2	5	< 2	< 2	< 2	2	< 2	< 2	< 2
U	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
V	475	319	165	283	418	321	328	280	325	324
Y	35	21	100	17	47	19	58	17	21	37
Zn	149	97	151	90	135	90	190	71	92	119
Zr	138	90	509	58	217	61	285	65	76	168

Note: B: average for WNW dykes

Binneringie Dyke, which extends across most of the width of the craton, is the longest. Two members of the swarm have been dated at about 2.4 Ga (Turek, 1966; Fletcher et al., 1987), and intrusion followed a widespread period of tectonism and granite intrusion at about 2.6 Ga.

The western termination of the Binneringie Dyke, and that of the associated xenolith-rich Binneringie Dyke South, appear to be at, or close to, the Darkan Fault, one of a number of prominent northwest trending magnetically defined lineaments cutting the southwest corner of the Yilgarn Craton (Tucker and D'Addario, 1986). These faults or fracture zones are associated with the Pinjarra Orogen, which is believed to have been initiated between 2.0 and 1.1 Ga (Myers, 1990), and are known to displace parts of the Albany Fraser Orogen, which is dated between 1.8 and 1.0 Ga. However, the Darkan Fault is also associated with the Saddleback greenstone belt, dated at 2.65 Ga (Wilde and Pidgeon, 1986), and pegmatite intruding a similar shear zone in the Greenbushes area is dated at 2.53 Ga (Partington et al., 1986). It is possible that the earliest movement on the Darkan Fault and other shear zones in the southwest is related to the 2.65 Ga proto-Darling Fault (Blight et al., 1981), and that further displacement occurred intermittently over an extended period. If this is so, the Darkan Fault would have existed before 2.4 Ga, and could have formed a terminating cross-fracture when the Binneringie Dyke was intruded.

Intrusion of the Boyagin dyke swarm followed the formation of the Pinjarra Orogen, a narrow belt of granites and gneisses west of the Darling Fault that is mostly buried

Table 3. Analyses of the Boyagin dyke swarm (northwesterly trending dykes)

Sample Number :	*104508*	*104512*	*104520*	*104527*	*104536*	*104540*	*104548*	*104551*		*104552*
Map Name :	*Darkan*	*Darkan*	*Darkan*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	*Crossman*	C	*Crossman*
Grid reference :	*961371*	*987287*	*678379*	*868493*	*671726*	*982847*	*907966*	*790943*		*672807*
					percent					
SiO_2	49.90	49.80	48.50	49.60	49.50	50.30	49.70	50.10	49.67	47.50
TiO_2	2.36	1.19	1.63	2.08	1.39	1.39	0.85	1.47	1.51	3.67
Al_2O_3	14.20	14.90	13.90	13.80	13.40	13.80	15.10	13.90	14.00	14.00
Fe_2O_3	2.57	3.12	3.89	2.56	2.79	2.38	3.26	2.14	2.84	3.54
FeO	9.81	8.39	10.00	10.30	9.90	9.18	6.49	9.62	9.21	10.90
MnO	0.22	0.22	0.24	0.24	0.24	0.22	0.19	0.23	0.22	0.25
MgO	5.53	6.49	5.84	5.77	6.80	6.76	8.02	6.63	6.48	5.31
CaO	9.21	11.30	10.50	9.03	11.00	10.30	12.20	10.40	10.49	8.58
Na_2O	2.66	2.28	2.27	2.60	2.36	2.34	1.61	2.36	2.31	2.95
K_2O	1.09	0.22	0.20	1.25	0.32	0.71	0.70	0.63	0.64	1.70
P_2O_5	0.25	0.09	0.11	0.26	0.11	0.15	0.07	0.15	0.15	0.71
CO_2	0.09	0.10	0.19	0.14	0.19	0.14	0.12	0.11	0.11	0.15
LOI	1.56	1.84	2.22	2.24	2.23	1.82	2.36	1.69	1.99	1.72
Rest	0.34	0.23	0.30	0.35	0.29	0.28	0.25	0.30	0.30	0.50
O=F,S	0.05	0.03	0.06	0.05	0.06	0.04	0.04	0.05	0.05	0.07
Total	**99.43**	**100.14**	**99.74**	**100.16**	**100.47**	**99.73**	**99.91**	**99.71**	**99.91**	**100.51**
					parts per million					
Ba	446	60	60	445	53	196	125	231	202	1 176
Ce	62	10	13	64	16	34	11	30	30	85
Cr	94	86	33	77	69	156	203	150	108	49
Cu	58	202	237	72	197	97	125	105	137	40
F	510	154	183	510	387	315	255	320	304	800
Ga	20	17	18	18	17	17	13	22	17	19
La	30	< 5	5	30	<5	16	7	17	14	43
Li	< 6	< 6	< 6	33	10	10	23	8	9	8
Nb	16	< 7	< 7	17	< 7	8	< 7	8	8	18
Ni	51	83	64	58	76	77	115	71	74	42
Pb	7	< 4	< 4	6	< 4	5	5	< 4	4	5
Rb	33	8	8	15	16	27	52	24	27	30
S	500	500	1 000	500	1 000	500	500	700	650	700
Sc	32	39	37	33	39	37	37	26	35	25
Sn	< 4	< 4	< 4	< 4	4	< 4	<4	< 4	< 4	< 4
Sr	283	146	116	261	127	213	141	231	193	598
Th	5	< 2	2	4	< 2	2	< 2	2	2	4
U	2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	<2
V	347	327	439	350	368	304	265	307	338	344
Y	31	21	24	32	25	24	18	[illegible]	[illegible]	22
Zn	113	103	118	137	113	96	79	99	107	91
Zr	193	74	88	208	88	126	62	123	119	204

Note: C = average for NW dykes

beneath a thick cover of Phanerozoic sediments forming the Perth Basin. Basement rocks of the orogen have Sm–Nd model ages between 2.1 and 1.1 Ga (Fletcher et al., 1985); but, between 1.1 and 0.7 Ga, there was a final phase of tectonic and metamorphic activity dominated by sinistral transcurrent faulting (Harris, 1987). Normal faulting continued on the Darling Fault into Palaeozoic and Mesozoic times. Dykes are not known to intrude the Leeuwin Complex, the only exposed portion of the southern part of the Pinjarra Orogen, but are found cutting the Moora and Cardup Group sedimentary rocks along the Darling Fault. The age of the Cardup Group is thought to be between 750 and 600 Ma (Compston and Pidgeon, 1962; Playford et al., 1976). Northeasterly trending dykes of the Muggamurra dyke swarm, which is broadly similar in age to the Boyagin swarm, intrude the Northampton Complex and have been dated at 750 and 550 Ma (Embleton and Schmidt, 1985). The only age determination on a dyke of the Boyagin swarm is from a sheared and metasomatized dyke margin; it gave an age of 560–590 Ma (Compston and Arriens, 1968). However, this dyke is from an elongated zone east of the Darling Fault, where biotite Rb–Sr ages have been extensively reset to 450–500 Ma (Libby and de Laeter, 1979), and the dating of the dyke may reflect this event. Thus, the age of the Boyagin dyke swarm is between 750 and 500 Ma, most probably around 650 Ma.

In the area studied, and for much of the area of the swarm, the structural pattern of the Boyagin dyke swarm is defined by two sets of dykes trending northwest and west-northwest, with a minor set trending east-northeast.

The northwesterly trending dykes follow the general geological grain of the region, particularly the major fracture zones of the Darkan Fault and its associates, the Saddleback greenstone belt, and the zone of ancient gneisses east of Perth. The west-northwesterly trending swarm of dykes truncates these structures at an angle of about 40°. The resulting dyke pattern is that of a conjugate set of Riedel shears produced within a broad wrench zone with sinistral principal displacement. As noted earlier, the final tectonic phase of the Pinjarra Orogen was dominated by sinistral transcurrent faulting concentrated in the proto-Darling Fault. Thus, the Boyagin dyke swarm may be seen as the final, post-orogenic phase of the Pinjarra Orogen. In addition, the major lineaments of the Darkan Fault, and the other shear zones which transect the southwest of the Yilgarn Craton, can also be interpreted as Riedel shears formed in the earliest, ductile phases of pre-orogenic sinistral movement along the proto-Darling Fault.

Between the time of formation of the Darkan Fault and its associated lineaments, and the emplacement of the Boyagin dyke swarm, the Binneringie Dyke was intruded. The emplacement of the dyke was the result of tectonic events in the eastern parts of the craton; but at its western end, its course may have been influenced by residual stresses associated with the proto-Darling Fault. As a result, the presence of the Binneringie Dyke influenced the emplacement of the Boyagin dyke swarm when sinistral stress was renewed in late Proterozoic times, causing the dyke trends to be deflected anticlockwise through about 20°.

Conclusions

The results of this study can be briefly summarized as follows:

1. In the Williams area there are two independent mafic dyke swarms:

    (a) the Widgiemooltha dyke swarm of calc-alkaline composition and Early Proterozoic age — represented by the large, gabbroic Binneringie Dyke, and the smaller, xenolith-rich Binneringie Dyke South; and

    (b) the Boyagin dyke swarm of quartz-tholeiite composition and Late Proterozoic (or early Palaeozoic) age — represented by many thin and impersistent dolerite dykes.

2. The Binneringie Dyke extends more than 600 km in a west-southwest direction across the width of the Yilgarn Craton and includes a parallel xenolith-rich dyke in the Williams area. Both dykes terminate at, or close to, the prominent magnetic lineament of the Darkan Fault.

3. The Boyagin dyke swarm comprises two intersecting sets of dykes, one trending northwesterly and the other trending west-northwesterly, and a minor set that trends east-northeasterly. The three sets of dykes are contemporaneous. The dyke pattern is best explained as intrusion along a conjugate set of Riedel shears formed in a broad sinistral wrench zone along the western margin of the Yilgarn Craton. The wrench zone is associated with the Pinjarra Orogen and its principal displacement was localized along the proto-Darling Fault.

4. The implications for the structural development of the southwest of Western Australia are that the prominent magnetic lineaments of the area are Riedel shears, which formed during the earliest and most ductile phase of deformation in a wrench zone that preceded the development of the Pinjarra Orogen and the emplacement of the Binneringie Dyke. The wrench zone (and associated shear zones), with its principal displacement localized along the proto-Darling Fault, continued to develop throughout the Pinjarra Orogeny.

The Boyagin dyke swarm intrudes Riedel shears of a reactivated wrench zone that represents the final phase of brittle deformation of the Pinjarra Orogen.

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