

**REPORT
53**



PROTEROZOIC ZONED TUNGSTEN-BEARING SKARNS AND ASSOCIATED INTRUSIVES OF THE NORTHWEST GASCOYNE COMPLEX WESTERN AUSTRALIA

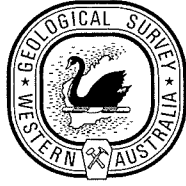
by B. M. Davies



**GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
DEPARTMENT OF MINERALS AND ENERGY**

**PROTEROZOIC ZONED TUNGSTEN-BEARING
SKARNS AND ASSOCIATED INTRUSIVES
OF THE NORTHWEST GASCOYNE COMPLEX,
WESTERN AUSTRALIA**





GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 53

**PROTEROZOIC ZONED
TUNGSTEN-BEARING SKARNS
AND ASSOCIATED INTRUSIVES OF THE
NORTHWEST GASCOYNE COMPLEX,
WESTERN AUSTRALIA**

by
B. M. Davies

Perth 1998

MINISTER FOR MINES
The Hon. Norman Moore, MLC

DIRECTOR GENERAL
L. C. Ranford

ACTING DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
David Blight

Copy editor: I.R. Nowak

REFERENCE

The recommended reference for this publication is:

DAVIES, B. M., 1998, Proterozoic zoned tungsten-bearing skarns and associated intrusives of the northwest Gascoyne Complex, Western Australia: Western Australia Geological Survey, Report 53, 54p.

National Library of Australia
Cataloguing-in-publication entry

Davies, Brett McDonald, 1955-.
Proterozoic zoned tungsten-bearing skarns and associated intrusives of the northwest Gascoyne Complex, Western Australia.

Bibliography.
ISBN 0 7309 6567 8

1. Tungsten ores — Western Australia — Gascoyne region.
2. Skarn — Western Australia — Gascoyne region.
3. Geology, Economic — Western Australia — Gascoyne region.
 - I. Geological Survey of Western Australia.
 - II. Title. (Series: Report (Geological Survey of Western Australia); no. 53).

553.4649099413

ISSN 0508-4741

Cover photograph:

Ridge of bimetasomatic skarn near the contact with the Mount Alexander Batholith, about 4 km southeast of the Mortgage skarn.

Frontispiece:

Iron formation and marble ridges, 1.5 km northwest of the Mortgage skarn.

Contents

Abstract	1
Introduction	1
Nomenclature	3
Analytical methods	3
Geological setting	3
Regional geology	3
Local geology	4
Mount Alexander	4
Kilba Well	5
Intrusive rocks	6
Mount Alexander batholith and Mortgage monzonite stock	7
Pegmatites	10
Geochemistry of the Mount Alexander batholith	10
Kilba Well intrusives	11
Pegmatites	12
Alteration in the Kilba Well monzogranite	12
Geochemistry of the Kilba Well intrusives	12
Monzogranite	12
Pegmatite	14
Alteration	14
Summary of granitoid characteristics	14
Contact metamorphism and metasomatism	15
Contact metamorphism	15
Mount Alexander	15
Kilba Well	15
Conditions of contact metamorphism	15
Bimetasomatic skarns	16
Mount Alexander	16
Kilba Well	18
Mineralized skarns (exoskarns)	18
Mount Alexander skarns	18
Petrology and geochemistry of the zoning	18
Mineralogical zoning patterns	19
Marble host	19
Prograde skarn zones	19
Wollastonite zone	19
Transition zone	21
Garnet–pyroxene zone	25
Retrograde skarn zones	27
Vesuvianite zone	27
Epidote zone	29
Amphibole zone	29
Mineralization in Mount Alexander skarns	30
Kilba Well skarns	30
Petrology and geochemistry of the zoning	34
Marble host	35
Prograde skarn zones	35
Wollastonite zone	35
Transition zone	36
Garnet–vesuvianite zone	36
Garnet–pyroxene zone	37
Pyroxene zone	37
Epidote zone	38
Retrograde skarn zones	39
Amphibole zone	39
Vesuvianite zone	39
Hydrosilicate zone	39
Mineralization in Kilba Well skarns	40
Summary	40
Intrusives	40
Exoskarns	40
Discussion	41
Granitoids related to tungsten skarns	41
Granitoid fabrics	41

Alteration	42
Sericitization and greisenization	42
Other alteration	42
Granitoid geochemistry	42
Depth of, and conditions during, magma emplacement	43
Conditions during bimetasomatic skarn formation	44
Significance of bimetasomatic skarns	44
Conditions during exoskarn formation	45
Prograde skarn	45
Retrograde skarn	46
Scheelite mineralization	46
Potential for more skarn mineralization	47
Potential for tungsten skarns elsewhere in the Gascoyne Complex	47
Conclusions	49
Evaluation of granitoids as source rocks for scheelite skarn deposits in the Gascoyne Complex	49
Mineralized exoskarns	50
Acknowledgements	50
References	51

Appendix

1. Specimen locations	54
-----------------------------	----

Figures

1. Location of the study area	2
2. Geology of the Mount Alexander area	5
3. Local stratigraphy (schematic) in the Mount Alexander area	6
4. Geological map of Kilba Well prospect	7
5. Simplified geological map of the Zone 11 area at Kilba Well prospect	8
6. Representative cross sections through skarns in Zone 11, Kilba Well prospect	9
7. Intense sericitic alteration adjacent to tourmaline-bearing veins in Kilba Well monzogranite	13
8. Bimetasomatic skarn in impure marble at Kilba Well	16
9. Idealized bimetasomatic zoning—Mount Alexander and Kilba Well	17
10. Cross section through the Mortgage skarn	19
11. Outcrop of Aladdins skarn	20
12. Schematic geometry and distribution of zones in Mount Alexander skarns.	21
13. Garnet compositions in Mount Alexander and Kilba Well skarns	23
14. Prograde clinopyroxene compositions in Mount Alexander and Kilba Well skarns	24
15. Photograph showing typical transition zone specimen from the White Lightning skarn	24
16. Epidote group compositions in Mount Alexander and Kilba Well skarns	25
17. Photograph showing very coarse vesuvianite with quartz and subcalcic garnet	26
18. Photograph showing banded garnet–pyroxene zone assemblage traversed by late quartz-rich vein	26
19. Photograph showing retrograde Vesuvianite zone, Mortgage skarn	28
20. Vesuvianite compositions in the Mount Alexander (Mortgage) and Kilba Well retrograde skarn zones	29
21. Photograph showing unusually coarse-grained actinolitic amphibole from the amphibole zone at Camp skarn	30
22. Amphibole compositions in Mount Alexander and Kilba Well skarns	32
23. Biotite–phlogopite compositions in Mount Alexander and Kilba Well skarns	33
24. Schematic geometry and distribution of zones in Kilba Well skarns	35
25. Photograph of outcrop displaying tremolite–chlorite dominant assemblages	36
26. Photograph of core from garnet–vesuvianite zone in Zone 11	37
27. Ternary Q–Ab–Or P_{H_2O} diagram	38
28. P–T phase diagrams for synthetic granitoid compositions	44
29. Grade–tonnage relationships between various skarn deposits	48

Tables

1. Geochemistry of Mount Alexander granitoids	11
2. Geochemistry of Kilba Well granitoids	13
3. Representative tourmaline compositions–granite contact zones	15
4. Mineralogical zoning in Mount Alexander skarns	21
5. Representative garnet compositions	22
6. Representative pyroxene compositions	23
7. Representative epidote–clinozoisite compositions	27
8. Representative vesuvianite compositions	28
9. Representative amphibole compositions	31
10. Representative phyllosilicate compositions	33
11. Mineralogical zoning in Kilba Well skarns	34

Proterozoic zoned tungsten-bearing skarns and associated intrusives of the northwest Gascoyne Complex, Western Australia

by

B. M. Davies

Abstract

Mount Alexander and Kilba Well are two areas of significant, but sub-economic scheelite-bearing skarns in Middle Proterozoic rocks in the northwestern Gascoyne Complex of Western Australia. The host sediments are regionally metamorphosed to upper greenschist grades and to hornblende hornfels grades in contact aureoles adjacent to monzogranite and granodiorite intrusives.

The intrusive rocks associated with the skarns are typically porphyritic, slightly peraluminous and highly evolved, with high SiO₂, K₂O, B, Li and Rb, and elevated Na₂O, K₂O, Sr, Th and Nb contents. Intense greisen alteration consisting of quartz–muscovite(–tourmaline) occurs in well defined linear zones that lie within 200 m of, and at high angles to, the contacts.

The skarns developed in formerly dolomitic rocks that were previously regionally metamorphosed to calcite–tremolite–chlorite marbles. Prograde and retrograde stages are recognized and these are characterized by the presence of several distinct mineralogical zones. At Kilba Well, prograde skarn formation was preceded by the development of large volumes of barren, iron-poor bimetasomatic skarns, which were subsequently overprinted by prograde and retrograde stage assemblages. This has resulted in a complex mix of prograde and retrograde zone assemblages.

Scheelite is the only tungsten-bearing mineral recognized in the skarns. It is irregularly distributed through prograde zones, where concentrations are generally low, but is more abundant in retrograde zones.

Lithostatic pressure at the time of granite emplacement and skarn formation, temperature, and CO₂ mole fraction conditions of the metasomatic fluid are estimated from the different skarn assemblages.

The potential for tungsten skarns in the central and southern Gascoyne Complex is low. In the northwestern region, especially in the Mount Alexander and Kilba Well areas, some potential remains. Further exploration there would require a substantial amount of drilling, and detailed logging of skarn assemblages. Exploration should focus on the identification of the better mineralized retrograde zones, and in particular their geometry and distribution.

KEYWORDS: Tungsten, tungsten deposits, scheelite, skarn, mineral chemistry, rock geochemistry, granitic rock, metamorphic petrology.

Introduction

The term 'skarn' was coined by Swedish miners and referred to Ca–Fe silicate gangue associated with magnetite and sulfide deposits, although deposits of the type were first recognized in the middle of the nineteenth century (Burt, 1982). The summaries of Einaudi et al. (1981) and Einaudi and Burt (1982) highlight the range of studies of skarn systems that have taken place in recent years. Much of the understanding of skarns has derived

from detailed study of deposits in North America (Nokleberg, 1981; Dick and Hodgson, 1982; Newberry, 1982; Cooke and Godwin, 1984), Japan (Ito, 1962; Sato, 1980) and Korea (John, 1963). Significant skarn-hosted tungsten deposits are known from Sweden (Ohlsson, 1979; Hellingwerf and Baker, 1985), France (Soler, 1980) and Australia (Large, 1971).

Scheelite mineralization was discovered to the south of Kilba Well in calc-silicate rocks of the northwestern Gascoyne Complex (Baxter, 1978) by the Australia and

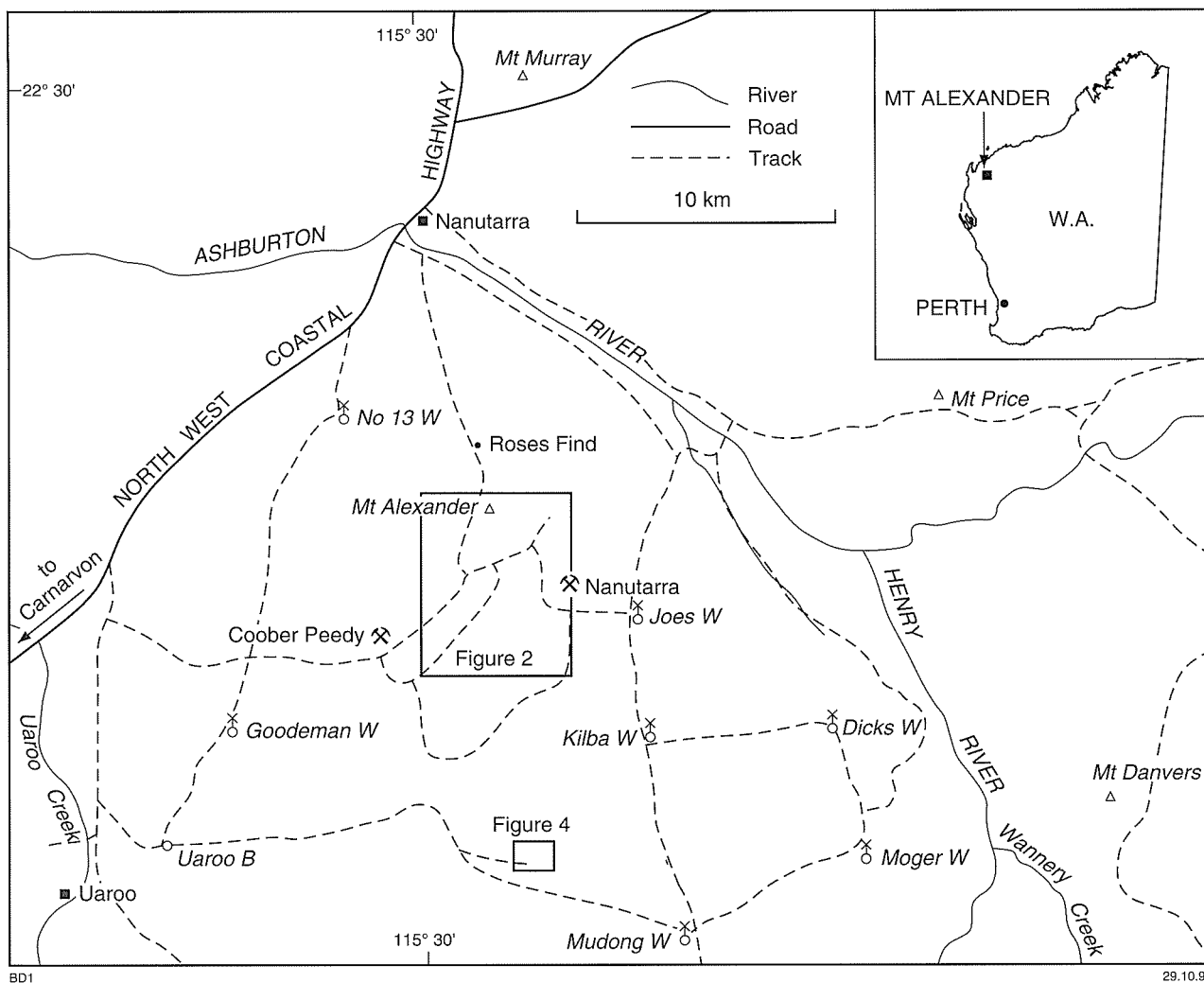


Figure 1. Location of the study area

New Zealand Exploration Company (ANZECO) in 1973 (Fig. 1). Further discoveries near Mount Alexander, approximately 15 km north of Kilba Well (Fig. 1), were investigated by Amax Australia Limited between 1978 and 1981. None of these occurrences was found at the time to be of a sufficient size and grade to justify development, although the Kilba Well occurrences have been re-evaluated in recent years.

The development of a mineralized skarn, an evolutionary process related to the emplacement and crystallization of a pluton, involves:

1. metasomatism (prograde skarn formation) resulting from the generation of a hydrothermal fluid during the final crystallization of the magma and its infiltration and reaction with the host rock type (normally a carbonate-rich host);
2. retrograde alteration of the prograde assemblages caused by the infiltration of a water-rich, cooler and compositionally different fluid that is an evolved product of the first fluid.

The overprinting nature of these processes generally results in distinctive zoning patterns. Much of the theoretical and experimental basis for these mechanisms was investigated by Korzhinskii (1970). Most mineralized skarns display the effects of a retrograde overprint, as it is during this event that most mineralization takes place.

Gascoyne Complex skarns occur as several, commonly small, discrete bodies at or near the contacts between Palaeo- to Mesoproterozoic calc-alkaline granodiorite or monzogranite and Proterozoic, carbonate-bearing, open to tightly folded metasedimentary rocks. Hosts include tremolitic marbles, metamorphosed argillaceous marbles, calc-silicate and biotite hornfels. Swarms of tourmaline- and garnet-bearing pegmatite dykes are common near the skarns.

The skarns display distinctive and regular mineralogical zoning patterns. Assemblages are varied, but typically consist of one or more of wollastonite, garnet, clinopyroxene, vesuvianite, actinolite-hornblende or epidote. Sulfides are uncommon and with rare exceptions account for less than 1% of the assemblage.

The Gascoyne Complex skarns belong to the 'reduced' class of tungsten skarns (Newberry, 1982), from which the bulk of known world WO_3 tonnage is produced. As such, they represent the first documented members of this type in Australia (the King Island skarns belong to the oxidized class). Reduced skarns contain abundant ferrous iron assemblages, including hedenbergitic pyroxene, almandine-rich garnet, biotite and hornblende (Newberry, 1979).

This Report details the geological setting, petrology and geochemistry of both the Mount Alexander and Kilba Well skarn systems. Data on these scheelite skarn systems and associated intrusives will provide, after comparisons with scheelite skarns and associated intrusives found elsewhere, a framework for exploration and evaluation of this skarn type in the Gascoyne Complex and throughout Western Australia. Emphasis during mapping and logging was placed on the mineralogy, timing and geometry of the alteration features in the skarns and, where possible, wall rocks. Mapping of surface exposures, mainly in costeans, was complemented by detailed logging of skarn intersections in diamond drillcore. A total of 430 polished and covered thin sections from the Mount Alexander and Kilba Well skarns and associated rocks was examined, of which 70 polished sections were selected for detailed microprobe investigations of skarn phases.

Nomenclature

Carbonate-hosted mineral deposits continue to suffer from a lack of a universally recognized nomenclature. As a result, considerable confusion exists over what constitutes a 'skarn'. The most recent scheme, proposed by Kwak and Askins (1981a), distinguishes between carbonate-hosted deposits that are in direct contact with an intrusive body and those that are not.

Hess (1919) introduced the word 'tactite' to describe skarns and the former term is still used by some geologists, particularly where scheelite mineralization is present. In many cases tactite is used in conjunction with the term skarn, thus creating unnecessary confusion. The term skarn is in general usage and will be used here; the use of tactite is not recommended. Skarns develop in response to reactions between a carbonate host and exotic cation- and metal-bearing fluids that have infiltrated the host and which were derived from a nearby igneous intrusive. The terms 'exoskarn' and 'endoskarn' refer respectively to skarn formed within the country rocks, usually carbonate rich, and skarn that has formed within the intrusive adjacent to the exoskarn. The term 'magmatic skarn' is a general one and is a synonym for exoskarn. While these terms are in general usage, only exoskarn will be used in this paper. No endoskarn was observed during the course of this study.

Calc-silicate rocks not associated with any known intrusive rock are frequently termed 'metamorphic skarns' (Kerrick, 1977), 'bimetasomatic skarns' and 'reaction skarns' (Kwak and Askins, 1981a; Einaudi and Burt, 1982). Unlike skarns formed through infiltration of

an exotic fluid, metamorphic (bimetasomatic, reaction) skarn assemblages have resulted from local diffusion of components across lithological boundaries. The equivalent rocks found in association with Gascoyne Complex skarns will be termed bimetasomatic, as this term appears to be more widespread than any of the others. In the Gascoyne Complex these rocks are unmineralized, and are mineralogically and texturally simple compared with the mineralized skarns.

Analytical methods

Whole-rock geochemical analyses were carried by XRF using fused glass buttons for major elements and pressed powders for trace elements. Classical techniques were used for FeO (titration) and LOI (gravimetric). Fluorine was determined using a specific ion electrode. All analyses were carried out at the Chemistry Centre (W.A.).

Major-element compositions of the main silicate phases in the skarns were determined on a MAC400S electron microprobe using an accelerating potential of 15 kV and a beam current of 20 nA. A counting interval of 100 seconds was used for each analysis and up to three spots were analysed per grain. Garnet, pyroxene and kaersutite standards were analysed following each sample change and prior to analysing unknowns. Mineral compositions were calculated using a slightly modified version of the correction program of Ware (1981). The analyses for garnet and pyroxene were recalculated to mole percent of the various end members. Garnet end-member calculations are based on the sequence and calculation procedure described by Rickwood (1968).

For the Mount Alexander area, analyses of minerals in marble and various zones in the skarns came from the Mortgage and White Lightning skarns. For the Kilba Well area, samples were predominantly from the Zone 11 mineralization.

Locations of all samples mentioned in this report are listed in Appendix 1.

Geological setting

Regional geology

The Gascoyne Complex forms part of the Capricorn Orogen, a major orogenic belt of predominantly Palaeo- to Mesoproterozoic age, bounded by the Archaean Pilbara and Yilgarn Cratons to the north and south respectively (Gee, 1979; Myers, 1990). The orogen also contains several sedimentary basins, including the Ashburton Basin (Thorne, 1990; Thorne and Seymour, 1991) and the Nabberu Basin (Bunting, 1986; Gee, 1986, 1990), both of which are dominated by argillaceous to arenaceous sedimentary rocks. Most of these older rocks have been covered by those of the Bangemall Basin (Muhling and Brakel, 1985; Williams, 1990).

The Gascoyne Complex, which represents the exposed crystalline core of the Capricorn Orogen, is characterized by several periods of metamorphism, deformation and intrusive activity (Williams, 1986; Myers, 1990). Geochronology indicates that the emplacement of granitic intrusives and tectonism peaked or terminated at 1600 Ma (Libby et al., 1986). Debate still surrounds interpretations of the origin of the complex, with one model invoking ensialic diapirism and gravity sliding (Williams, 1986), and another collision zone tectonics (Tyler and Thorne, 1990; Myers, 1990, 1993).

The geology of the Gascoyne Complex is characterized by large, regionally deformed and undeformed batholithic acid igneous intrusives separated by deformed metasedimentary sequences of the Morrissey Metamorphics. Individual plutons within the batholiths range from granodioritic to granitic in composition and are commonly porphyritic. The porphyritic members are marked by randomly orientated K-feldspar (microcline) megacrysts. Most batholiths are foliated and many plutons display a concentric, internal aureole foliation (Williams, 1986). The metasedimentary rocks are representative of both shelf and trough depositional environments and have been metamorphosed to amphibolite facies, although areas of greenschist facies and granulite facies are present (Turner, 1968; Williams, 1986). Early mapping correlated the Morrissey Metamorphics with the Wyloo Group (Daniels, 1970) supported by recent remapping, which correlates them with metamorphosed Ashburton Formation (Seymour et al., 1988). The latter forms the upper part of the Wyloo Group (Williams et al., 1983), and consists of tremolitic marbles, biotite-muscovite schists, recrystallized BIF, quartzites and amphibolites.

In the Mount Alexander area, which lies within Zone E ('Granitoid plutons and metasedimentary rocks' of the Gascoyne Complex, as described by Myers (1990)), regional metamorphic grade reaches upper greenschist facies, which is lower than the grade attained in the central and southern parts of the Gascoyne Complex (Williams, 1986). The pelitic assemblages typically consist of quartz, biotite, plagioclase, minor muscovite, clinozoisite and tourmaline, and the carbonates contain calcite, tremolite-actinolite and chlorite. Highly impure carbonate bearing rocks are locally dominated by talc and actinolite. Amphibolites have assemblages containing hornblende, plagioclase, sphene and locally minor garnet.

Marbles and calc-silicate units are present throughout the Gascoyne Complex (Williams et al., 1983). Most of the calc-silicate units appear to have a bimetasomatic origin (see below) and occur as bands less than one metre thick within marble. Minor scheelite has been reported from several of these calc-silicate units located in the central Gascoyne Complex (Williams et al., 1983), suggesting that some have an exoskarn component. Contact metamorphism to hornblende hornfels facies overprints the regional metamorphic assemblages. The known mineralized skarns are, however, restricted to the aureoles of several smaller porphyritic plutons that intrude the metasedimentary rocks in the northwestern part of the complex.

Local geology

Mount Alexander

Figure 2 shows the geology of the Mount Alexander area. Metasedimentary rocks have been tentatively correlated with the Morrissey Metamorphic Suite (Daniels, 1975; Williams et al., 1983) and these are surrounded on all but the southern side by the informally named Mount Alexander batholith. The metasedimentary rocks have been folded into a large scale, upright to overturned antiform that plunges to the north-northeast and has an east-southeast vergence. Tight minor folds are common and locally result in complex outcrop patterns.

The local stratigraphy is divided into five informally named metasedimentary units (Fig. 3). The lowermost of these, Unit 1, is dominated by variable but generally fine-grained schistose amphibolite. Unaltered, laminated marbles become common in the upper part of this unit, which is also marked by an increase in the amount of pelitic material. Garnetiferous (almandine) and disseminated sulfide-rich bands are locally present within the amphibolitic members. Pyrrhotite dominates the sulfide assemblages, although minor chalcopyrite and sphalerite are also present. Some of the sulfides may be breccia-hosted in part. Discontinuous lenses of biotite schist, generally less than one metre thick, form a minor part of the Unit 1 sequence. The Mortgage and White Lightning skarns occur as interbedded units up to 7 m thick in marble hosts towards the upper part of the unit.

Unit 2 consists of banded iron-formation (BIF), which averages 200 m in thickness, and minor hematitic sandstone. The unit is discontinuous and wedges out in the southwest and on the eastern limb of the antiform.

Fine-grained mica schists dominate Unit 3. Laminated fine-grained marbles are relatively common, and locally host the scheelite-bearing Aladdins and Camp skarns (Fig. 2). Amphibolites also occur, but these are volumetrically insignificant.

Unit 4 consists of a massive, fine-grained quartzite. A basal conglomerate containing well-rounded quartzite pebbles is locally present.

Unit 5, which consists of mica schists and amphibolites with minor marbles and quartzites, occupies a tight synform in the western part of the area, and forms a belt adjacent to the regional batholith in the east. In the eastern area, many of the marbles adjacent to the batholith show barren bimetasomatic skarn development in fine-grained, laminated marbles. Thin chrysotile veins have developed in some of these. Massive talc and/or tremolite has formed within impure marbles in the northwest.

The whole sequence has been extensively intruded by tourmaline-garnet pegmatite dykes, which do not occur within the regional batholithic rocks, but are closely associated with the non-porphyritic, tourmaline-bearing Mortgage monzogranite (Fig. 2) and local equivalents that are associated with the mineralized skarns.

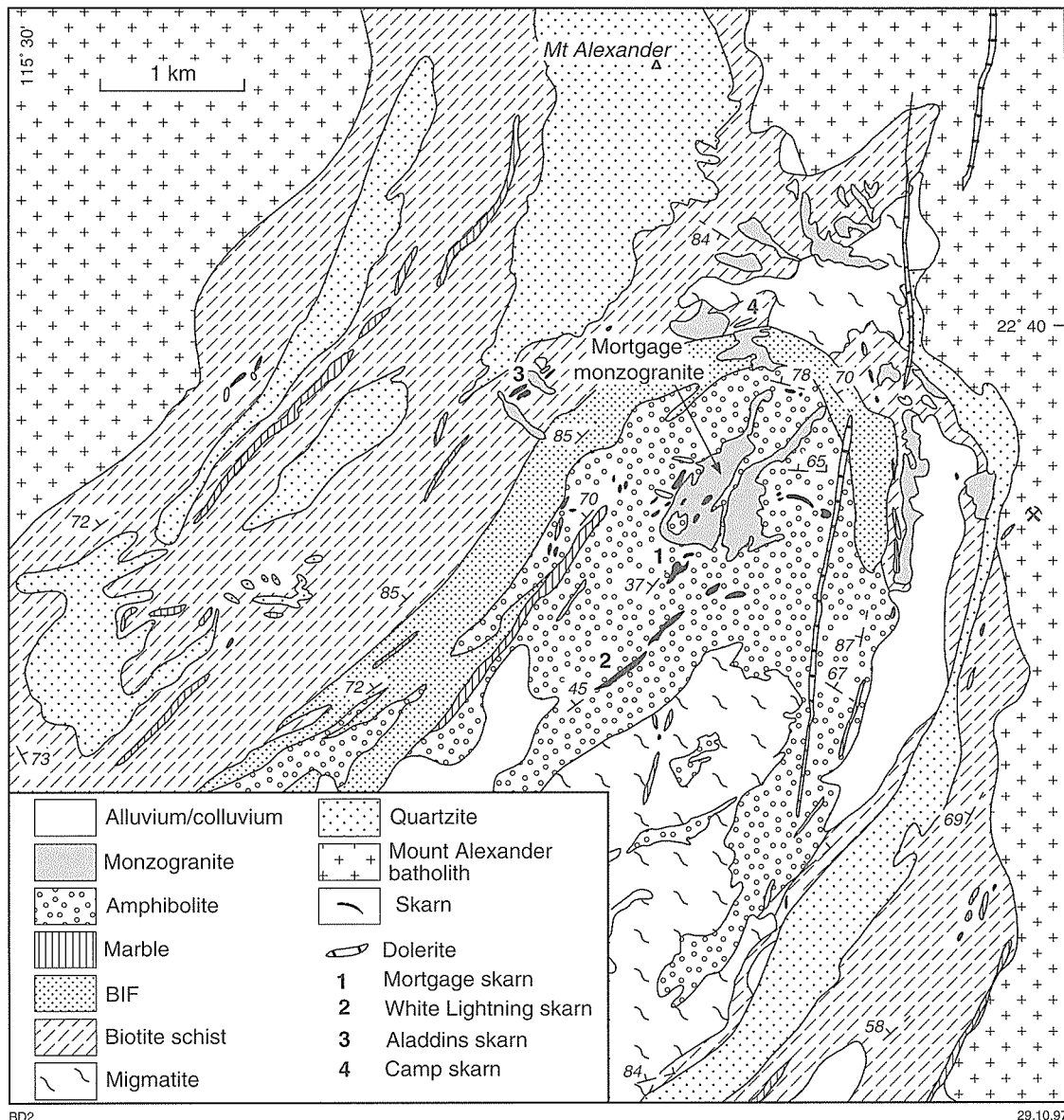


Figure 2. Geology of the Mount Alexander area showing location of Mortgage, White Lightning, Aladdins, and Camp skarns

The mineralized skarns in the Mount Alexander area are the Mortgage, White Lightning, Aladdins and Camp skarns (Fig. 2).

Kilba Well

Figure 4 shows the general geology around the Kilba Well skarns. The metasedimentary rocks have been divided into three units, all of which wrap concentrically around, and dip outwards from, a central monzogranite stock. Unit boundaries are gradational and are not so well defined as in the Mount Alexander area.

Unit 1 is in contact with the stock and consists of mica schist, concordant fine-grained amphibolite and minor

quartzite. This lowermost unit grades into Unit 2, which averages 200 m in thickness and is dominated by biotite- and muscovite-bearing psammitic schists, marble and skarn with minor amphibolite and quartzite. Marbles are laminated and are fine to medium-grained. Folding on meso- and macroscales is common in all rock types in Unit 2, with hinge surfaces subparallel to the monzogranite contact. The two-mica psammitic schists commonly contain tourmaline as an accessory phase. Quartzites, which are massive and partly micaceous, locally grade into psammitic schists.

Unit 3 is dominated by massive, banded to partly flaggy and schistose quartzites bearing clinzoisite-epidote and actinolite. Muscovite schists, minor marbles and rare skarns are also present.

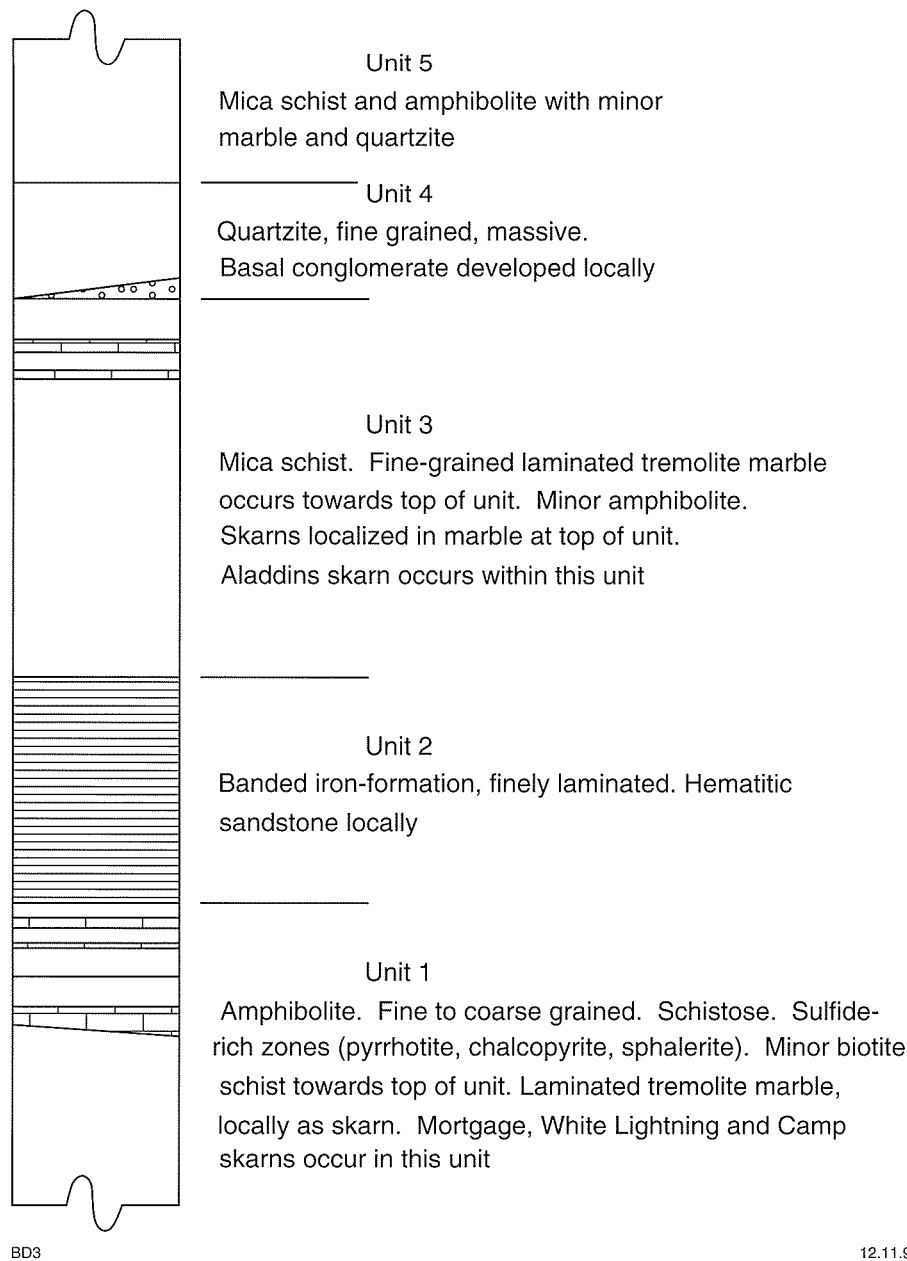


Figure 3. Local stratigraphy (schematic) in the Mount Alexander area

All three units are extensively intruded by tourmaline-bearing pegmatite dykes (Figs 5 and 6) which are probably related to the monzogranite stock that has intruded the sequence. Tourmaline-dominant assemblages locally define an alteration halo adjacent to these dykes. The monzogranite stock has a distinct aureole foliation which is approximately parallel to both the steep, outwardly dipping contact and bedding in the metasedimentary rocks.

Intrusive rocks

Three distinctive intrusive phases have been recognized in the Nanutarra and Uaroo areas. The first of these

comprises the porphyritic members of the Mount Alexander batholith, which occurs to the east, north and west of Mount Alexander, and to the east and northeast of, and adjacent to the Kilba Well skarns; the second phase is essentially equigranular and is closely associated with the Mount Alexander skarns; the third phase consists of swarms of pegmatite dykes and sills that are common within the metasedimentary country rocks.

Reconnaissance petrological, whole-rock geochemical and modal analyses were undertaken on a suite of samples representing all of the known intrusive phases. The nomenclature used in this Report follows that of Streckeisen (1976).

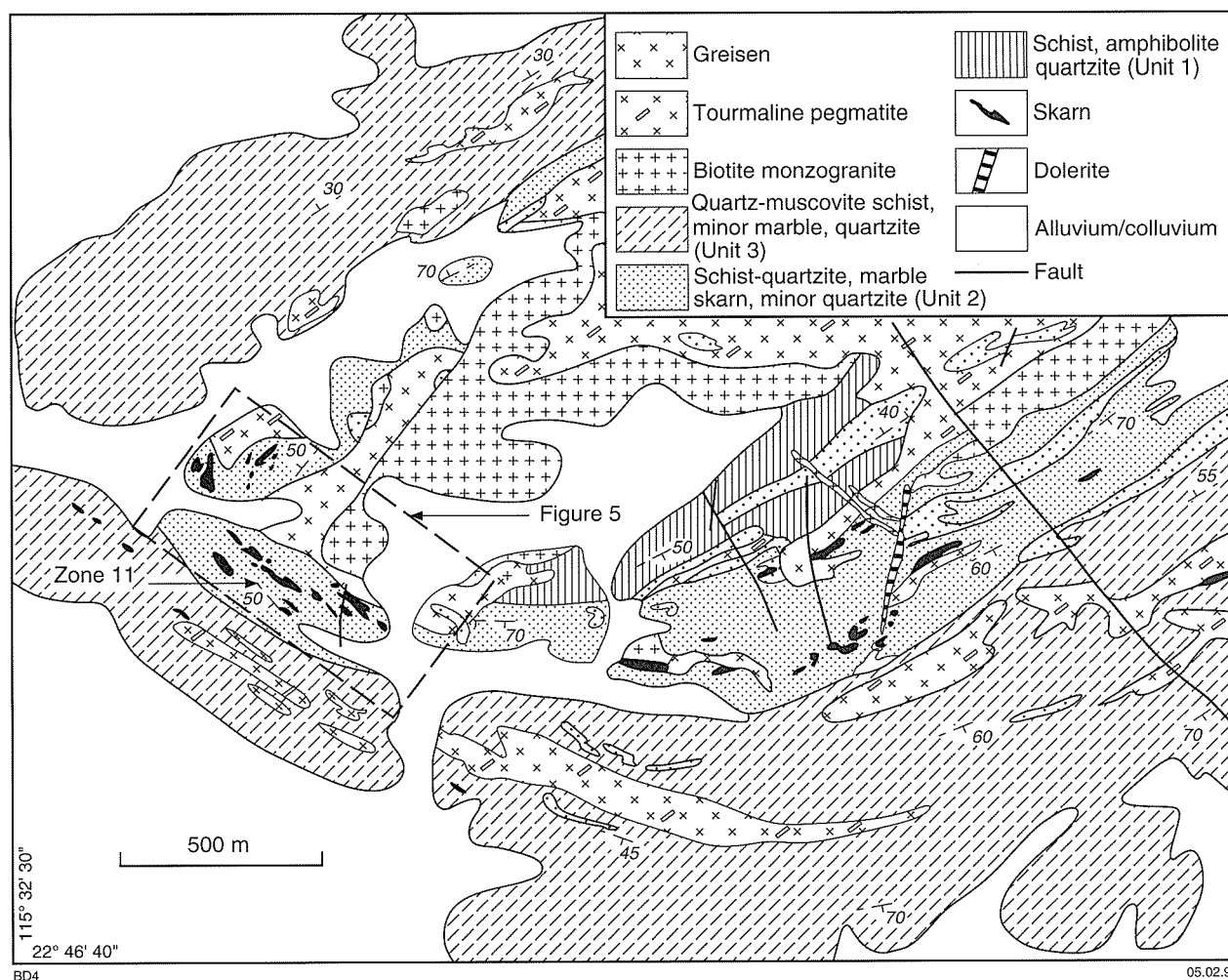


Figure 4. Geological map of Kilba Well prospect showing location of the Zone 11 area

Mount Alexander batholith and Mortgage monzonite stock

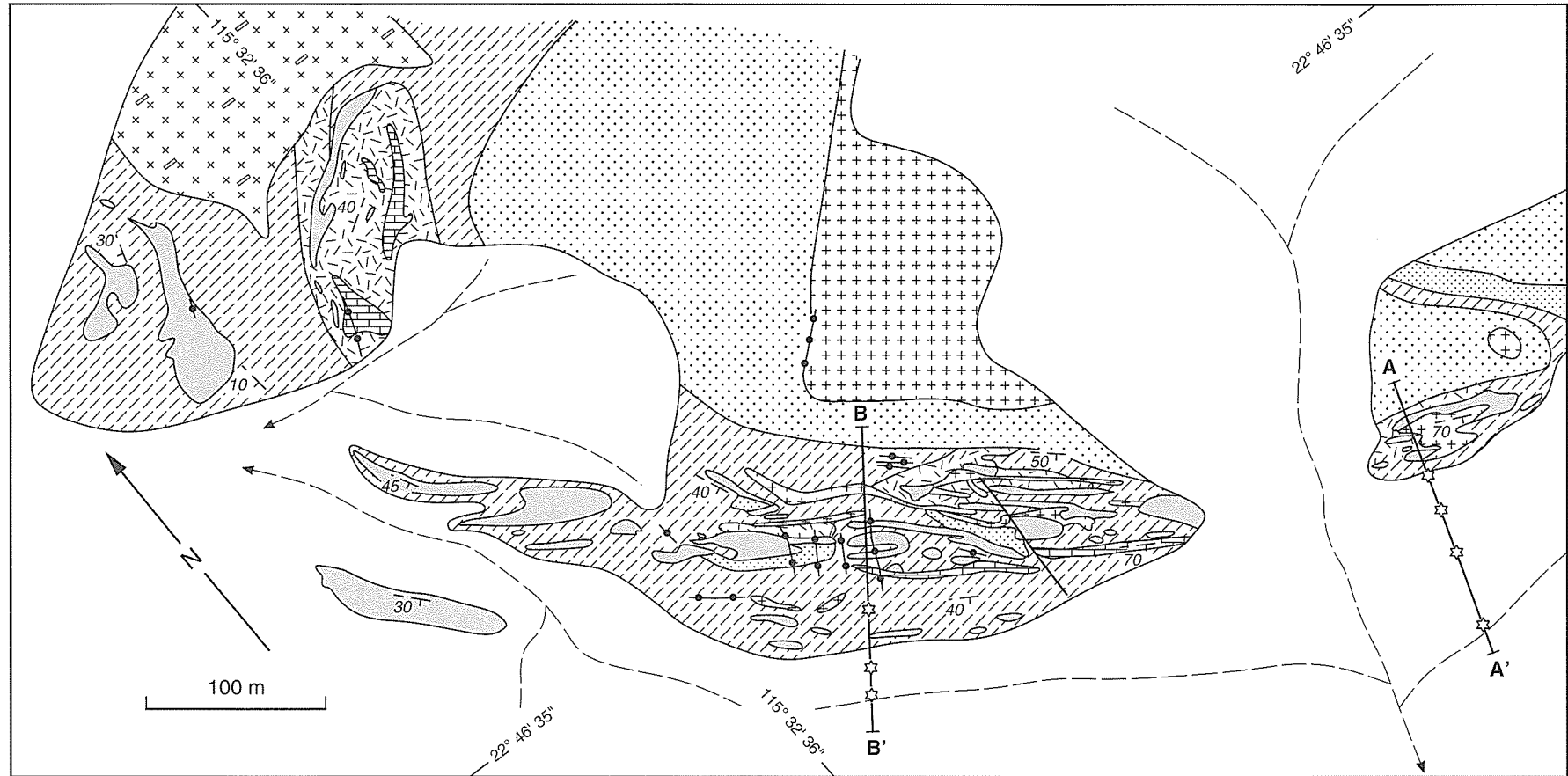
The Mount Alexander batholith has an inverted 'U shaped' outcrop pattern centred on Mount Alexander and covers approximately 450 km² (Fig. 2). The batholith was referred to as the Kilba Granite by Daniels (1965) and consists predominantly of porphyritic granodiorite and monzogranite. Late and generally weak syn- and/or post-emplacement alteration has resulted in departures from what would normally be considered 'average' compositions for these rock types. These effects are evidenced by apparent inconsistencies between geochemical and mineralogical compositions of samples collected from the Mount Alexander area. Appendix 1 lists locations of analysed granitoid samples.

The granodioritic phases in the east and in areas to the north of Mount Alexander consist of subhedral to euhedral microcline megacrysts up to three centimetres long, set in a coarse hypidiomorphic-granular, quartz-plagioclase-microcline-biotite groundmass. The modal mineralogy ranges from 30 to 45% quartz, 25 to 35%

zoned plagioclase (predominantly oligoclase), 5 to 10% microcline, 2 to 20% biotite and 5 to 10% muscovite. Biotite occurs in irregularly shaped clots, commonly in conjunction with muscovite. A weak, contact parallel, magmatic foliation, defined by a preferred phenocryst orientation, is found adjacent to the metasedimentary rocks. The remainder of the granodiorite contains no pervasive or regular penetrative fabrics.

Dyke-like zones of sericitic alteration up to 3 m wide and several tens of metres, long within which a relict porphyritic texture is preserved, constitute an unusual feature of the granodiorite. They have been observed only in the marginal zones of the eastern porphyritic granodiorite. A more irregular zone of sericitic alteration is present at Roses Find (Fig. 1), where a mineralized (U, Pb) quartz vein system is hosted by a sub-porphyritic monzogranite to the north of Mount Alexander. Such alteration does not appear to occur as abundantly in the northern areas as it does in the eastern granodiorite.

Multiple intrusive episodes are suggested by the presence of subporphyritic to hypidiomorphic granular monzogranite in the batholith. No distinct



BD5

29.10.97

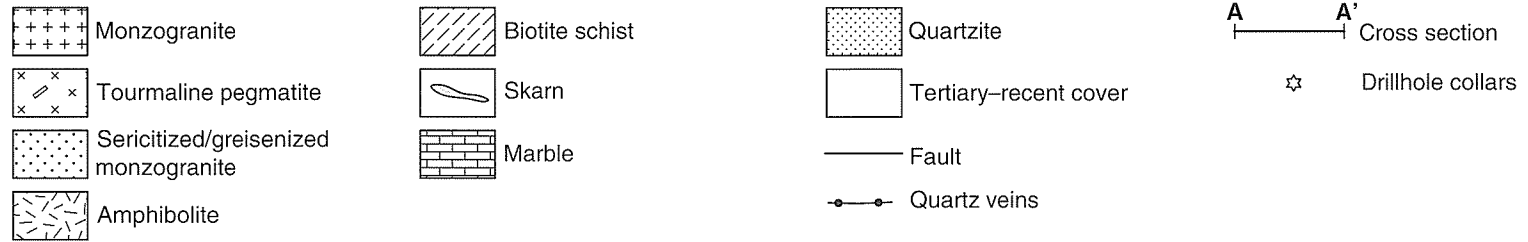


Figure 5. Simplified geological map of the Zone 11 area at Kilba Well prospect

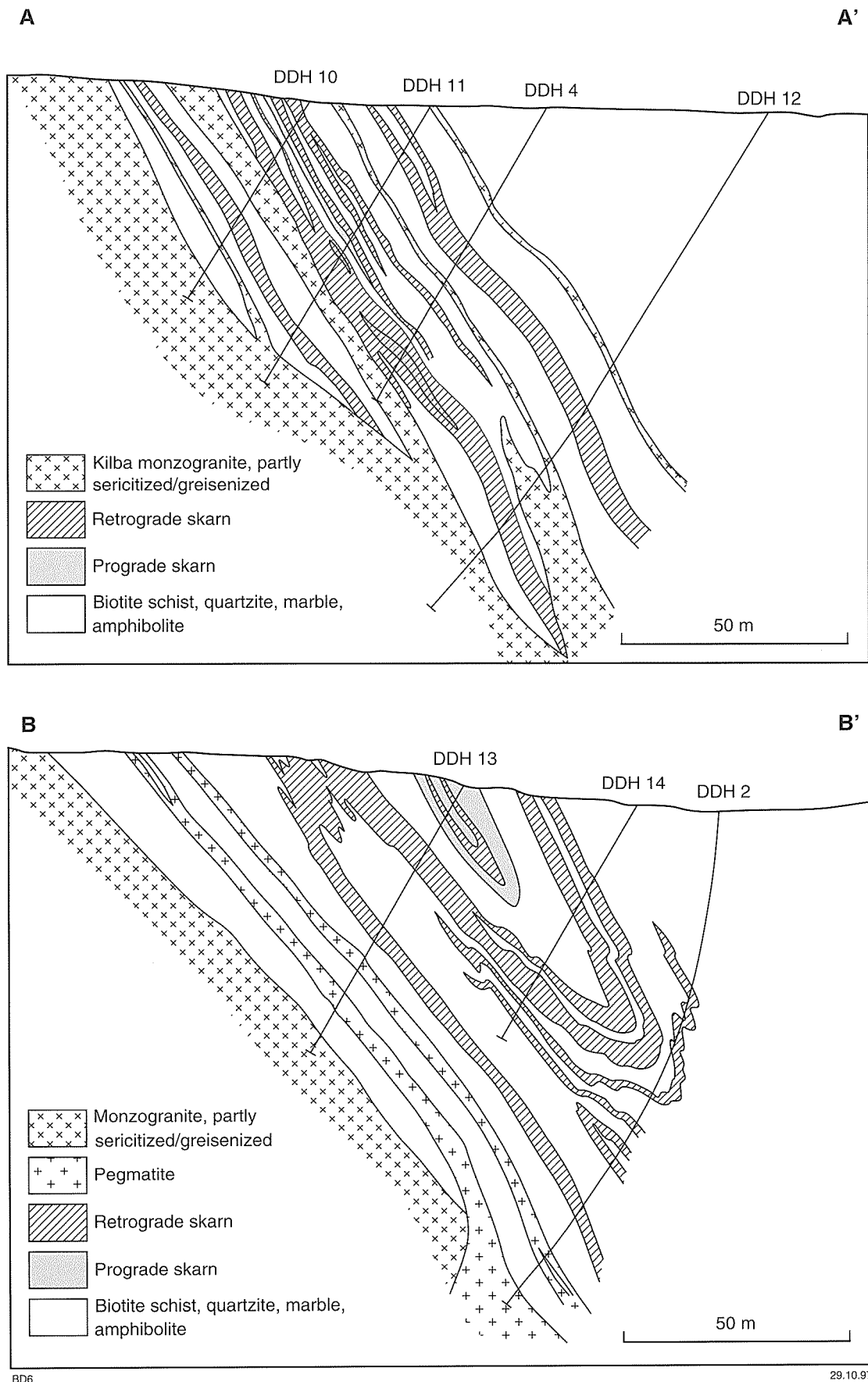


Figure 6. Representative cross sections through skarns in Zone 11, Kilba Well prospect. See Figure 5 for locations of sections

boundaries between monzogranite and granodiorite have been observed and the relative proportions are unknown. Modal analyses indicate that some of these are transitional with respect to granodiorite and it is not clear whether they represent local differentiated phases, or discrete plutons. The results from thin-section counts show that the monzogranitic phases typically contain 20 to 30% quartz, 25 to 40% plagioclase (average An 15), 20 to 25% K-feldspar, 10 to 15% biotite and 5 to 10% muscovite. The proportions of K-feldspar may be higher, as the modal analyses were carried out on unstained samples.

The monzogranites are typically myrmekitic in contrast to the granodioritic phases. In the subporphyritic monzogranite phase north of Mount Alexander, myrmekite is particularly common, occurring in conjunction with coarse muscovite and biotite, and microcline phenocrysts. Myrmekite is also associated with fine granular quartz–plagioclase–microcline domains in a coarse inequigranular to subporphyritic monzogranite stock that has intruded the metasedimentary rocks some 4 km south of Mount Alexander. Myrmekite is present, but uncommon, in the Mortgage monzogranite stock which intrudes Unit 1 amphibolites approximately 2.5 km south of Mount Alexander and just north of one of the larger skarns in the area. This monzogranite typically displays a foliation defined by the alignment of biotite clots and is locally sheared. This fabric is weakly developed, although up to 30% of the rock is composed of anastomosing, or patchy, very finely grained feldspar–quartz domains in which the myrmekite occurs. The stock also contains tourmaline-bearing quartz veins and rare amphibolite xenoliths and is intruded by pegmatite dykes.

It is not clear whether the monzogranite stocks south of Mount Alexander are part of the Mount Alexander batholith, or represent a period of unrelated magmatism.

Pegmatites

Pegmatites are generally uncommon within the main body of the batholith. In this setting they are discontinuous, forming dykes, lenses and podiform masses within the granodiorite. They may extend for tens of metres and reach three metres in width. Podiform pegmatites are up to three metres thick and generally have transitional boundaries with respect to the granodiorite host. They probably represent trapped pockets of an evolved aqueous fluid-rich phase in the cooling granodiorite. The majority of the pegmatites within the batholith contain simple assemblages of quartz, alkali feldspar and muscovite, and are of variable grainsize and texture.

Pegmatites in the swarms that occur in and around the two monzogranite stocks south of Mount Alexander have more varied mineralogy. Feldspars are dominated by microcline and sodic plagioclase, mainly albite (An 6–9) with minor oligoclase (to An 16), muscovite, tourmaline and garnet. Tourmaline is ubiquitous and occurs as fine to coarse-grained, subhedral to euhedral blue to green grains, and display irregular, but distinct, concentric zoning in basal sections. Modes range from <1% to 10%. Pink to pale-brown, fine-grained garnets

are almost always associated with the tourmaline. In thin section the garnets are anhedral to euhedral and usually well fractured. Some also show fracture-controlled alteration by phyllosilicates, mainly biotite. Altered garnets may be accompanied by unaltered garnets and both types are commonly intergrown with tourmaline, muscovite and the other silicates.

Little pervasive alteration of the pegmatites has occurred. Fine-grained muscovite or sericite is present along some feldspar grain boundaries and as disseminated fine-grained muscovite and sericite in plagioclase. With the exception of a patchy, fine, brownish dusting, microcline remains essentially unaltered.

A slightly modified assemblage was noted from a single dyke that intersects a skarn and consists of albite–oligoclase with minor quartz and accessory apatite, muscovite, calcite and clinozoisite. Only minor K-feldspar is present and this is concentrated around the margins of quartz-rich domains. An unidentified very fine-grained reddish brown mineral, possibly garnet, and rare pale blue tourmaline have also been observed. The feldspars display strong concentric and reverse zoning. The latter is evident in individual grains and also in what appear to be single, coarse grains, suggesting overgrowths of plagioclase of similar or equivalent composition on primary, fine-grained plagioclase.

Geochemistry of the Mount Alexander batholith

A suite of eleven representative samples from the main members of the Mount Alexander batholith and of the stocks and pegmatites intruding the metasedimentary rocks were collected and analysed (Table 1). All phases are highly evolved, as indicated by high SiO_2 , K_2O and Rb values. Alteration has caused some modification of the composition.

The granites are characteristically silicic and appear to be compositionally homogeneous. They have an average of 73.8% SiO_2 , 13.9% Al_2O_3 , 0.7% CaO and 7.8% combined alkalis. They are peraluminous with $(\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO})/\text{Al}_2\text{O}_3$ ranging between 0.84 and 0.76, and contain minor normative corundum. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios differ little, averaging 0.66. Anomalous F and Li and elevated B values are typical.

The monzogranite (90651)* to the north of Mount Alexander shows minor increases in Ca and Zr, and a major increase in Sr, but decreases in Rb, Nb, and F relative to a granodiorite sample collected from an area southeast of Mount Alexander (90646). The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio is 0.76, but the rock remains marginally peraluminous and contains minor corundum in its norm. Granodiorites intruding the metasedimentary rocks show a significant change in geochemical characteristics relative to those forming part of the main batholith. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios have increased to 1.22 and 2.36 for samples 90652 and 90658 respectively. This increase reflects the overall lower phyllosilicate and K-feldspar

* specimen identifiers — see Appendix 1 for locations

Table 1. Geochemistry of Mount Alexander granitoids

Specimen	Granodiorite			Monzogranite		Garnet-tourmaline pegmatites					Altered
	90646	90648	90651	90652	90658	90645	90649	90653	90654	90655	90647
	Percentage										
SiO ₂	73.60	74.00	73.50	74.40	73.00	74.90	77.00	75.00	71.30	70.40	77.30
TiO ₂	0.10	0.12	0.15	0.01	0.14	bld	bld	bld	bld	bld	0.12
Al ₂ O ₃	13.90	15.00	13.90	14.00	15.40	14.00	13.10	14.50	16.80	17.40	13.80
Fe ₂ O ₃	0.40	0.40	0.40	0.10	0.20	bld	0.70	0.60	0.20	0.20	0.70
FeO	0.75	0.75	1.08	0.47	0.96	0.21	0.57	0.43	0.36	0.47	0.50
MgO	0.30	0.21	0.28	0.09	0.25	0.02	0.04	0.05	0.02	0.04	0.50
MnO	0.05	0.03	0.02	0.02	0.02	0.01	0.20	0.11	0.06	0.06	0.02
CaO	0.66	0.73	1.32	0.75	1.59	3.97	0.30	0.23	0.51	0.44	0.08
Na ₂ O	3.18	3.09	3.52	4.80	5.53	4.84	4.09	4.55	7.46	6.96	0.08
K ₂ O	4.85	4.59	4.66	3.95	2.34	0.33	2.86	3.31	1.90	2.34	4.60
P ₂ O ₅	0.09	0.13	0.09	0.05	0.05	0.49	0.21	0.25	0.49	0.40	0.11
LOI	1.44	1.29	0.97	0.51	0.62	0.66	0.62	0.52	0.69	0.78	2.04
Others	0.14	0.17	0.52	0.04	0.09	0.11	0.52	0.51	0.32	0.23	0.17
Total	99.46	100.51	100.41	99.19	100.19	99.54	100.21	100.06	100.11	99.72	100.02
	Parts per million										
B ₂ O ₃	37	25	80	8	9	38	4 311	3 858	1 146	52	75
F	985	1 574	853	42	108	758	422	653	1 217	1 003	1 324
Li	50	60	48	14	22	6	22	16	160	210	78
Mo	bld	bld	bld	bld	bld	bld	bld	bld	bld	bld	bld
Nb	20	28	13	8	11	9	105	80	81	98	21
Rb	357	332	266	129	128	25	334	613	711	932	431
Sn	bld	bld	bld	bld	bld	bld	bld	bld	24	24	bld
Sr	51	71	208	87	361	473	18	bld	19	20	6
Th	28	19	37	11	24	bld	13	bld	bld	bld	32
U	4	14	4	2	2	1	2	1	4	3	2
W	bld	bld	bld	bld	bld	bld	bld	bld	bld	bld	bld
Zr	108	62	160	51	160	29	27	22	28	21	112

LOI = loss on ignition; bld = below limit of detection
Sample locations are listed in Appendix 1

content of these marginally peraluminous intrusives. Major differences are also found in trace element abundances, particularly for B, F, Li, Rb and Th, which are generally less abundant relative to the main batholithic monzogranite and granodiorite. Strontium contents are slightly higher.

Pegmatite compositions (Table 1) show significant variations, particularly for minor and trace elements. The dyke (90645) that intrudes the Mortgage skarn 2.5 km south of Mount Alexander is compositionally distinct from the granodiorites or monzogranites, but does show some affinity with the tourmaline-garnet pegmatites. Of the major elements, Ti, Fe³⁺, Fe²⁺, K and particularly Mg are all significantly lower than in the main batholithic phases. However, P and Ca are higher, reflecting increased modal amounts of apatite and accessory calcite. The trace elements F and Sr are anomalously high, particularly Sr (473 ppm). Significant depletions in Li, Nb, Rb, Th, U and Zr relative to members of the Mount Alexander batholith are also evident.

Pegmatites containing tourmaline and garnet are compositionally more heterogeneous. Their SiO₂ contents vary from 70.4 to 77.0%, Al₂O₃ from 13.1 to 17.5%, Na₂O from 4.09 to 7.46% and K₂O from 1.90 to 3.31%. Phosphorus is higher and Ti lower than in the granitoids. Pegmatites close to skarns containing the higher tungsten grades have Na₂O/K₂O ratios of 1.37 and 1.43 (90653 and 90649 respectively), whereas those associated with the

poorly mineralized skarns show the higher and more disparate ratios of 2.97 and 3.93 for samples 90655 and 90654 respectively. Highly anomalous B contents result from the presence of abundant tourmaline. Fluorine is variable, but anomalous, reaching a maximum of 1217 ppm in sample 90654. Lithium contents are also highly variable, ranging from 16 to 210 ppm in the four samples analysed. Of the other elements, Nb and Rb are more abundant than in the granitoids, but Sr, Th and Zr are lower.

A single sample (90647, Table 1) of the sericitized dyke-like zones, which transgress the contact zone of the granodiorite at the western margin of the Mount Alexander batholith, shows an increase in SiO₂ and a major decrease in Na₂O, CaO and Sr abundances. These variations correspond to the breakdown of plagioclase. Fluorine, Li, Rb and to a lesser extent Th and Zr are variably enriched in the altered zones.

Kilba Well intrusives

Skarns in the Kilba Well area (Figs 4 and 5) are spatially related to an oval-shaped porphyritic monzogranite stock which intrudes metasedimentary rocks about 4 km from the nearest contact with the Mount Alexander batholith. Structural data from the contact zone suggest a forceful and possibly diapiric emplacement of the stock. A low-angle, concentric aureole foliation (S_A) is developed in

the country rocks and marginal zones of the stock. The intensity of S_A in the monzogranite decreases towards the core of the intrusive and is probably magmatic, based on the criteria of Paterson et al. (1989).

Although the core of the monzogranite is equigranular, the mid to outer parts contain very coarse, anhedral, microcline phenocrysts up to 2 cm in the long axis set in an equigranular quartz–plagioclase–microcline–mica groundmass. The average primary modal composition is 27% quartz, 30% plagioclase (An 14), 22% microcline, 12% biotite, $\leq 1\%$ muscovite and minor apatite and chlorite. Quartz is highly strained and frequently fractured with irregular, anastomosing but discontinuous zones of fine subgrain-like recrystallized quartz and plagioclase. This suggests a component of solid-state deformation during cooling following emplacement. These features form up to approximately 15% of the rock. Myrmekite is common, particularly in conjunction with the fine, granoblastic quartz zones. Fine muscovite or sericite is found along grain boundaries and incipiently replacing plagioclase. The latter usually displays well developed concentric zoning.

Pegmatites

Numerous tourmaline–garnet-bearing pegmatite dykes intrude the metasedimentary rocks near the monzogranite contact, and the marginal zone of the stock itself. They are generally coarse-grained, equigranular rocks, locally subidiomorphic. The dykes contain subhedral, green to bluish-green, distinctly zoned tourmaline. Fractured anhedral to subhedral garnet is altered in places to chlorite and sericite. Minor myrmekite is also present.

Alteration in the Kilba Well monzogranite

The marginal zones of the stock show varying degrees of pervasive sericitic and greisen alteration. Along the western contact zone of the monzogranite this alteration is of an intermediate intensity and is expressed as a dense dusting of plagioclase by fine- to very fine-grained sericite. Coarse secondary muscovite is present but uncommon, whereas chlorite and variably chloritized biotite occur throughout. Clinozoisite is common, although it is fine-grained and normally associated with muscovite. Carbonates, dominated by calcite, form a minor component of the assemblage. Along the southern margins of the stock, the intensity and volume of alteration increases with secondary muscovite and tourmaline becoming more abundant.

The most intense alteration in the stock is restricted to narrow linear zones up to 5 m wide and 20 m long within 50 m of the southwestern and southern contacts. These zones occur at various but often moderate to high angles to the contact and overprint S_A . Quartz veins up to 3 cm wide, many containing drusy cavities, are common to most of these zones. Crackle brecciated wall rocks are ubiquitous. Three alteration facies can be recognized: 1) a quartz–muscovite rock; 2) a quartz-rich rock in which muscovite is a minor constituent; 3) a

tourmaline-rich rock in which tourmaline occurs as pods within one of the former two styles.

The quartz–muscovite rock also occurs in discontinuous zones that are aligned parallel or subparallel to S_A . The siliceous rock is known, however, to be associated only with the veins and breccias that are transgressive to S_A .

Quartz–muscovite alteration is characterized by coarse-grained and radiating aggregates of muscovite set in a medium-grained quartz–calcite–apatite and fine-grained sericitic matrix. Rare feldspar remains, but this alteration replaces primary mineralogy and is texturally destructive. The relatively high apatite and calcite abundances are not known from other alteration types encountered in the area. Relict vugs, now infilled by quartz, calcite and apatite occur sporadically throughout the rock. A relict primary equigranular texture is preserved in the quartz-rich siliceous alteration assemblage, although very fine-grained sericite almost completely replaces feldspar. Coarse secondary muscovite is preferentially developed adjacent to quartz–muscovite veins in this facies and skeletal green-brown tourmaline is common. Relict biotite is normally associated with an iron-oxide phase.

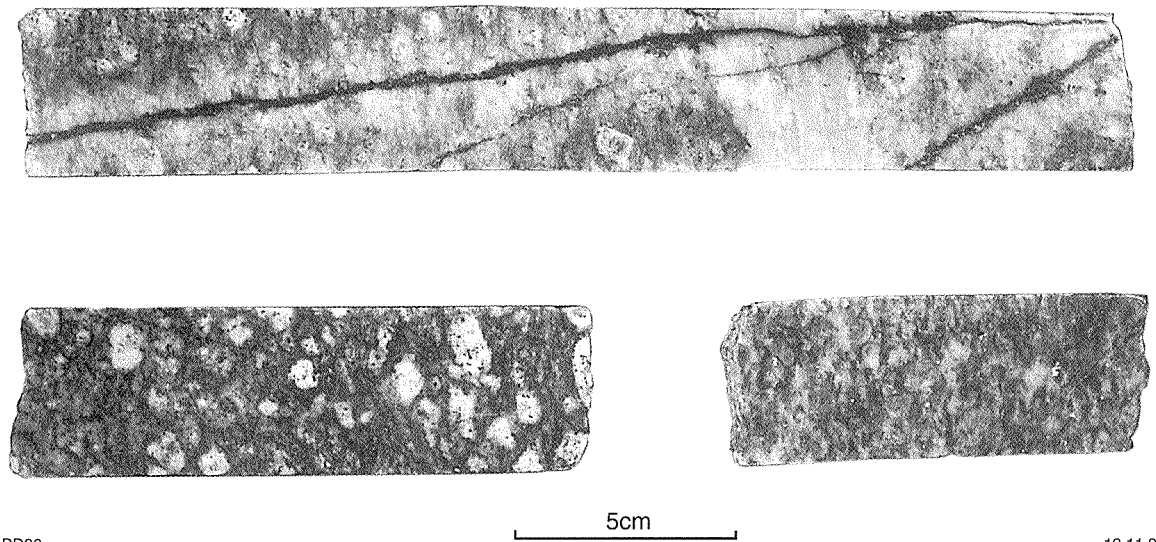
Quartz–tourmaline veining is common within the altered margin of the monzogranite with quartz fill typically predominant. Where tourmaline dominates, it is accompanied by chlorite, sericite, calcite, pyrrhotite and chalcopyrite. Cassiterite has been tentatively identified in two of the tourmaline-rich veins. Sericite with subordinate tourmaline forms alteration selvages up to 6 cm wide adjacent to veins, tourmaline forming clots up to a centimetre in diameter in places (Fig. 7).

Geochemistry of the Kilba Well intrusives

Monzogranite

Three samples of monzogranite were geochemically analysed (Table 2). The monzogranite here is also highly evolved with 73.6% SiO_2 , 4.26% K_2O and 250 ppm Rb in a sample (90491) collected from the central, unaltered part of the stock. The $(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})/\text{Al}_2\text{O}_3$ ratio of 0.91 for this sample indicates that it is marginally peraluminous. All three samples have consistent major-element compositions with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios ranging between 0.78 and 0.91, although the lowest was derived from the unaltered sample. Variations in the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios result from the pervasive sericitization evident in samples collected from the western and southern margins of the stock. Total iron contents increase dramatically in the latter areas as a result of changes in FeO. This is shown by an $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio of 0.72 for unaltered monzogranite, compared with 0.25 (90490) and 0.23 (90492) for the marginal rocks.

The minor-element signature of the unaltered monzogranite is indistinguishable from that of the monzogranites in the Mount Alexander area. Only marginal increases in Li, Sr and Th were noted, and local



BD30

12.11.97

Figure 7. Intense sericitic alteration adjacent to tourmaline-bearing veins in Kilba Well monzogranite. Note zoning of alteration in feldspar phenocrysts (specimen 90364)

Table 2. Geochemistry of Kilba Well granitoids

Specimen	Monzogranite			Garnet-tourmaline pegmatites				Altered	
	90490	90491	90492	90493	90496	90609	90610	Q-musc 90497	Siliceous 90498
	Percentage								
SiO ₂	72.90	73.60	73.90	74.10	74.80	75.70	74.10	59.10	77.70
TiO ₂	0.17	0.13	0.13	0.01	bld	bld	0.01	0.02	0.15
Al ₂ O ₃	14.00	14.00	14.00	15.10	14.70	13.50	14.40	22.80	13.70
Fe ₂ O ₃	0.40	0.70	0.30	0.70	0.60	0.20	0.20	0.70	0.90
FeO	1.58	0.97	1.33	0.35	0.43	0.26	0.23	0.30	0.66
MgO	0.42	0.31	0.32	0.12	0.08	0.12	0.17	0.60	0.56
MnO	0.03	0.03	0.03	0.04	0.05	0.02	0.02	0.10	0.02
CaO	1.61	1.43	1.47	0.53	0.50	2.06	1.40	3.94	bld
Na ₂ O	3.46	3.33	3.60	3.85	4.02	3.95	3.58	0.19	0.06
K ₂ O	3.82	4.26	4.34	4.20	3.80	2.05	4.26	6.96	4.63
P ₂ O ₅	0.09	0.07	0.08	0.12	0.15	0.13	0.15	1.25	0.06
LOI	1.05	0.64	0.85	0.74	0.69	2.24	1.45	4.96	2.07
Others	0.10	0.09	0.11	0.48	0.50	0.13	0.25	0.24	0.11
Total	99.63	99.56	100.46	100.34	100.32	100.36	100.22	101.16	100.62
	Parts per million								
B ₂ O ₃	30	18	42	4 236	4 305	858	1 768	318	71
F	350	73	370	131	325	295	573	1 533	187
Li	54	64	52	10	12	12	14	80	84
Mo	bld	bld	bld	bld	bld	bld	bld*	bld	bld
Nb	13	14	17	6	10	5	9	bld	15
Rb	193	250	280	291	367	150	202	584	405
Sn	bld	bld	bld	bld	bld	bld	bld	32	bld
Sr	149	124	116	36	21	52	51	33	5
Th	28	26	25	17	11	bld	bld	23	30
U	2	2	1	6	6	1	1	2	2
W	bld	bld	bld	bld	bld	bld	bld	bld	bld
Zr	168	139	144	56	39	14	19	167	151

LOI = loss on ignition; bld = below limit of detection; Q-musc = quartz-muscovite alteration
Sample locations are listed in Appendix 1

increases in B and F in the marginal zones of the monzogranite reflect the pervasive alteration present in those zones.

Pegmatite

There are some significant variations in composition among the four tourmaline–garnet pegmatites samples (Table 2). Components are highly variable, although distinctions can be made on the basis of whether the rocks are associated with skarn mineralization, or intrude metasedimentary rocks in the absence of skarn.

Samples 90493 and 90496 represent the large dyke-like bodies of pegmatite that intrude the metasedimentary rocks near the contact with the monzogranite. These show relatively consistent compositions amongst the major elements with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of 0.92 and 1.06 respectively. High B values in both samples reflect the abundant tourmaline in these rocks. Fluorine, and to a lesser extent Rb, Sr and Zr, also shows minor variations between the samples.

Samples 90609 and 90610 were collected from pegmatites that intrude skarns and/or their immediate host rocks. The analytical results reflect the slight changes in mineralogy resulting from alteration. The most significant variations in the major elements are lower Fe_2O_3 , FeO and MnO, and higher and more varied CaO compared with those pegmatites with no skarn association. These variations reflect the presence of calcite and the generally lower modal proportion of tourmaline in the skarn-related pegmatites. Lower B, Rb, U, Th and Zr are characteristic trace-element trends, as is a minor enrichment in Sr relative to the other pegmatites.

Alteration

Samples of both the quartz–muscovite and siliceous alteration facies were collected from the contact zone of the monzogranite. The quartz–muscovite assemblage (sample 90497; Table 2) is characterized by low SiO_2 and Na_2O and high Al_2O_3 , MgO, MnO, CaO, K_2O and P_2O_5 , which reflects the dominance of muscovite and the presence of calcite and apatite. That tourmaline is present in only minor proportions is indicated by the relatively low but anomalous B value obtained for this sample. The values of F, Li, Rb and Sn are the highest of any rock from the Kilba Well area analysed during this study. Strontium and Nb are depleted relative to analyses of the other rocks, whereas Zr remains at levels similar to those found in unaltered monzogranite.

In the siliceous alteration facies (90498), a slight increase in FeO and MgO compared with that in the quartz–muscovite facies can be linked to the presence of minor amounts of tourmaline and relict biotite in the sample. The low CaO and Na_2O confirms the absence of calcite and feldspar in this facies. Variations in trace-element contents compared with those in the monzogranite are restricted to a decrease in F, increases in B, Li and Rb, and a significant depletion in Sr. These features can be related to the complete replacement of feldspars by sericite and are similar to the patterns in the

samples (90490, 90492) of monzogranite collected from the margins of the stock. Boron, F, Rb and Sr values are all substantially lower in this facies compared with those of the quartz–muscovite facies, with F showing almost a ten-fold depletion.

Analysis of tourmalines (Table 3) from the altered zones indicates a dominance of the schorl component. Tourmalines generally display a strong colour zonation in basal section, ranging from blue-green in the cores to the yellowish brown of increasing dravite towards the rims (Table 3).

Summary of granitoid characteristics

Intrusive rocks associated with the northwest Gascoyne Complex tungsten skarns are granodiorites and monzogranites. Most phases occur as part of the Mount Alexander batholith, although the mineralized skarns are spatially associated with monzogranite stocks. It is unclear whether these stocks are directly related to emplacement of the Mount Alexander batholith. Pegmatites are common near the contacts, with garnet- and tourmaline-bearing pegmatites very common within, and near the monzogranite stocks more closely associated with skarns. Intense tourmalinization of the metasedimentary rocks characterizes the contact of these pegmatites.

The granitoids are typically highly differentiated. They are characterized by high SiO_2 , B, F, Li, Rb and varied, but also generally high Sr, Th and Nb contents. Variable, but generally high K_2O values with a range of $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios between 0.66 and 2.36 are characteristic. The granodiorites are typically peraluminous, with an average $(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})/\text{Al}_2\text{O}_3$ ratio of 0.80. The associated monzogranites are generally only marginally peraluminous with average $(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})/\text{Al}_2\text{O}_3$ ratio of 0.94.

The pegmatites associated with the monzogranite stocks are characterized by high SiO_2 and Na_2O , with variable, but generally low K_2O contents. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio for the pegmatites in the Mount Alexander region ranges between 1.38 and 3.93, and those at Kilba Well lie between 0.84 and 1.93. Boron is high in all pegmatites, F, Rb, Li, Sn and Nb high in some, and Sr, U, Th and Zr are low. At Kilba Well, Li is depleted relative to the monzogranite average.

Alteration in the granodiorite of the Mount Alexander batholith and in the monzogranite stock associated with the Kilba Well skarns is expressed as weak pervasive sericitization to intense sericitization and greisenization. The most intense alteration occurs in the Kilba Well monzogranite where it is largely fracture controlled. Pervasive alteration may extend outwards from these structures for several metres. The composition of the altered zones is highly variable, but is always potassic. High to very high B, F, Li and Rb contents are characteristic of the trace-element composition.

Table 3. Representative tourmaline compositions — granite contact zones

Specimen	Mount Alexander				Kilba Well				
	90656	90656	90397	90397	90306	90334	90381	90381 core	90381 rim
	Percentage								
SiO ₂	36.22	36.33	35.81	36.37	36.91	37.22	36.06	37.83	37.30
TiO ₂	1.14	1.36	1.02	0.53	0.59	0.32	0.61	0.18	0.95
Al ₂ O ₃	32.21	32.33	28.91	32.22	33.23	30.93	32.35	34.43	31.67
FeO _{tot}	8.37	10.47	8.33	5.51	7.41	6.06	10.28	9.76	8.71
MnO	0.10	0.26	0.17	0.00	0.00	0.10	0.19	0.20	0.15
MgO	5.45	3.88	7.08	7.45	5.65	8.24	4.65	3.97	6.08
CaO	0.34	0.63	2.89	2.59	0.66	0.87	0.71	0.30	1.29
Na ₂ O	2.13	1.93	1.93	1.99	1.66	2.14	2.19	1.88	2.04
K ₂ O	0.07	0.14	0.00	0.00	0.13	0.23	0.05	0.00	0.00
Total	86.03	87.33	86.14	86.66	86.24	86.11	87.09	88.55	88.19
Fe/Fe+Mg	0.46	0.60	0.40	0.29	0.43	0.29	0.55	0.58	0.45

90306 and 90334 are from contact metamorphosed schist
90381 is from greisen
Sample locations are listed in Appendix 1

Contact metamorphism and metasomatism

Contact metamorphism

Mount Alexander

In the study area contact metamorphic effects are most notable in the rocks of Unit 1 (amphibolites) and Unit 3 (pelites and carbonates). Recrystallization dominates contact effects in all rock types. In carbonates, this has resulted in the formation of marbles. Cordierite and andalusite porphyroblasts are locally developed and indicate that hornblende hornfels conditions were reached.

Typical assemblages in rock types in the Mount Alexander area are as follows:

Quartzo-feldspathic

quartz–plagioclase–biotite–?cordierite
quartz–plagioclase–muscovite–biotite–tourmaline
quartz–actinolite–clinozoisite–plagioclase–biotite
plagioclase–quartz–actinolite–chlorite
plagioclase–microcline–quartz–actinolite

Pelitic

biotite–actinolite(tremolite)–plagioclase–quartz
biotite–quartz–plagioclase–actinolite–tourmaline
quartz–biotite–chlorite–andalusite–cordierite

Calcareous

calcite–tremolite–chlorite
calcite–chlorite
calcite–phlogopite–quartz
calcite–tremolite

Magnesian (always with some calcite)

tremolite–chlorite–quartz
tremolite–clinopyroxene–talc–chlorite

Basic

actinolite–plagioclase(–clinozoisite–biotite–quartz)

Kilba Well

In the Kilba Well area, contact metamorphic assemblages also indicate that hornblende hornfels facies conditions were reached. The presence of wollastonite-bearing assemblages suggests that pyroxene hornfels facies may have existed locally, but it is possible that these assemblages represent the early development of exoskarn.

The contact assemblages associated with the Kilba Well stock are essentially the same as for Mount Alexander. Typical assemblages are as follows:

Quartzo-feldspathic

quartz–plagioclase–biotite–muscovite(–tourmaline)
quartz–plagioclase–biotite–tourmaline(–actinolite)
quartz–biotite–actinolite–clinozoisite
quartz–biotite–plagioclase–actinolite

Pelitic

biotite–plagioclase–quartz(–chlorite–tourmaline)

Calcareous

calcite–tremolite–chlorite(–phlogopite)
tremolite–calcite
diopside–grossular–vesuvianite–wollastonite(–calcite)

Conditions of contact metamorphism

The presence of cordierite at Mount Alexander implies minimum temperatures of approximately 450°C (Turner, 1968) for contact metamorphism. The apparent rarity of andalusite in what appear to be favourable rock types close to the skarns may be related to sampling problems caused by the poor exposure. However, both cordierite and andalusite are more abundant adjacent to the nearby Boolaloo Granodiorite. Andalusite places a 3 kb upper

limit on the pressure at the time of metamorphism, and assuming the cordierites have a high Fe/(Fe+Mg) ratio, conditions for metamorphism of around $P=2$ kb and $T=550^{\circ}\text{C}$ are indicated. This is supported by the presence of grossular and wollastonite in the outer parts of the skarns at Kilba Well and White Lightning, which require similar pressures and temperatures for stability (Gordon and Greenwood, 1971; Greenwood, 1967).

Assuming that the wollastonite-bearing assemblages at Kilba Well have contact metamorphic origins, then X_{CO_2} must have been low at the temperatures postulated for metamorphism. However, the absence of wollastonite from the majority of carbonate units close to the intrusive contacts could be the result of insufficiently high temperatures and/or high X_{CO_2} (Greenwood, 1967; Vidale, 1969). High X_{CO_2} implies that the removal of CO_2 through fluid circulation adjacent to the stock (Shieh and Taylor, 1969) was not occurring. The presence of wollastonite in the outer zones of the skarns, together with the presence of epidote group minerals in the contact aureoles, suggests no significant flow of H_2O -rich fluids from or past the intrusive until some time after emplacement. The wollastonite–grossular assemblage may therefore represent a transitional stage between contact metamorphism and metasomatism–exoskarn formation. Gradients in fluid composition (changing $X_{\text{H}_2\text{O}}/X_{\text{CO}_2}$ ratios) must therefore have characterized the

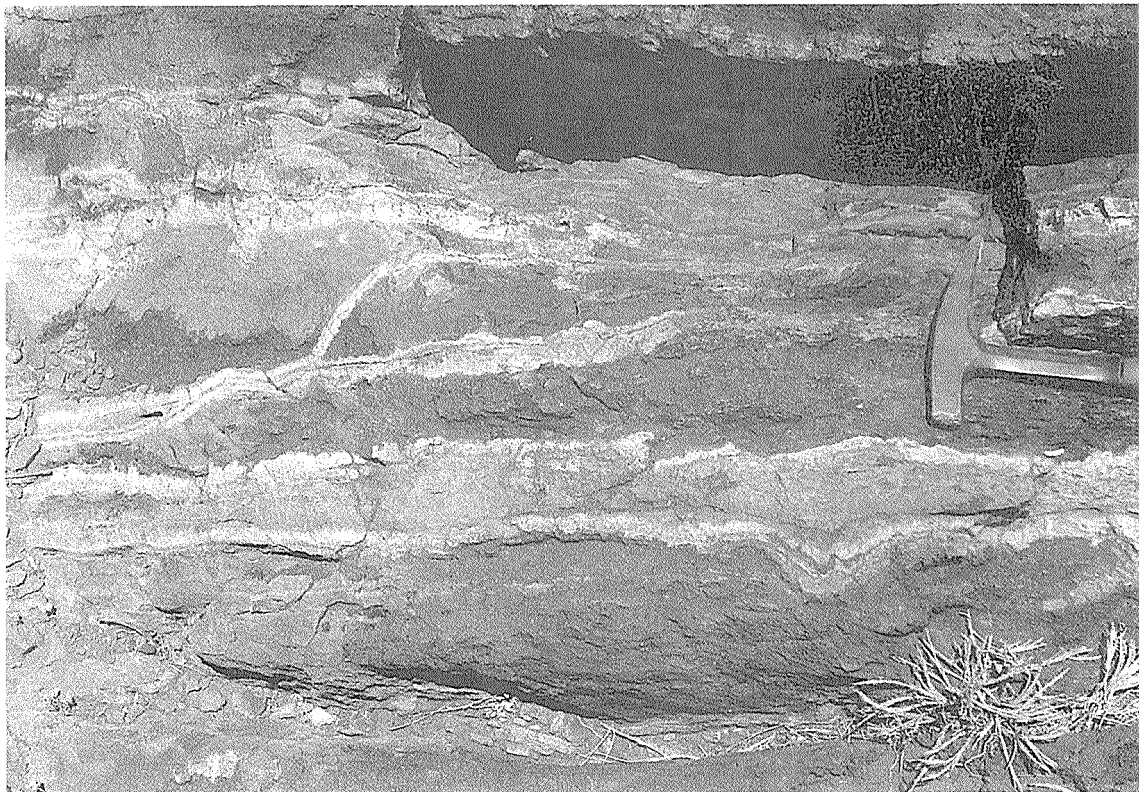
pore fluids within the carbonate hosts at the transition between metamorphism and the beginning of exoskarn formation.

Bimetasomatic skarns

Bimetasomatic skarns are recognized at both Mount Alexander and Kilba Well. They are largely the product of regional and contact metamorphism and are only briefly described here. This skarn type has developed at the boundaries between wallrock and carbonate host (Fig. 8), but forms a volumetrically minor proportion of the total skarn volume. They form layers or bands parallel to the boundaries and are characterized by a distinctive mineralogical zonation that has developed in response to the diffusion of chemical components across these boundaries (Thompson, 1975). Bulk compositions of the wallrocks controlled the assemblages that developed in these skarns.

Mount Alexander

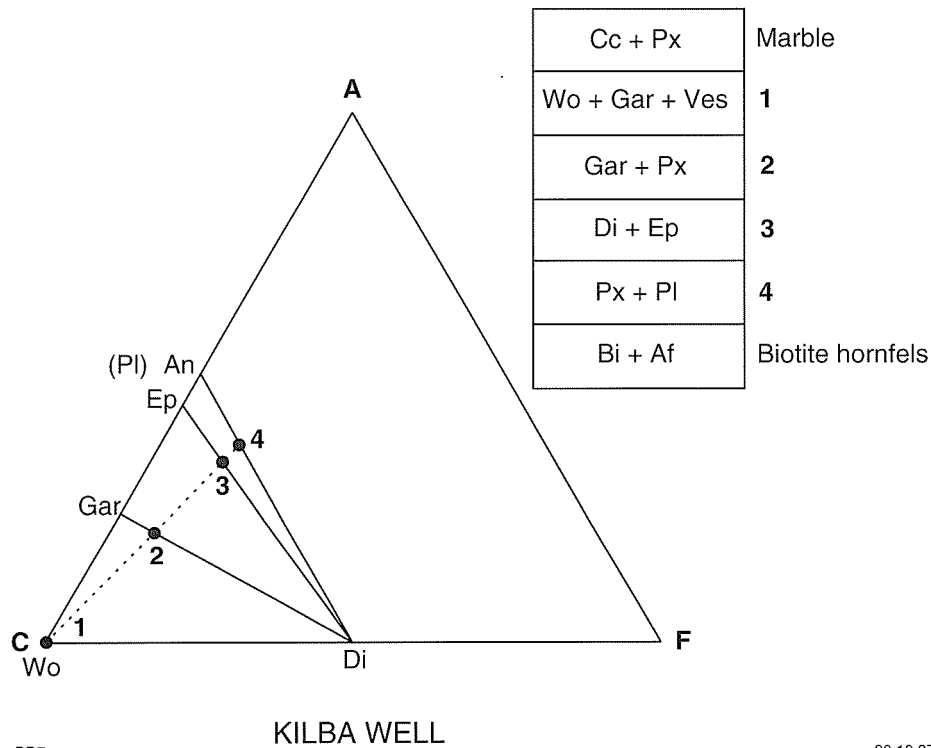
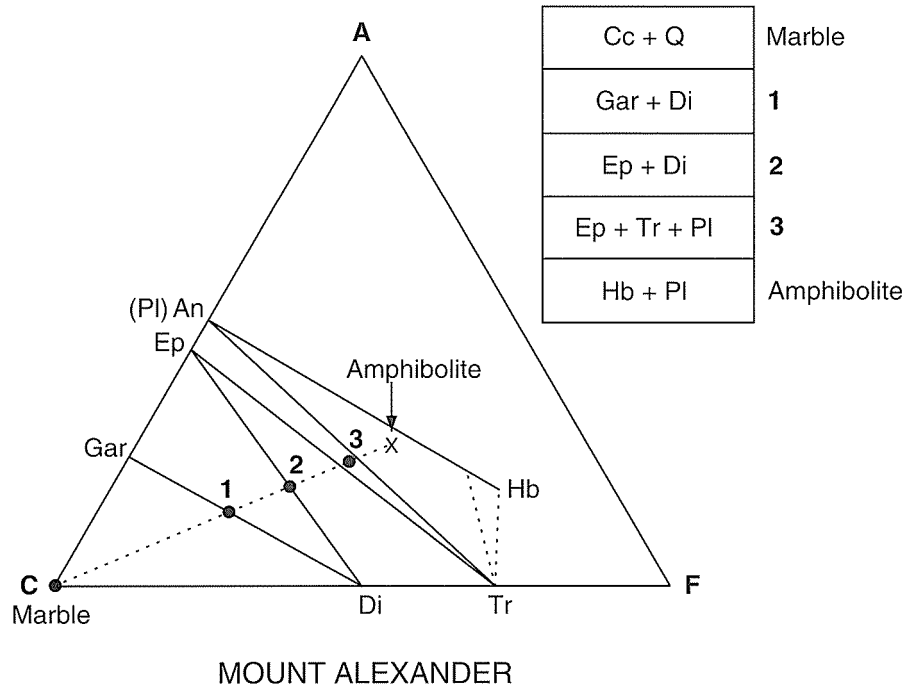
Bimetasomatic skarns have developed at the boundary between amphibolite and marble of Units 3 and 4. The zoning sequence (Fig. 9) is similar to that observed between amphibolite and marble in the Sierra Nevada



BD21

9.03.98

Figure 8. Bimetasomatic skarn in impure marble at Kilba Well. Skarn assemblages are ferro-tremolite–chlorite(–phlogopite)



BD7

30.10.97

Figure 9. Idealized bimetasomatic zoning — Mount Alexander and Kilba Well. Cc = calcite, Gar = garnet, Di = diopside, Px = pyroxene, Wo = wollastonite, Ep = epidote, Tr = tremolite, Pl = plagioclase, An = anorthite, Hb = hornblende, Bi = biotite, Ves = vesuvianite, Af = alkali feldspar (after Kerrick, 1977)

roof pendants (Kerrick, 1977). At Mount Alexander the assemblages corresponding to the zones are:

1. amphibolite (hornblende–actinolite–plagioclase–garnet)
2. actinolite–epidote–sphene–calcite(–feldspar–quartz)
3. epidote–quartz–calcite–feldspar–actinolite(–sphene), clinopyroxene
4. epidote–clinopyroxene–quartz–calcite(–garnet)
5. grossular–clinopyroxene–calcite–sphene–quartz
6. wollastonite–grossular–clinopyroxene
7. marble (calcite–tremolite–chlorite).

Minor chlorite or biotite may occur in Zones 2 and 4 assemblages and clinozoisite is often present with epidote. The Zone 6 assemblage has not been directly observed, but is inferred from quartz–calcite pseudomorphs after wollastonite fibres that are locally present in garnet and clinopyroxene of Zone 5. Zone 2 assemblages have developed adjacent to veinlets present in amphibolite at the margins of the bimetasomatic zones.

Kilba Well

Bimetasomatic skarns have been tentatively identified close to the monzogranite in the Kilba Well area. Hornfelsed wallrocks typically contain quartz, biotite and feldspar with lesser amounts of muscovite, tourmaline and epidote. The bimetasomatic skarn assemblages listed below (Fig. 9) are similar to those documented for other bimetasomatic skarns (Ito, 1962; Thompson, 1975; Kerrick, 1977). The interpreted zonation is as follows:

1. biotite hornfels
2. epidote–biotite–quartz
3. actinolite–epidote–clinozoisite
4. clinopyroxene–epidote
5. garnet–clinopyroxene(–vesuvianite)
6. wollastonite–garnet–vesuvianite(–clinopyroxene)
7. marble

Most of the observed bimetasomatic skarns at Kilba Well have been overprinted by exoskarn. This means that it is difficult to unequivocally identify these skarns by visual inspection alone, because of the considerable mineralogical complexity arising from the overprinting reactions during exoskarn formation.

Mineralized skarns (exoskarns)

In this section the nature and composition of the scheelite-bearing skarns at Mount Alexander and Kilba Well are described. These Gascoyne Complex occurrences represent the only significant skarn-related tungsten occurrences reported in Western Australia.

A considerable volume of exoskarn has developed in the host carbonates at Mount Alexander and Kilba Well. The exoskarns are distinctively zoned, with only slight differences evident between the two areas. Although these differences are small, the proportions of prograde and retrograde domains are different. It is therefore useful to describe and discuss the two skarn systems separately.

Mount Alexander skarns

Four main areas of skarn (the Mortgage, White Lightning, Aladdins and Camp skarns; Fig. 2) are present in the Mount Alexander area. The largest of these, the Mortgage and White Lightning skarns, occur within Unit 1 (Fig. 10). The other skarns, which are relatively small and of limited areal extent, consist of several thin skarn units interbedded with muscovite–biotite schists of Unit 3 (Fig. 11). The apparently small volume of skarn formed in these two systems may partially be the result of truncation of the carbonate host through intrusive activity (the Camp skarn), and through facies variations into unfavourable hosts (the Aladdins skarn).

At the Mortgage and White Lightning locations, massive skarn occurs in continuous, gently to moderately dipping layers averaging 5 and 3 m thick respectively. The White Lightning skarn outcrop can be traced for about 700 m and is the most laterally extensive skarn in the area. Only limited downdip data are available for either of these skarns and the extent of their development in this direction is unknown. The Aladdins skarn is present in several thin (<1 m) thick, impure carbonate units, which display considerable lateral facies variation. Individual skarn bodies have lenticular to podiform morphologies and these are irregularly distributed in the area. The Camp skarn occurs as several small, poorly exposed bodies, the largest of which is approximately one metre wide in outcrop.

Petrology and geochemistry of the zoning

The lack of a complete and uninterrupted section through any of the skarns in the Mount Alexander area makes estimation of the dimensions of any of the observed zones difficult. An assemblage rich in garnet–pyroxene dominates in virtually all outcrops and clearly forms a considerable proportion of the skarn. The interpreted zoning sequence is therefore based on information gathered from outcrop, drillcore and petrological studies of thin and polished sections.

All skarns in the Mount Alexander area share some common petrographic features. They are predominantly granoblastic and have grain sizes that average about 2.0 mm and range from 0.1 to 4 mm. Coarse- to very coarse-grained garnet, vesuvianite and amphibole are encountered locally. Vugs up to 5 cm in diameter and veins may be present in some zones.

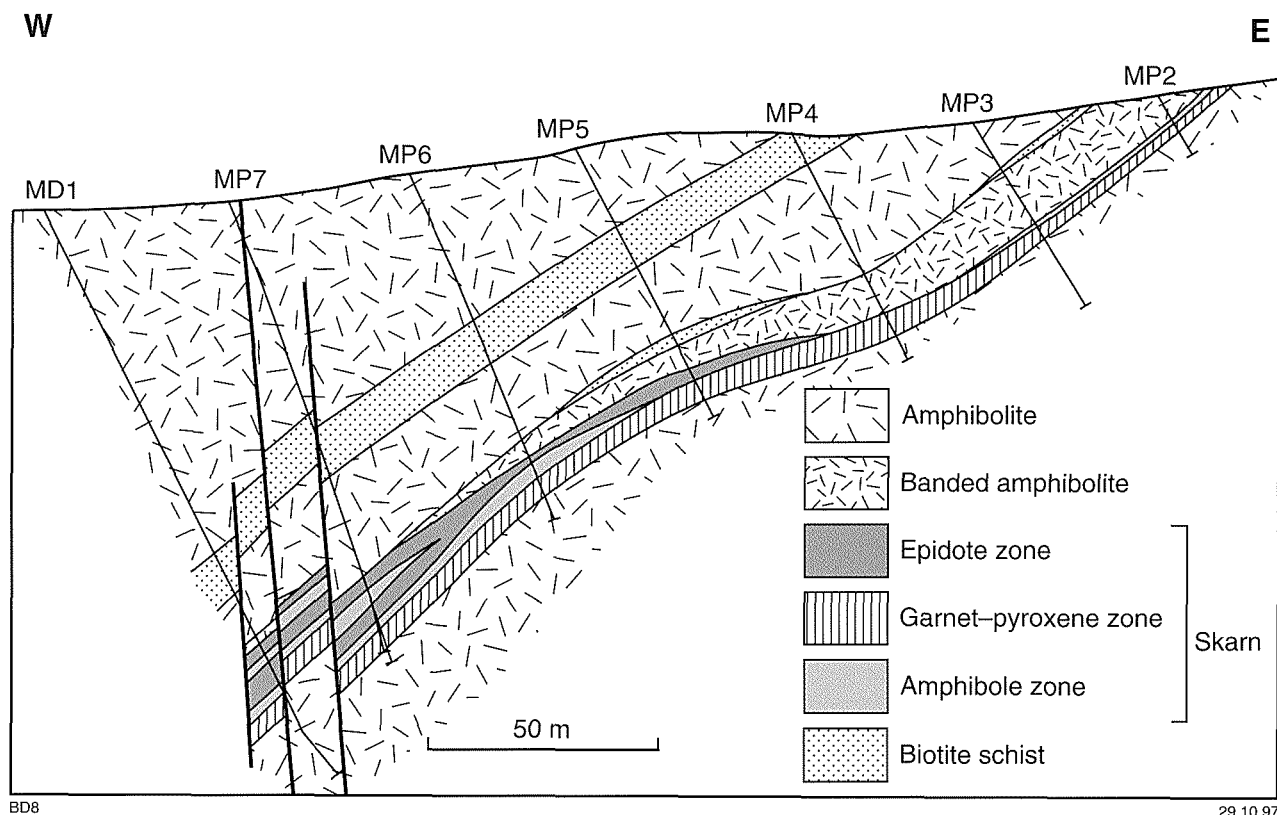


Figure 10. Cross section through the Mortgage skarn (Mount Alexander area). The presence of epidote or amphibole zone assemblages determined the zone boundaries depicted. Substantial volumes of prograde garnet-pyroxene assemblages may still occur within the retrograde zones

Mineralogical zoning patterns

The interpreted prograde zoning sequence for the Mount Alexander skarns, from marble to intrusive, is:

1. a wollastonite(-garnet-pyroxene) zone;
2. a transition zone in which wollastonite is lost and replaced by calcite and quartz, together with increasing garnet and pyroxene; and
3. a garnet-pyroxene zone (plus quartz and possible epidote/clinozoisite), which may be either garnet dominant (garnet subfacies) or pyroxene dominant (pyroxene subfacies).

Vesuvianite is a minor prograde phase present only in minor amounts in the transition and garnet-clinopyroxene zones, where it may occur as very coarse subidioblastic to idioblastic crystals in quartz-filled vugs or veins. The characteristic assemblages encountered in each zone are presented in Table 4.

Retrograde stage assemblages are characterized by the presence of fluorite, vesuvianite, actinolite, scheelite, apatite, calcite, quartz, epidote, pyrrhotite, chalcopyrite and sphalerite. Three retrograde zones can be distinguished.

1. an outermost vesuvianite zone;
2. an innermost epidote(-fluorite) zone; and
3. a marginal amphibole(-clinopyroxene) zone.

Retrograde assemblages occur along the footwall and hangingwall margins of the prograde skarn bodies, as well as outwards from veins that traverse them. There has been modification of early retrograde assemblages in some areas towards the end of this stage.

The interpreted geometry of the prograde and retrograde zoning patterns is shown in Figure 12.

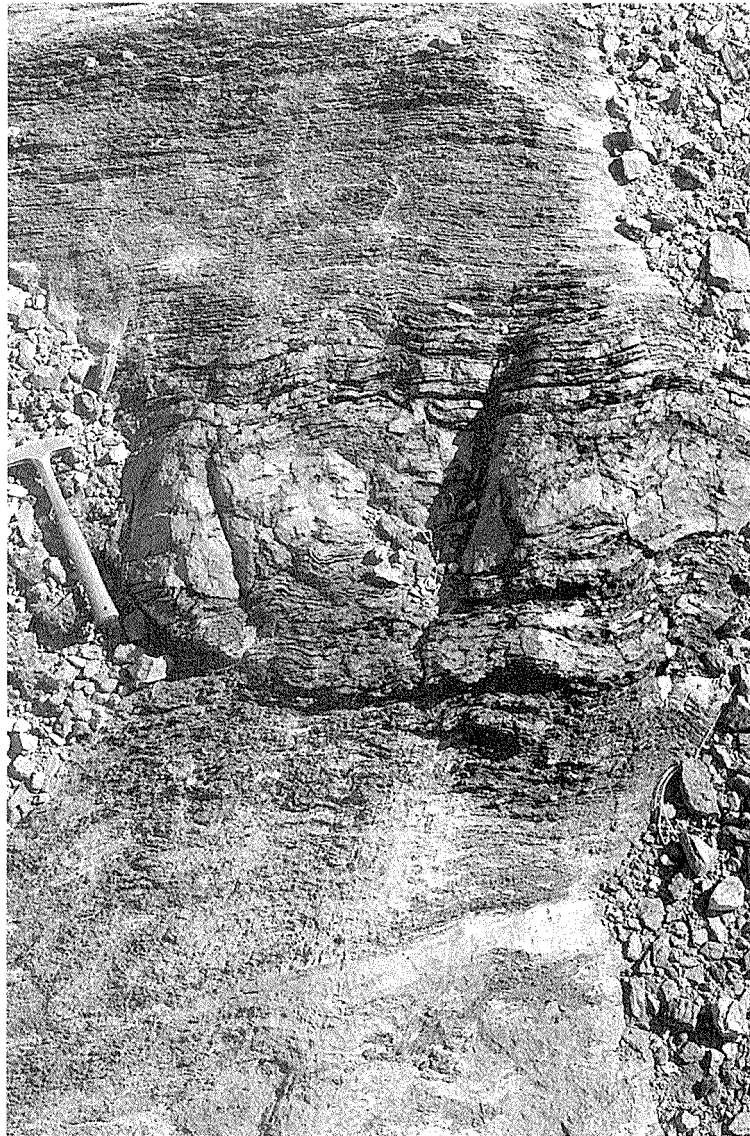
Marble host

Host marbles are granoblastic, fine-grained rocks composed mainly of calcite with variable but generally minor amounts of tremolite and chlorite. Textures and assemblages reflect the effects of greenschist metamorphism on variably impure limestone.

Prograde skarn zones

Wollastonite zone

Medium- to coarse-grained, cream to brownish rocks dominate the wollastonite zone. Wollastonite is present as individual randomly oriented to radiating grains, or as fine- to coarse-grained, columnar to fibrous aggregates. It is commonly intergrown with medium- to coarse-grained garnet and diopsidic pyroxene. The generally subidioblastic garnets and the pyroxenes have ragged



BD22

12.11.97

Figure 11. Outcrop of Aladdins skarn (Mount Alexander area) showing one of several thin skarn bands in laminated impure carbonate host

margins due to the intergrowths of wollastonite, and contain inclusions of fine-grained wollastonite laths. Garnets are commonly partly anisotropic and zoned. Fine granular pyroxene is also present as locally abundant inclusions in poikiloblastic garnet. Textures indicate that the assemblage developed as part of one event.

The wollastonite zone marks the contact between the host carbonate and the skarn. Calcite, tremolite and chlorite are lost as the marble is replaced. The absence of magnesian phases in the wollastonite zone possibly reflects variations in the tremolite and chlorite contents in the host in addition to possible sampling bias resulting from the poor exposure of this zone. The presence of vesuvianite and scheelite containing pseudomorphed wollastonite in the transition zone suggests that these phases may have occurred during wollastonite skarn formation. The presence of minor scheelite with

ragged grain margins suggests that some tungsten mineralization occurred during the formation of the wollastonite zone.

Garnets in this zone have consistent compositions. The grossular component is dominant and varies to a maximum of 6.8 mole percent (Table 5; Fig. 13), spessartine contents remain relatively constant at 1.9 mole percent, and almandine contents vary between 0.1 and 2.2 mole percent. These variations correspond to the widely varying anisotropy evident in the garnets. Pyroxenes are dominantly hedenbergitic (Table 6; Fig. 14) despite a variation in the diopside component up to 18 mole percent. The johannsenite component averages close to 4 mole percent. No systematic relationship between pyroxene composition and position within any zone, either horizontally or vertically, was apparent. Wollastonite remained essentially pure CaSiO_3 .

Table 4. Mineralogical zonation in Mount Alexander exoskarns

Zone	Mineralogy		
	Dominant	Intermediate	Minor
Host			
Marble	calcite	tremolite, chlorite	pyrrhotite, tremolite
Prograde zones			
Wollastonite	wollastonite	garnet, cpx	calcite
Transition	garnet cpx	calcite, quartz, epidote/czs	(scheelite)
Garnet–pyroxene	garnet or cpx	epidote/czs calcite	quartz, sphene (scheelite)
Retrograde zones			
Vesuvianite	vesuvianite or garnet	cpx, fluorite quartz, epidote/czs, scheelite, calcite, plagioclase, microcline	apatite, plus all intermediate mineralogy
Epidote	epidote/czs fluorite	scheelite, quartz, vesuvianite	actinolite, chlorite, calcite
Amphibole	actinolite	quartz, cpx, calcite, epidote	sphene

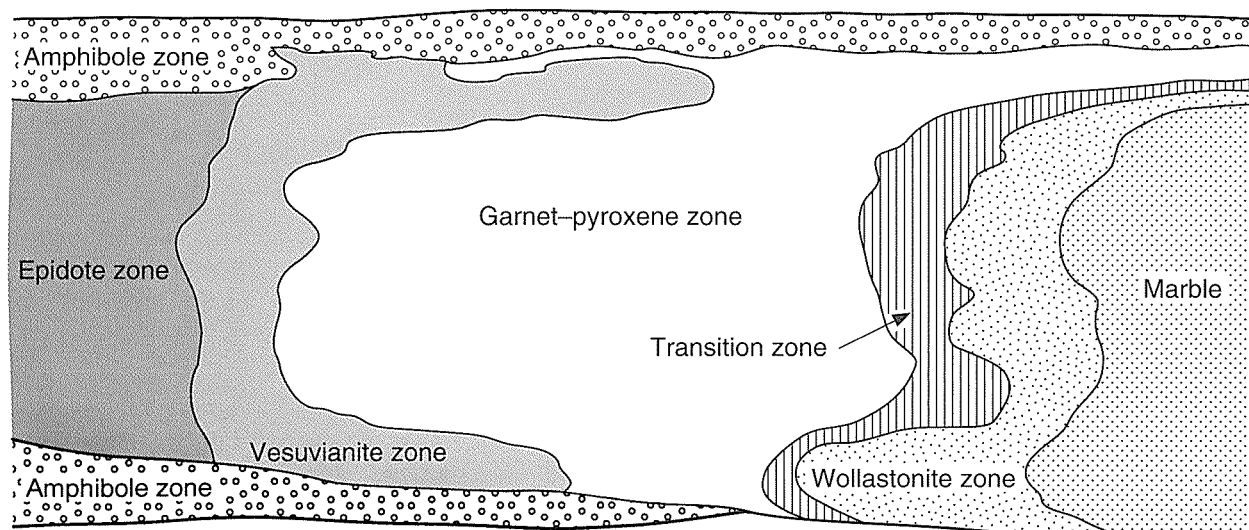
cpx = clinopyroxene; czs= clinozoisite; (mineral) = trace

Transition zone

The transition zone lies between the main garnet–clinopyroxene zone and the wollastonite zone described above. The assemblage is typically granoblastic and is marked by more abundant medium-grained garnet and clinopyroxene (Fig. 15), quartz and calcite pseudomorphs after wollastonite, and the presence of epidote and clinozoisite. Vesuvianite is locally present as medium- to coarse-grained subidioblasts. Inclusions of very fine-

grained, fibrous quartz–calcite pseudomorphs after wollastonite in vesuvianite indicate that vesuvianite formed during the development of this zone.

Garnet and clinopyroxene compositions essentially duplicate those in the wollastonite zone. Epidotes are moderately aluminous with the mole fraction of the pistacite (Ps) component averaging Ps 19 (Fig. 16). No compositional data for transition zone vesuvianite are available.



BD9

30.10.97

Figure 12. Schematic geometry and distribution of zones in Mount Alexander skarns

Table 5. Representative garnet compositions

Specimen	Mount Alexander skarns												Kilba Well skarns				
	90440	90420	90434	90439	90435	90643	90424	90386	90392	90406	90385	90382	90351	90316	90635	90314	90314
	Percentage																
SiO ₂	37.91	38.60	38.95	38.82	39.11	39.24	39.27	38.32	38.08	38.25	39.43	39.15	38.76	40.06	39.52	40.02	39.54
TiO ₂	0.00	0.11	0.25	0.12	0.22	0.11	0.46	0.00	0.00	0.14	0.46	0.83	0.00	0.23	0.29	0.00	0.00
Al ₂ O ₃	20.82	19.67	19.61	18.63	17.84	18.65	19.14	21.02	19.71	19.20	16.88	18.43	20.72	21.00	21.41	22.16	22.07
FeO _{tot}	18.77	16.27	14.33	12.15	10.65	6.92	5.81	18.94	15.67	10.95	8.04	6.49	5.76	3.11	2.56	1.67	1.69
MnO	6.60	6.23	4.31	3.22	1.15	0.61	0.67	6.90	6.08	4.76	0.83	0.20	2.61	0.22	0.15	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	15.98	18.67	23.37	27.90	31.10	34.22	34.60	14.12	20.38	26.26	34.23	34.40	32.00	35.62	35.90	36.68	36.46
Na ₂ O	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.08	0.09	0.00	0.11	0.09	0.09	0.06	0.00	0.10	0.06	0.15	0.11	0.08	0.10	0.11	0.12
Total	100.08	99.91	100.91	100.84	100.18	99.84	100.04	99.93	99.92	99.85	99.93	99.65	99.96	100.32	99.93	100.64	99.88
	Mole percentage																
Almandine	39.8	31.8	23.6	15.2	9.9	3.6	2.0	41.6	28.5	15.4	1.4	1.8	5.8	2.4	1.6	1.7	1.8
Andradite	2.5	7.4	9.1	14.5	17.1	14.6	11.9	1.8	7.8	10.8	21.2	13.6	6.1	5.6	3.6	2.0	1.2
Grossular	42.9	46.6	57.7	63.2	70.4	80.5	84.6	39.1	50.1	63.2	75.5	84.1	82.4	91.5	94.5	96.3	97.0
Pyrope	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spessartine	14.8	14.2	9.6	7.1	2.6	1.3	1.5	15.8	13.6	10.6	1.9	0.5	5.7	0.5	0.3	0.0	0.0

Sample locations are listed in Appendix 1

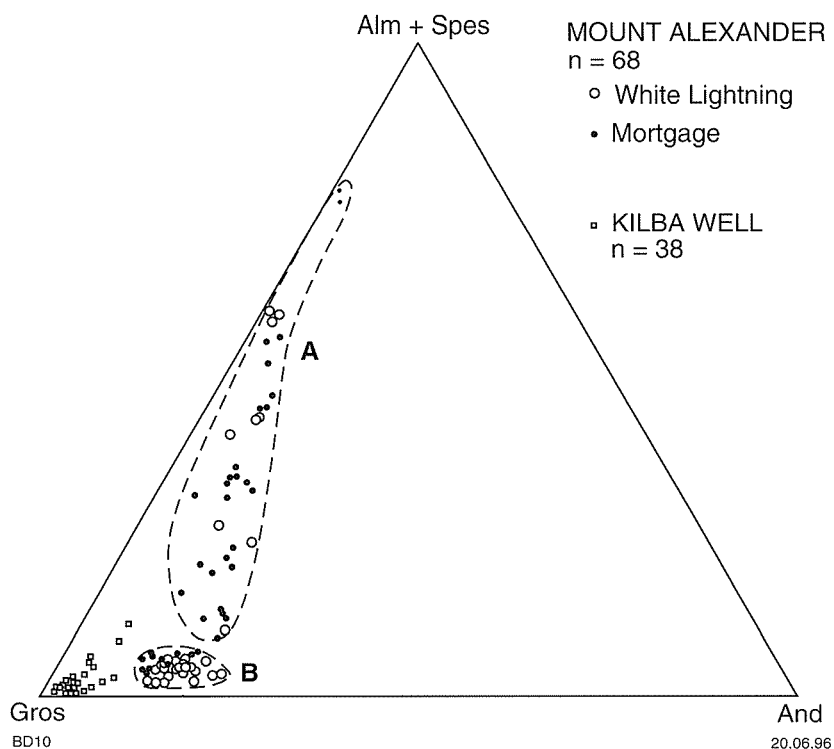


Figure 13. Garnet compositions in Mount Alexander and Kilba Well skarns. Field A encloses younger subcalcic garnet compositions; field B encloses early prograde garnets adjacent to or as selvages in veins and vugs. Kilba Well prograde garnets are calcic with less than 5 mole percent andradite component

Table 6. Representative pyroxene compositions

Specimen	Mount Alexander skarns				White Lightning skarn				Kilba Well skarns			
	Mortgage skarn											
	90438	90424	90642	90382	90383	90386	90385	90360	90634	90613	90302	90304
	Percentage											
SiO ₂	50.97	50.78	50.84	51.88	50.93	50.56	50.10	54.45	53.96	53.13	53.12	52.30
Al ₂ O ₃	0.00	0.00	0.00	0.17	0.00	0.00	0.50	0.00	0.16	0.36	0.00	0.00
FeO _{tot}	16.44	18.09	19.61	14.85	16.84	19.94	21.03	5.14	6.55	9.05	11.47	15.00
MnO	1.36	1.17	0.70	1.20	0.91	1.19	1.22	0.21	0.00	0.34	0.17	0.17
MgO	7.59	6.30	5.47	8.77	7.62	4.88	4.22	15.09	14.17	12.55	11.21	8.92
CaO	23.17	23.46	23.40	22.89	23.14	22.82	23.07	25.03	24.78	23.95	24.33	24.15
Na ₂ O	0.29	0.22	0.00	0.24	0.29	0.41	0.30	0.00	0.17	0.00	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.07	0.00	0.09	0.07	0.00	0.06	0.00	0.00	0.00
Total	99.82	100.02	100.02	100.07	99.73	99.89	100.51	99.92	99.85	99.38	100.30	100.54
	Mole percentage											
Diopside	43	37	32	49	43	29	25	83	79	70	63	51
Hedenbergite	53	59	66	47	54	67	71	16	21	28	36	48
Johannsenite	4	4	2	4	3	4	4	1	0	2	1	1

90438, 90424, and 90642: Mortgage skarn
 90382, 90383, 90386 and 90385: White Lightning skarn
 Sample locations are listed in Appendix 1

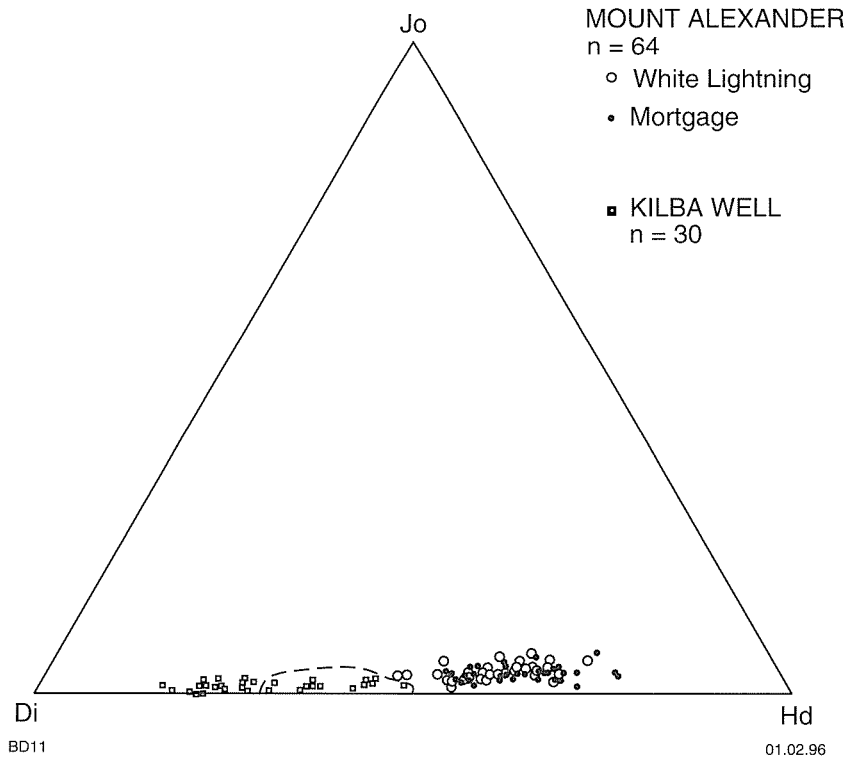


Figure 14. Prograde clinopyroxene compositions in Mount Alexander and Kilba Well skarns. Field enclosed by dashed line indicates more iron-rich pyroxenes in the garnet-pyroxene zone of Kilba Well. Pyroxene compositions show little variation between zones

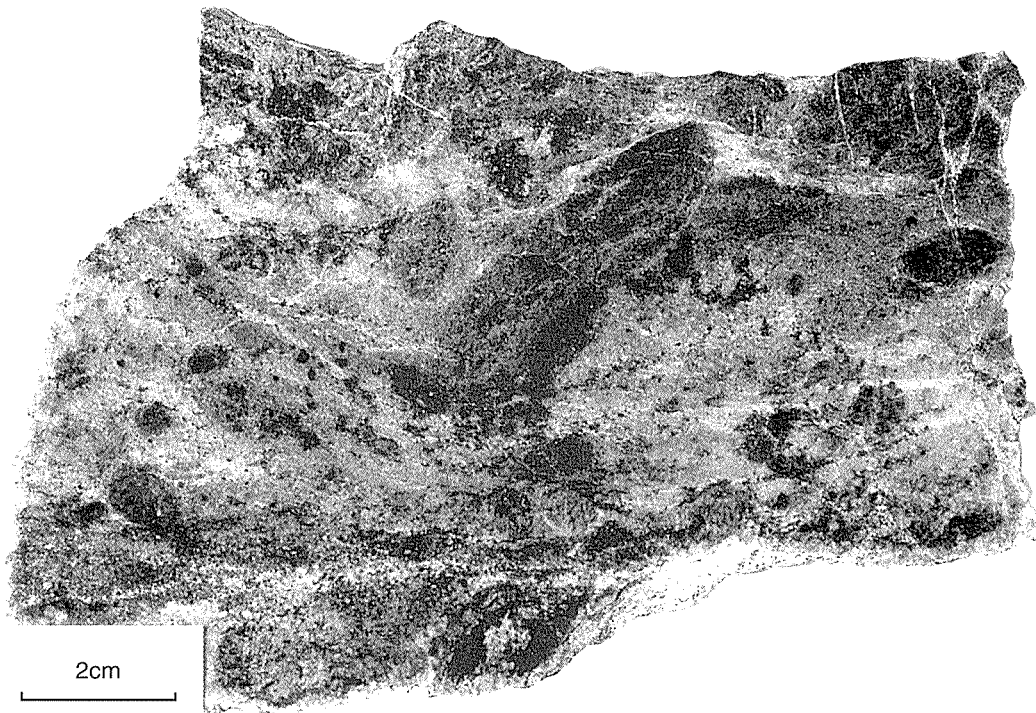


Figure 15. Photograph of slab showing typical transition zone specimen from the White Lightning skarn (Mount Alexander area). (48239)

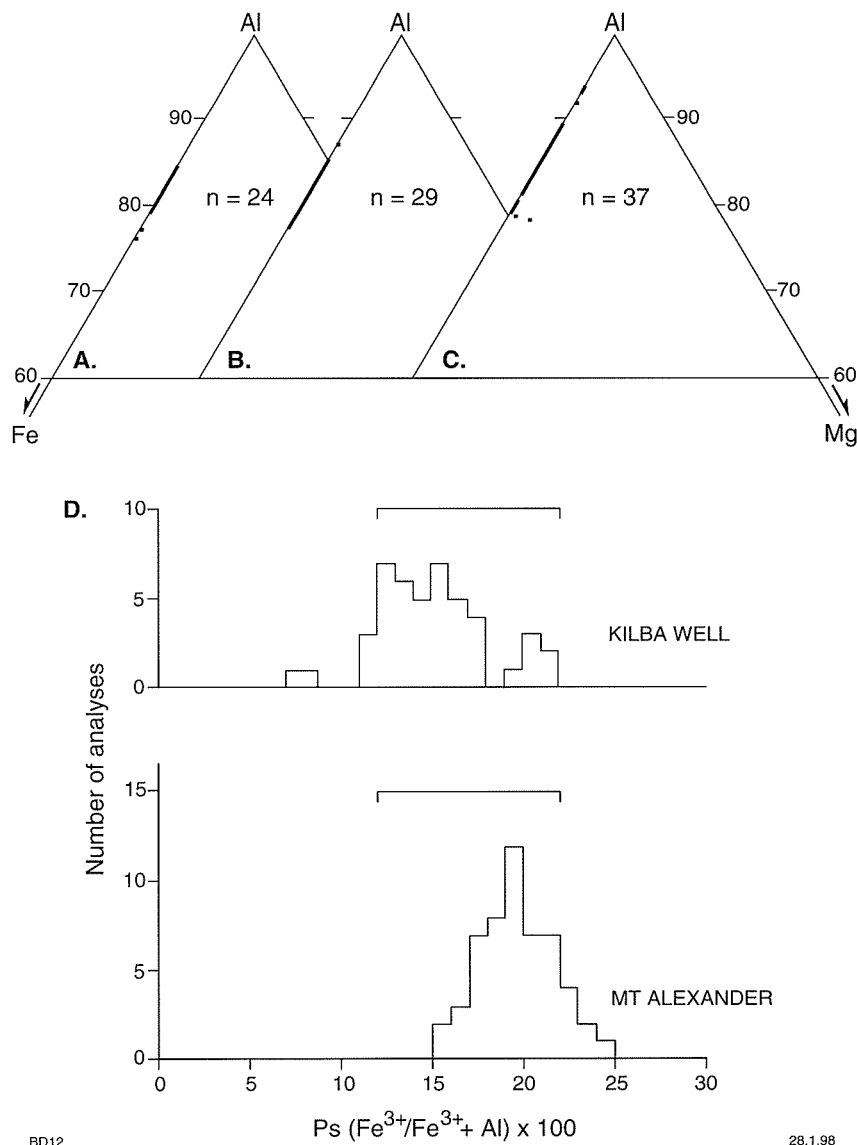


Figure 16. Epidote group compositions in Mount Alexander and Kilba Well skarns. A. Wollastonite and transition zones from White Lightning; B. Mortgage skarn — all zones; C. Kilba Well — all zones; D. Expressed in terms of pistacite (Ps) component

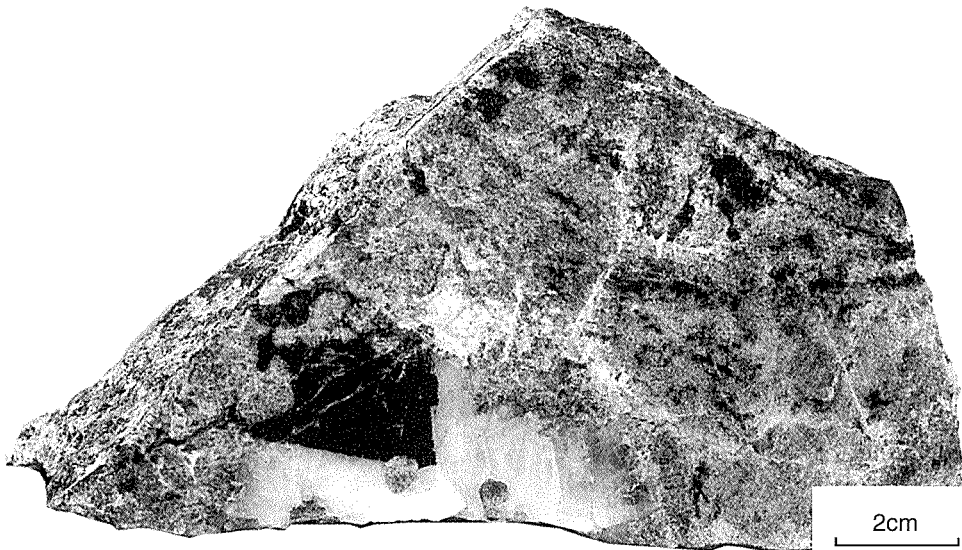
Garnet–pyroxene zone

This is the dominant zone in outcrop and core samples for both the Mortgage and White Lightning skarns. The zone is distinguished by a medium- to coarse-grained granoblastic texture and is characteristically banded. Bedding-parallel banding is defined by alternating and discontinuous garnet- and clinopyroxene-rich zones up to a centimetre thick and generally less than 10 cm long. Massive, almost monomineralic, assemblages of garnet or clinopyroxene with minor epidote, calcite and quartz are irregularly distributed throughout the zone. Clinopyroxene bands consist of a granoblastic intergrowth of pyroxene and epidote with minor to trace feldspar, calcite, quartz, alanite and actinolite. Disseminated scheelite (<<5 cm) is locally present as fine interlocking grains. Small (≤5 cm) garnet-lined vugs, infilled by

epidote, calcite and/or quartz, clinopyroxene and vesuvianite occur throughout the zone (Fig. 17). Transgressive quartz veins are uncommon, but where present are lined by second-generation garnets (Fig. 18).

The garnet–pyroxene zone overprints the transition zone and is itself replaced by the retrograde vesuvianite and epidote zones. The boundary between the transition zone and the garnet–pyroxene zone is gradational and is marked by the almost total disappearance of calcite and quartz, the incoming of scheelite (albeit in minor quantities), and a large modal increase in garnet and clinopyroxene.

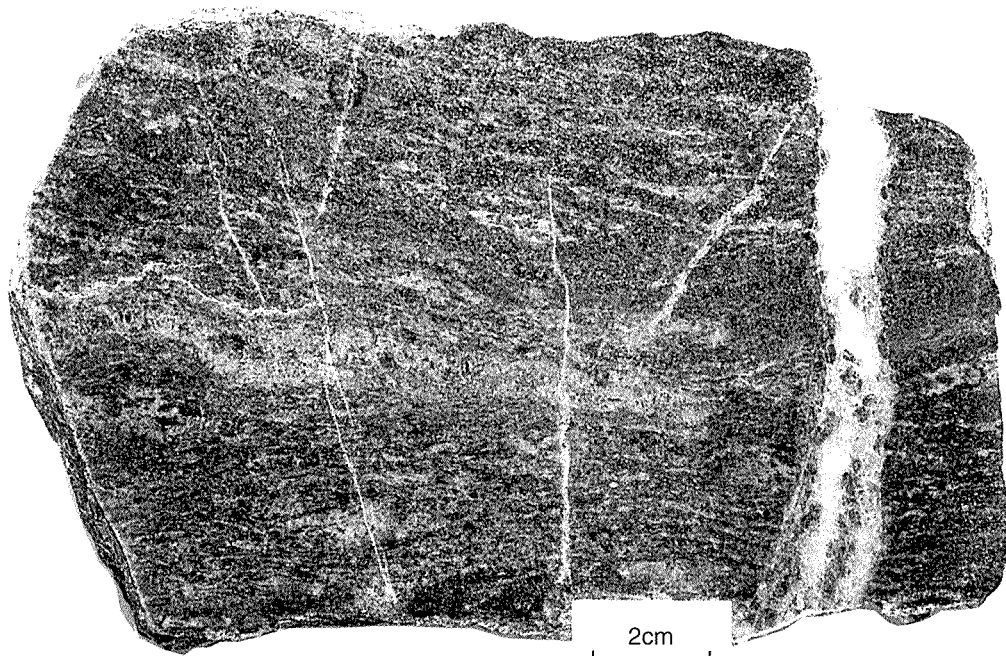
Garnet compositions are calcic and are dominated by the grossular component (Table 5, Fig. 13). This suggests that changes in skarn fluid compositions were minimal



BD24

12.11.97

Figure 17. Photograph showing very coarse vesuvianite with quartz and subcalcic garnet in partially retrograded garnet–pyroxene zone, Mortgage skarn. (48244)



BD25

12.11.97

Figure 18. Photograph showing banded garnet–pyroxene zone assemblage traversed by late quartz-rich vein containing subcalcic garnets; Mortgage skarn. (48255)

in terms of Fe^{3+} and Fe^{2+} during the formation of this zone compared with those of the wollastonite and transition zones. The maximum andradite content is 18.7 mole percent. No discernible variations in composition were present vertically or laterally within the skarn horizon. Significant changes in composition of the garnets occurred late during the formation of the garnet–pyroxene zone. Petrographically younger garnets, including those lining late-stage quartz veins (Fig. 18), are moderately to highly subcalcic (Table 5; Fig. 13). Subcalcic garnet is defined here as garnet containing more than 5 mole percent almandine + spessartine. These garnets occupy a field which extends from the early calcic garnets to the grossular–(almandine + spessartine) junction at about 59 mole percent almandine + spessartine (Fig. 13). Andradite contents are restricted to values less than 18.6 mole percent. As almandine + spessartine contents increase, andradite content decreases.

Pyroxene compositions have a relatively restricted compositional range (Table 6). The hedenbergite component predominates in all but two analyses (Fig. 14), that are marginally diopside dominant. Johannsenite content remains low, reaching a maximum of only 7 mole percent. The overall compositional range is about 29 mole percent with limits, in terms of the hedenbergite component, of 46 and 75 mole percent. No zoning was noted within individual pyroxene grains.

Epidote compositions show no significant departure from the average determined for the early skarn zones (Table 7; Fig. 16). They range between Ps 17 and Ps 23, averaging Ps 19, with one analysis from a late subcalcic garnet-bearing vein having a composition of Ps 24.

Retrograde skarn zones

Vesuvianite zone

Vesuvianite predominates in this zone, together with fluorite, calcite, actinolite and scheelite. Quartz, epidote, apatite, plagioclase, microcline and subcalcic garnet are

present in variable proportions (Table 4). Prograde garnet and pyroxene are normally replaced by epidote, and actinolite and/or calcite respectively. Pseudomorphed prograde calcic garnets from the garnet–pyroxene zone are present as inclusions in vesuvianite. Minor to trace pyrrhotite, sphalerite and chalcocopyrite are present in some samples. Vesuvianite typically occurs as subidioblastic and coarse to very coarse poikiloblastic grains that may include all or some of the other phases. At Aladdins skarn, scheelite-bearing vesuvianite skarn is found adjacent to, and in contact with the garnet–tourmaline intrusive described previously.

In outcrop, this zone appears as a coarse- to very coarse-grained dark-green to brown rock that contains visible calcite-, feldspar- or quartz-filled interstices between coarse poikiloblastic vesuvianite grains. Fine- to coarse-grained scheelite, which fluoresces pale blue in ultraviolet light, is visible in some samples (Fig. 19).

Vesuvianite shows little significant variation in composition (Table 8; Fig. 20), although there are minor variations in $\text{Fe}/(\text{Fe}+\text{Mg})$ ratios, which range between 0.66 and 0.76. Titanium dioxide contents vary from 0.32 to 1.22%, and the variations are often evident in several grains from the one sample. There was no change in $\text{Fe}/(\text{Fe}+\text{Mg})$ ratios despite the differing Ti contents in these samples. Sampling restrictions prevented the establishment of a systematic relationship between compositional variation and distribution of vesuvianite in the zone.

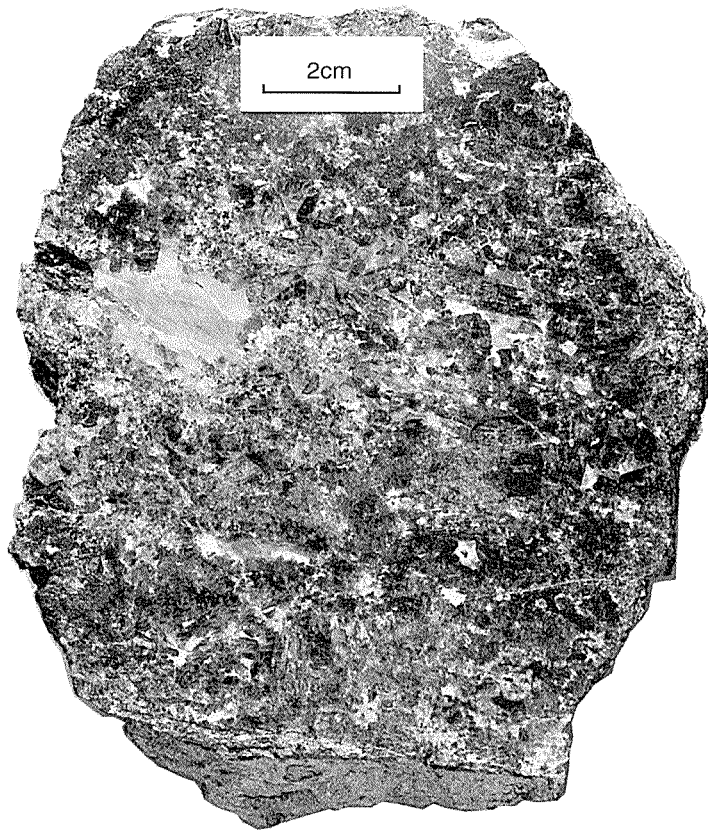
Epidote compositions show no significant variations within the zone, or in comparison with those analysed from other zones. The garnets that form part of the vesuvianite zone are marginally to highly subcalcic. Semi-quantitative analysis of scheelite indicates that powellite contents are very low.

Textural and compositional relationships indicate that vesuvianite zone minerals are replacing garnet–pyroxene zone assemblages. The exact geometric relationship of this zone with the rest of the skarn is not clear, although an interpreted geometry of the zone is shown in Figure 12.

Table 7. Representative epidote–clinzoisite compositions

Specimen	Mount Alexander skarns							Kilba Well skarns				
	90429	90440	90438	90439	90383	90382	90387	90301	90319	90302	90334	90317
	Percentage											
SiO_2	38.94	38.95	38.39	38.17	38.55	39.03	38.72	39.50	40.03	39.45	39.17	39.53
TiO_2	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	26.63	26.15	25.07	23.84	25.67	25.42	25.27	30.30	29.29	28.88	27.62	26.81
Fe_2O_3 tot	8.67	9.55	10.12	11.75	9.68	10.44	10.89	4.25	5.58	5.90	7.89	8.71
MnO	0.17	0.23	0.11	0.13	0.00	0.20	0.21	0.00	0.09	0.00	0.12	0.10
CaO	24.01	23.54	22.84	23.53	23.44	23.51	23.48	24.05	23.82	23.61	23.04	23.66
Na_2O	0.00	0.21	0.40	0.00	0.00	0.00	0.13	0.00	0.00	0.13	0.17	0.15
K_2O	0.09	0.06	0.00	0.09	0.07	0.00	0.09	0.10	0.12	0.07	0.11	0.07
Total	98.51	98.69	97.02	97.51	97.41	98.60	98.79	98.20	98.93	98.04	98.12	99.03
Pistacite	17	19	21	24	19	21	22	8	11	12	15	17

Sample locations are listed in Appendix 1



BD26

12.11.97

Figure 19. Photograph showing retrograde vesuvianite zone, Mortgage skarn. Dark vesuvianite dominates, but specimen also contains calcite, quartz, and coarse-grained scheelite. (48257)

Table 8. Representative vesuvianite compositions

Specimen	Mount Alexander skarns			Kilba Well skarns					
	90434	90407	90641	90360	90311	90314	90301	90351	90351
	Percentage								
SiO ₂	37.81	37.46	37.62	37.80	37.72	37.64	37.21	38.29	37.77
TiO ₂	1.20	1.06	0.36	0.00	1.07	0.69	0.15	0.00	0.00
Al ₂ O ₃	18.42	17.27	17.55	18.77	17.91	17.22	18.36	19.85	19.02
FeO _{tot}	3.77	4.94	5.11	2.44	3.14	4.32	3.43	3.17	4.22
MnO	0.00	0.28	0.23	0.00	0.00	0.12	0.00	0.32	0.42
MgO	0.97	1.13	0.88	1.81	1.72	1.64	1.04	0.61	0.59
CaO	35.63	34.68	35.37	36.48	35.61	35.72	35.06	35.67	35.73
Na ₂ O	0.00	0.19	0.00	0.00	0.21	0.00	0.00	0.16	0.14
K ₂ O	0.13	0.13	0.07	0.07	0.16	0.13	0.12	0.14	0.16
Total	97.93	97.14	97.19	97.37	97.54	97.48	95.37	98.21	98.05
Fe/Fe+Mg	0.69	0.71	0.76	0.39	0.51	0.60	0.65	0.74	0.80

Sample locations are listed in Appendix 1

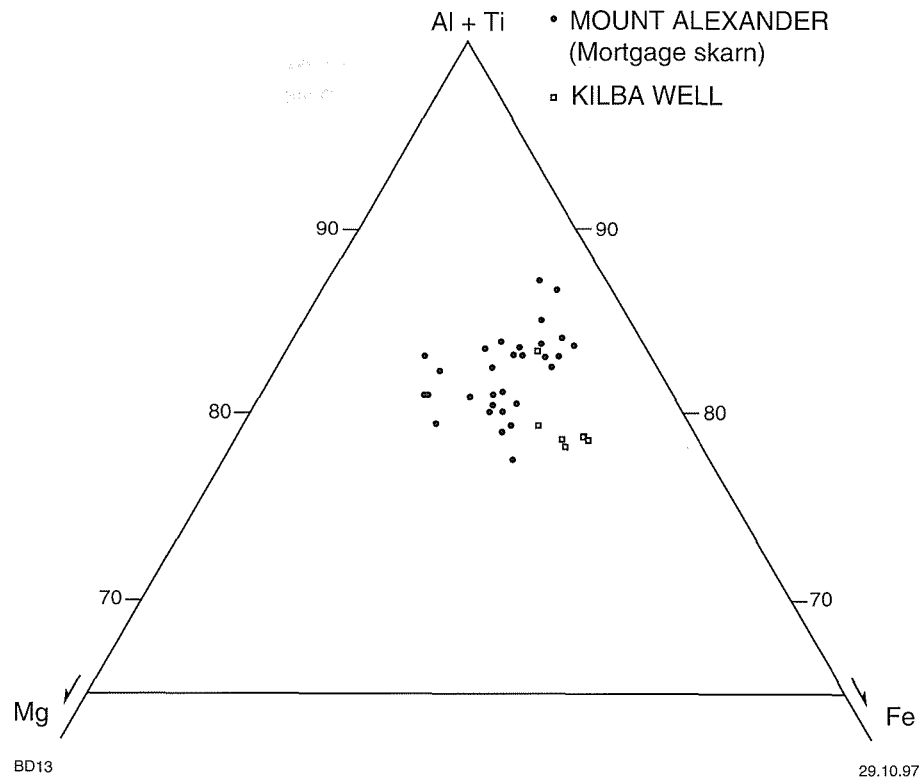


Figure 20. Vesuvianite compositions in the Mount Alexander (Mortgage) and Kilba Well retrograde skarn zones

Epidote zone

Skarn of the epidote zone is medium- to coarse-grained granoblastic rock that is cream to greenish cream in hand specimen. Disseminated medium- to coarse-grained scheelite is common. At the Camp skarn, the zone has developed within 3 to 4 m of the intrusive and is defined by the dominant presence of epidote and clinozoisite, with lesser fluorite, and subordinate quartz, calcite, actinolite, scheelite, vesuvianite, sphalerite, pyrrhotite and relict pyroxene. Vesuvianite is only a minor phase, and the assemblage is so overwhelmingly dominated by epidote group minerals, fluorite, and scheelite that it has been classed as a separate skarn zone.

Scheelite occurs as disseminated anhedral grains in coarse epidote and fluorite. Actinolite replaces and pseudomorphs clinopyroxene. Vesuvianite is locally replaced by epidote, which implies that at least a partial disequilibrium existed between the fluids responsible for epidote zone formation and vesuvianite zone assemblages. Quartz and calcite exist with epidote and scheelite in veinlets throughout the zone. Phase relations between fluorite, epidote and scheelite indicate simultaneous crystallization of these minerals. Owing to weathering effects, no analytical data are available for minerals in this zone.

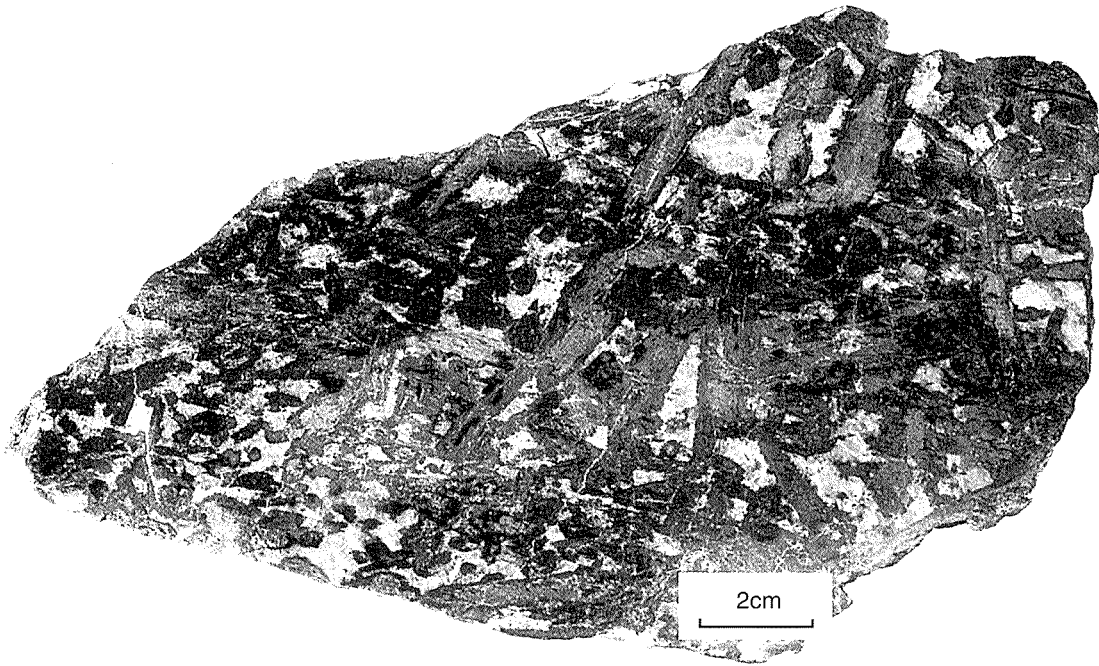
The distribution of epidote zone assemblages in the various skarns at Mount Alexander is not well known. To date, this zone has been observed only in one small

outcrop at the Camp skarn, and at depth along the hangingwall of the Mortgage skarn.

Amphibole zone

Amphibole zone rocks are dark green to black, coarse to very coarse-grained and contain coarse laths of actinolitic amphibole in a quartz-dominant matrix. This assemblage is completed by epidote, calcite, biotite, phlogopite, fluorite, alkali feldspar, scheelite, sphene, chlorite and sulfides, and altered pyroxene. The relative proportions of amphibole and other phases vary considerably, although actinolite is usually dominant. Fluorite and scheelite are rarely present, but pyrrhotite, chalcocopyrite and sphalerite are more common than in other skarn zones. Textural relationships indicate that the sulfides formed together with the actinolite in this zone.

The development of this zone appears to be restricted to the footwall and hangingwall margins of the main skarn bodies that are close to the intrusive. Very coarse actinolite laths up to 5 cm long exist with very coarse subidioblastic to idioblastic clinopyroxene in quartz along the wallrock margins of the epidote skarn (Fig. 21). Pyroxene and garnet are being replaced to varying extents by amphibole, epidote, calcite and quartz, which suggests that these minerals predate the amphibole zone assemblages. The zone is therefore interpreted to be replacing a prograde skarn assemblage that was similar to that which defines the garnet-pyroxene zone.



BD27

12.11.97

Figure 21. Photograph showing unusually coarse-grained actinolitic amphibole from the amphibole zone at Camp skarn (48229)

Amphiboles in skarns are compositionally distinct from those in the amphibolite wallrocks. Those occurring in the amphibole skarn or retrograde skarn range from ferro-actinolite to ferro-hornblende (Table 9; Fig. 22). These contrast with amphiboles from prograde zones and wallrocks where ferro-edenitic compositions are indicated. Biotite plots well within the biotite compositional field shown on Figure 23 (Table 10). Epidotes are marginally enriched in Fe and average Ps 20. Garnets are typically subcalcic.

Mineralization in Mount Alexander skarns

Metal deposition within prograde skarn appears to have been limited. Scheelite was not directly observed in the wollastonite zone, although coarse relict scheelite and scheelite inclusions in pseudomorphed wollastonite within the transition zone indicate that some scheelite deposition occurred during the formation of the wollastonite zone.

Substantial mineralization did not take place until the development of retrograde skarn, when concentrations of up to 1.0% WO_3 may be present. The highest grades are within the vesuvianite and epidote zones. In the former zone, very coarse dark-green to brown vesuvianite commonly forms a massive interlocking mass in which scheelite, clinozoisite-epidote, calcite and quartz are interstitial. Large calcite vugs are characteristic and fluorite is commonly present as inclusions in the vesuvianite, and as an interstitial phase. Scheelite occurs

in generally fine, but locally coarse anhedral to subhedral grains up to 3 mm across and fluoresces blue under ultraviolet light, indicating a low molybdenum content. Scheelite is more common where fluorite is present. Bands and lenticular domains of vesuvianite-fluorite-calcite-quartz within prograde zones contain relatively abundant scheelite, which ranges from subidioblastic, where totally included in vesuvianite or fluorite, to idioblastic, showing terminations into quartz-filled vugs and intergrown with clinopyroxene. Mineral assemblages filling vugs typically include quartz, clinopyroxene, subcalcic garnet, fluorite, calcite and scheelite. This style of mineralization has been observed only near the footwall and hangingwall margins of the skarns. Scheelite distribution within the zones is, however, highly irregular.

In the epidote zone, scheelite occurs as coarse anhedral interlocking grains with epidote-clinozoisite and clinopyroxene. Two generations of garnet are evident: early calcic garnet is partly replaced by epidote-clinozoisite and to a lesser extent calcite, and idioblastic subcalcic garnets are present as inclusions in calcite and fluorite. Subidioblastic to idioblastic clinopyroxene also occurs as inclusions in these minerals and in quartz. Garnet and clinopyroxene may also be included in coarse scheelite.

Kilba Well skarns

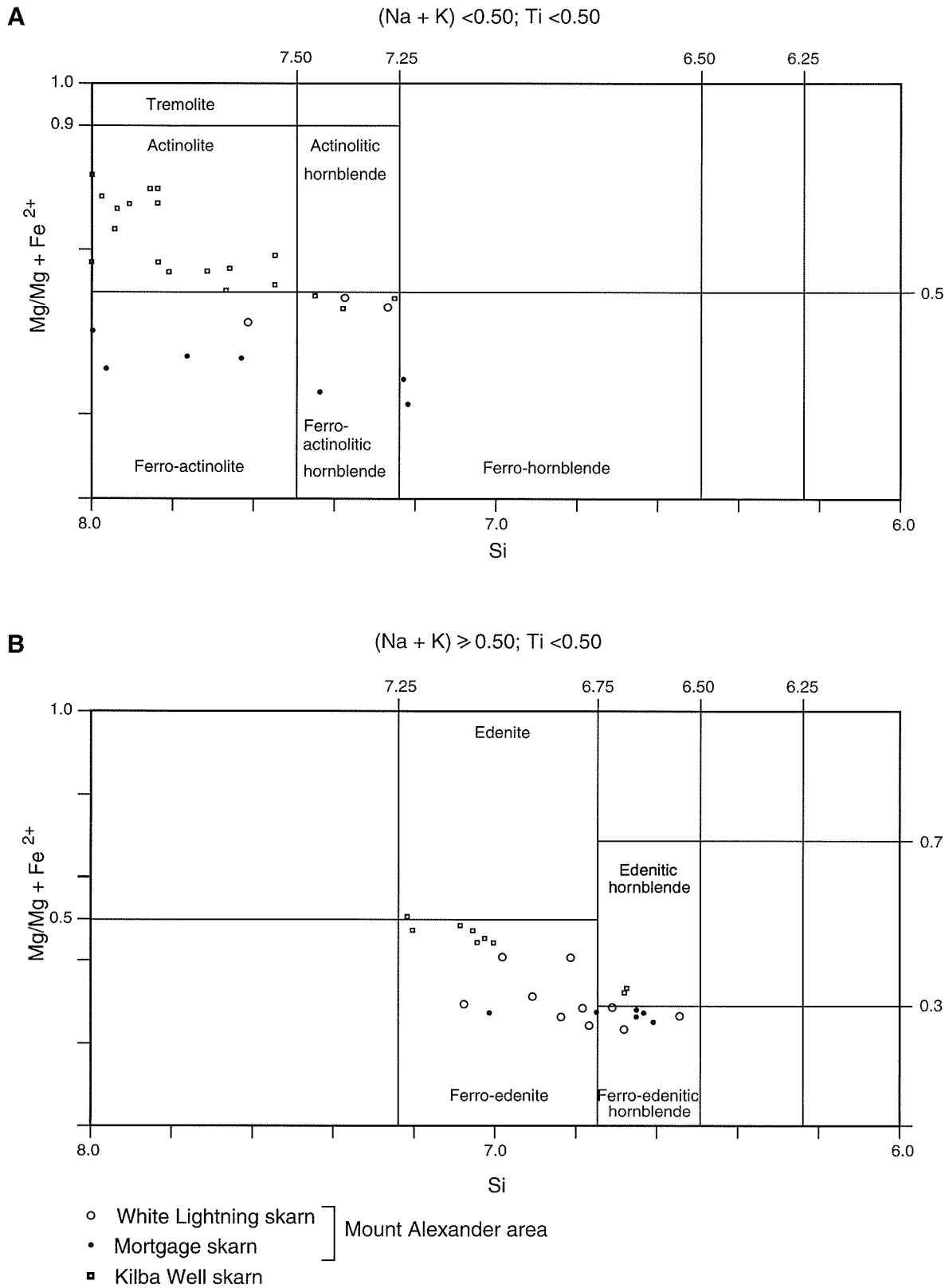
Skarns are present in a series of apparently discontinuous bodies surrounding the monzogranite stock described

Table 9. Representative amphibole compositions

Specimen	<i>Mount Alexander skarns</i>							<i>Kilba Well skarns</i>						
	90414	90429	90440	90644	90383	90383	90390	90392	90315	90312	90327	90304	90372	90341
SiO ₂	40.84	51.65	48.69	44.98	44.23	48.43	47.73	41.85	54.49	53.18	50.11	47.49	44.75	45.06
TiO ₂	0.37	0.00	0.00	0.18	0.42	0.16	0.28	0.26	0.00	0.00	0.26	0.09	0.95	0.31
Al ₂ O ₃	13.80	1.85	4.47	8.69	10.35	6.31	8.35	11.33	1.98	4.10	6.12	7.89	10.36	9.26
FeO _{tot}	23.83	23.26	24.44	24.94	21.33	20.87	19.06	24.27	10.17	10.17	18.33	19.08	19.79	18.46
MnO	0.51	1.01	0.91	0.89	0.48	0.76	0.44	0.83	0.44	0.36	0.35	0.47	0.28	0.09
MgO	4.80	8.64	7.18	5.64	7.67	8.41	9.94	5.45	17.37	17.48	10.87	9.63	9.01	9.83
CaO	11.16	11.80	11.65	11.37	11.39	11.84	11.61	11.79	12.86	12.54	11.77	12.14	11.38	12.64
Na ₂ O	1.49	0.42	0.60	1.37	1.20	0.66	1.01	1.17	0.50	0.58	0.84	1.37	1.42	1.25
K ₂ O	1.00	0.11	0.36	0.31	1.32	0.58	0.21	1.4	0.22	0.58	0.21	0.31	0.44	1.16
Total	97.80	98.74	98.30	98.37	98.39	98.02	98.63	98.35	98.03	98.99	98.86	98.47	98.38	98.06
Na+K ^(a)	0.68	0.20	0.26	0.49	0.64	0.32	0.34	0.66	0.18	0.28	0.29	0.47	0.52	0.61
Mg/Mg+Fe	0.26	0.39	0.34	0.29	0.39	0.42	0.48	0.29	0.75	0.75	0.51	0.47	0.45	0.49

Sample locations are listed in Appendix 1

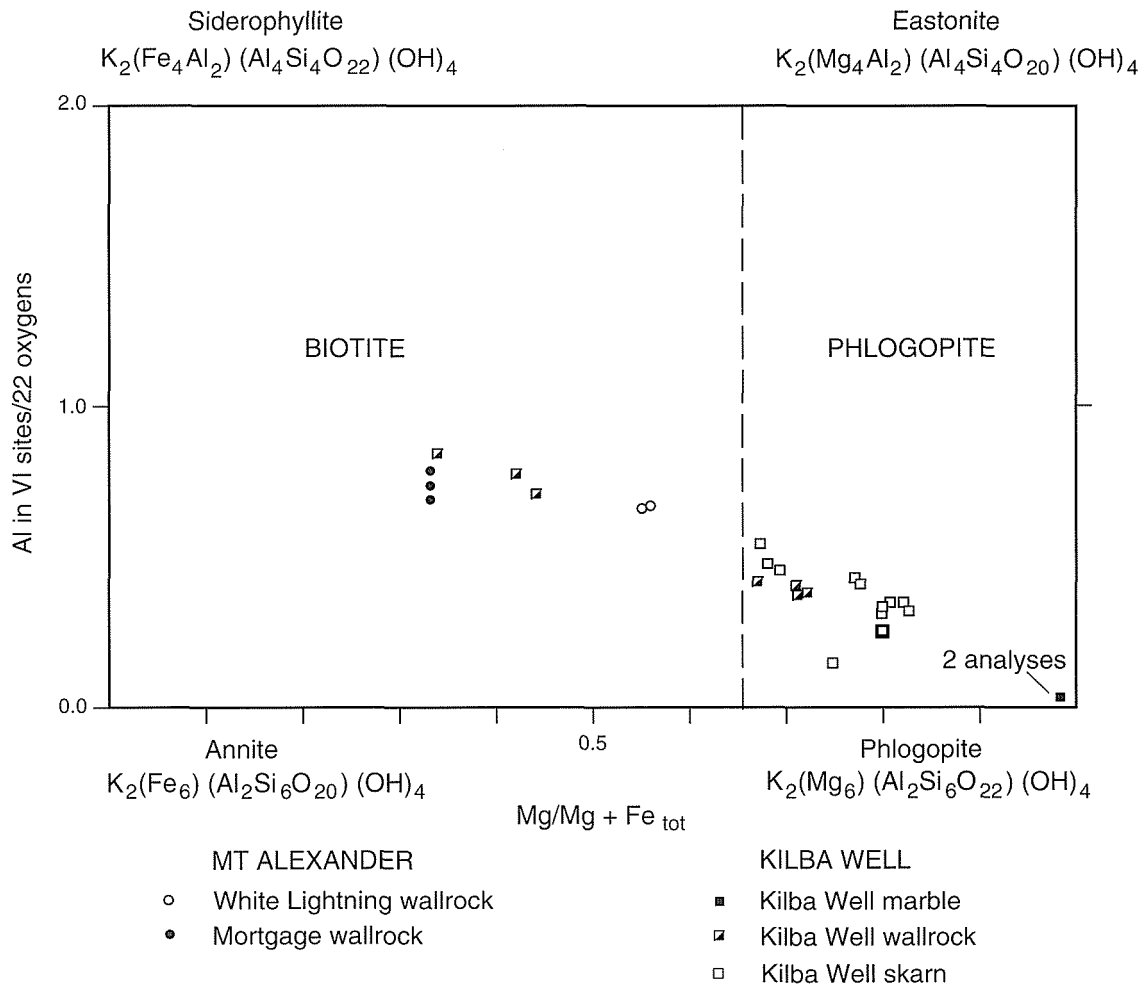
(a) Figures refer to number of Na+K ions in a formula unit based on 24 oxygens



BD14

29.10.97

Figure 22. Amphibole compositions in Mount Alexander and Kilba Well skarns and boundary layer wallrocks. A — from retrograde assemblages; B — from variably skarnized wallrocks. Fe_{tot} recalculated as Fe^{2+}



BD15

29.10.97

Figure 23. Biotite–phlogopite compositions in Mount Alexander and Kilba Well skarns

Table 10. Representative phyllosilicate compositions

Specimen	Mount Alexander skarns		Kilba Well skarns			
	90413	90390	90352	90376	90617	90617
	Percentage					
SiO ₂	39.84	36.93	45.06	41.92	31.20	62.96
TiO ₂	1.14	1.37	0.00	0.35	0.15	0.00
Al ₂ O ₃	18.00	17.54	10.44	13.58	20.08	0.00
FeO _{tot}	13.93	21.04	0.91	12.81	0.57	0.80
MnO	0.33	0.23	nd	nd	nd	nd
MgO	15.39	9.83	27.21	18.22	35.55	30.76
CaO	0.00	0.28	0.73	0.00	0.32	0.35
K ₂ O	8.92	10.15	10.26	9.03	0.00	0.00
Total	97.55	97.37	94.61	95.91	87.87	94.87
Mg/Mg+Fe	0.67	0.46	0.98	0.72	0.99	0.99

90352, 90376 = phlogopite; 90413, 90390 = biotite; 90617 = clinocllore; 90617 = talc; nd = not determined
 Sample locations are listed in Appendix 1

previously (Figs 4 and 5). The largest and best exposed of these, the Zone 11 skarn, was selected for detailed study.

The skarns are present as bands generally less than 10 m and averaging around 3 m thick. Deformation in the contact aureole resulted in some of the marble hosts being locally tightly folded. The hosts belong to Unit 2 of the local stratigraphic sequence, a unit dominated by hornfelsed psammitic biotite schists. The large volume of skarn formed at Kilba Well indicates that large quantities of fluid were released from the monzogranite following emplacement of the stock. It is probable that skarn developed simultaneously in all currently recognized zones around the stock.

Petrology and geochemistry of the zoning

Nine metasomatic zones (Table 11) have been recognized in skarns at Kilba Well. These are, from marble to intrusive:

1. wollastonite zone, defined by a wollastonite–garnet–clinopyroxene–vesuvianite assemblage

2. transition zone
3. garnet–vesuvianite zone, dominated by massive garnet and vesuvianite
4. garnet–pyroxene zone, which may be locally dominated by either of the main phases
5. pyroxene zone
6. epidote zone
7. amphibole zone
8. vesuvianite zone
9. hydrosilicate (biotite) zone.

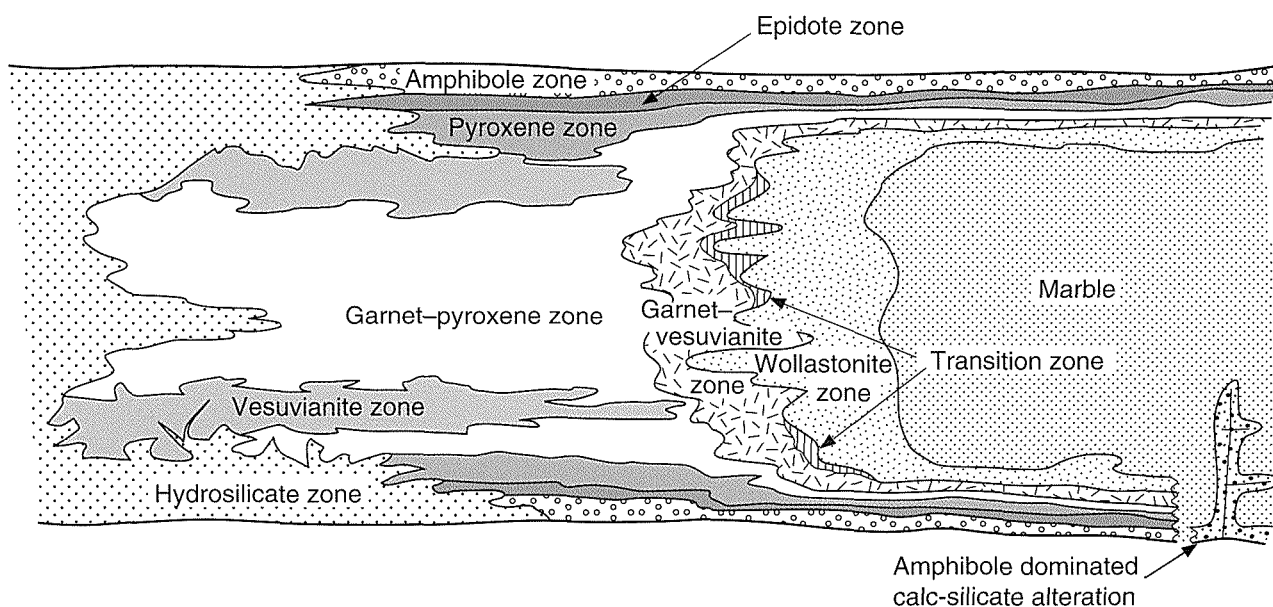
As at Mount Alexander, skarn formation can be divided into prograde and retrograde stages. Of the nine zones, the first six define the prograde period of skarn development, although the pyroxene and epidote zones may mark the onset of the hydrous retrograde stage. All are typically granoblastic with grain sizes of the constituent phases ranging from fine to very coarse; garnets in the vesuvianite zone are up to 5 cm across.

The prograde facies are overprinted by the amphibole, vesuvianite and hydrosilicate zones. The retrograde assemblages represented by these zones are characterized

Table 11. Mineralogical zonation in Kilba Well exoskarns

Zone	Mineralogy		
	Dominant	Intermediate	Minor
Host			
Marble	calcite	tremolite, chlorite	phlogopite, tremolite, quartz, talc
Prograde zones			
Wollastonite	wollastonite	garnet, cpx vesuvianite	calcite
Transition	garnet, cpx	vesuvianite, calcite cpx	quartz, scheelite sphalerite, pyrrhotite
Garnet–vesuvianite	garnet or vesuvianite	microcline, czs quartz	calcite
Garnet–pyroxene	garnet	cpx, vesuvianite, epidote/czs, quartz, feldspar	actinolite, scheelite
Pyroxene	cpx	epidote/czs, plagioclase, quartz, garnet	sphalerite, muscovite, actinolite, pyrrhotite, pyrite, (?)scheelite
Epidote	epidote/czs	quartz, cpx, garnet, calcite, actinolite	sphene, feldspar, apatite
Retrograde zones			
Amphibole	actinolite	quartz, calcite, epidote/czs, feldspar, sphene	phlogopite, apatite, alanite, cpx
Vesuvianite	vesuvianite	epidote/czs, calcite, feldspar	quartz, scheelite, fluorite, apatite, actinolite, cpx, garnet

cpx = clinopyroxene
czs = clinozoisite



BD16

30.10.97

Figure 24. Schematic geometry and distribution of zones in Kilba Well skarns. The presence of subfacies for some zones and the incomplete exposure of Kilba Well skarns means that zonal relationships are probably more complex than depicted. The large relative volume of retrograde assemblages possibly reflects the proximity of Kilba Well skarns to the monzogranite, as well as a higher volume of late hydrothermal fluids

by the dominance of hydrous minerals such as vesuvianite, biotite/phlogopite, and amphibole, and typically contain the highest scheelite grades. Unlike the Mount Alexander skarns, in which retrograde alteration of the prograde assemblages occurs preferentially along footwall and hangingwall margins, at Kilba Well the generally thin hosts have resulted in the retrograde zones occupying the entire host thickness. This also occurs in the thicker units in the Kilba Well skarns, but to an extent that cannot be determined owing to the paucity of exposure.

A schematic cross section has been constructed (Fig. 24) outlining the interpreted zoning geometry based on the above facies scheme.

Marble host

The host marbles are granoblastic, fine- to medium-grained rocks consisting almost entirely of calcite and variable amounts of tremolite, chlorite and phlogopite. They are generally massive, but are locally laminated and contain pelitic interbeds. Concordant and discordant zones of tremolite-chlorite(-phlogopite) form an alteration halo around fractures and follow bedding in manto-like bodies (Fig. 25). These features represent reactions between hydrothermal fluids derived from skarn formation and the marble host.

Prograde skarn zones

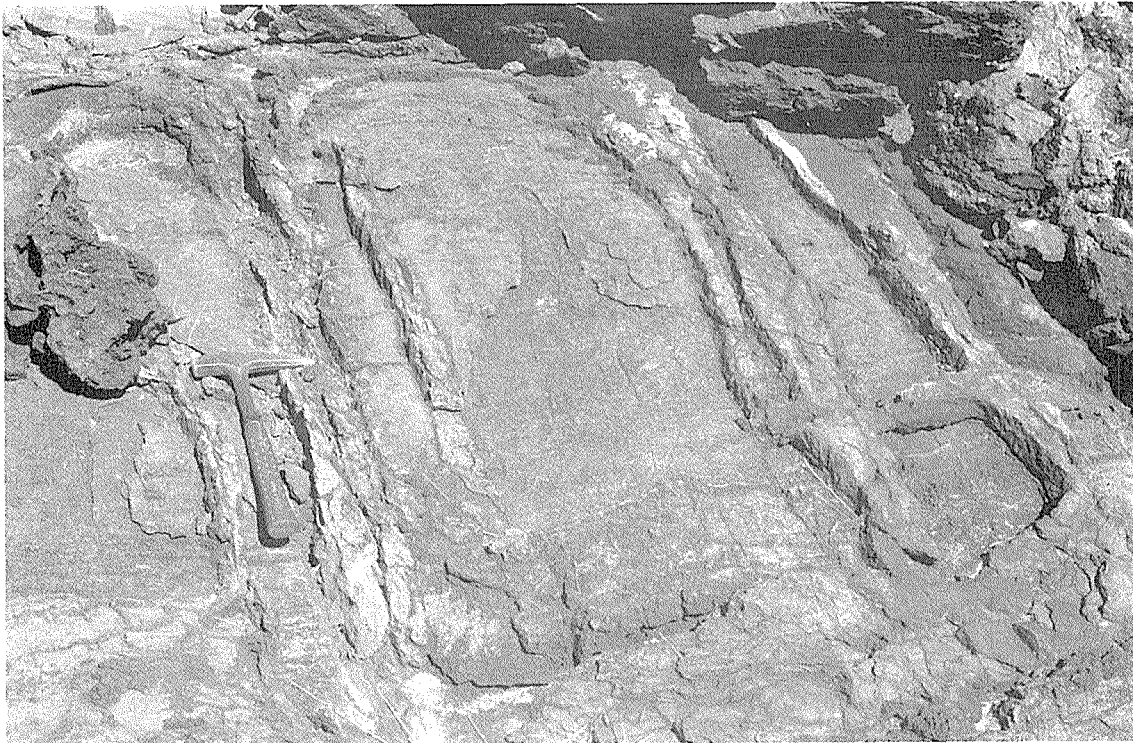
Wollastonite zone

This zone is the outermost of the skarn zones and is a cream, fine- to coarse-grained granoblastic rock. The

assemblage is dominated by wollastonite with subordinate garnet, and minor pyroxene, calcite and vesuvianite. Wollastonite is present as fibrous to columnar aggregates and dominates the matrix, where it occurs in association with minor fine-grained calcite and ragged xenoblastic pyroxene. Garnet and vesuvianite occur as coarse porphyroblasts with rims that are somewhat diffuse due to high densities of wollastonite inclusions. Garnet cores are generally free of wollastonite, although inclusions of xenoblastic, fine-grained pyroxene and calcite are common. Vesuvianite typically contains high densities of wollastonite inclusions. This suggests that garnet nucleated and began to grow prior to wollastonite and that vesuvianite nucleated and grew at the same time as wollastonite.

The metamorphic tremolite, phlogopite, chlorite, and most of the calcite in the marble was lost during the development of the zone. The magnesium released from the loss of tremolite and chlorite was probably incorporated in vesuvianite. Scheelite was not directly observed in the zone, although the ragged and possibly relict scheelite in the transition zone suggests that it probably was present.

Garnet compositions are typically near-end-member grossular with less than 0.6 mole percent almandine + spessartine and 5.1 mole percent andradite (Table 5; Fig. 13). No zoning is evident in the garnets and all display a weak anisotropy. Clinopyroxenes also show little compositional variation and are diopside rich with an average of about 23 mole percent hedenbergite and no more than 1 mole percent johannsenite (Table 6; Fig. 14). Vesuvianite is iron poor (Table 8) and wollastonite is end-member CaSiO_3 .



BD28

12.11.97

Figure 25. Photograph of outcrop displaying tremolite–chlorite dominant assemblages adjacent to fractures in marble at Kilba Well (Zone 11)

Transition zone

A thin intermediate zone of transition between the wollastonite and garnet–pyroxene zones is similar to the transition zone identified in the Mount Alexander skarns. The transition zone in the Kilba Well skarns is marked by the loss of wollastonite and the increasing abundance of garnet and pyroxene. Garnet shows varying degrees of anisotropy, is generally unzoned and is occasionally present as very coarse poikiloblasts. Subordinate and minor phases include vesuvianite, pyroxene, calcite, quartz, scheelite, sphalerite and pyrrhotite. Calcite and quartz pseudomorphs after wollastonite fibres are common and inclusions of these pseudomorphs are also present in vesuvianite. Wollastonite zone garnet, partially replaced by calcite and clinozoisite, also occurs as inclusions in the vesuvianite. Domains of quartz–calcite–pyroxene are common. Minor medium-grained anhedral scheelite occurs within this transition.

The abundant granoblastic pyroxene in the quartz–calcite zones does not exhibit the ragged grain boundaries evident for those of the wollastonite zone. This, together with inclusion-free garnet, indicates that both garnet and pyroxene formation dominated during this stage and that the transition zone probably represents an immediate stage between the wollastonite and the garnet–pyroxene zone.

Scheelite distribution is irregular; it occurs within vesuvianite that does not contain inclusions of pseudomorphed wollastonite, and in the matrix. The scheelite

in inclusion-free vesuvianite suggests that deposition probably occurred first during the formation of this transitional zone. Although no scheelite was observed in the wollastonite zone, its existence as inclusions within vesuvianite, together with the ragged margins of scheelite in the calcite–clinozoisite–microcline–pyroxene domains, could be interpreted as wollastonite zone mineralization that has survived. The ragged margins, which imply disequilibrium during the development of the domains, supports the presence of scheelite in the wollastonite zone.

There is little variation in garnet composition in this zone (Fig. 13). All are calcic, with almandine + spessartine components accounting for less than 2 mole percent and the andradite content less than 5 mole percent (Table 5). Pyroxene compositions are dominated by the diopside component and contain an average of 20 mole percent hedenbergite (Table 6; Fig. 14). These compositions coincide with those of the wollastonite zone. A single analysis of clinozoisite shows an aluminium-rich Ps 12 composition (Table 7; 90302). Vesuvianite is typically magnesium rich (Table 8; Fig. 20), with the range in Fe/(Fe+Mg) ratios of 0.38 to 0.43 being similar to those determined for vesuvianite in the wollastonite zone. The carbonate phase is end-member calcite.

Garnet–vesuvianite zone

This zone is also intermediate between the wollastonite skarn and garnet skarn. Its relationship to the transition zone is not known and it is possible that the two represent

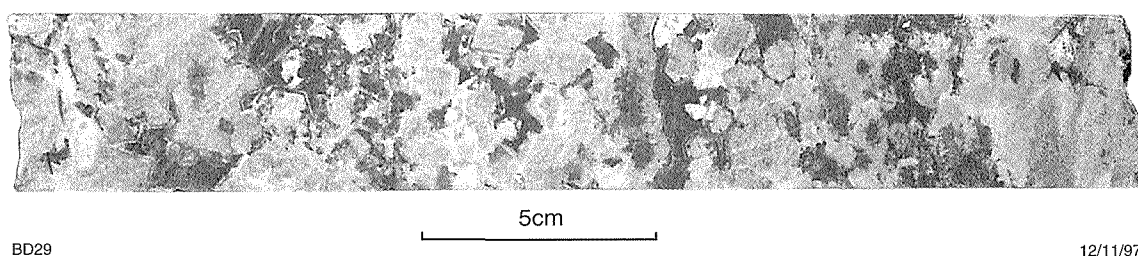


Figure 26. Photograph of core from garnet-vesuvianite zone in Kilba Well (Zone 11) skarn. (90373)

sub-zones of a broad transitional skarn facies separating the garnet-pyroxene zone from the wollastonite zone. The zone replaces the wollastonite zone and is defined by the loss of wollastonite. The boundary between the two facies has not been observed. Outcrop mapping in the western part of the stock suggests that the transition between the two zones extends over an interval of less than 1 m, and probably less than 0.5 m.

The assemblage is dominated by coarse-grained, intergrown, idioblastic and subidioblastic garnet and growth-banded vesuvianite (Fig. 26). Garnets up to several centimetres across are present and these commonly contain included zones of wollastonite pseudomorphed by fibrous calcite-epidote-clinozoisite. Inclusion-free overgrowths indicate continued garnet formation following the loss of wollastonite. Intergrowth geometry is determined by vesuvianite, which ranges from subidioblastic-tabular, to coarse-grained radiating crystals. Epidote, calcite and microcline fill the interstices between the coarse-grained vesuvianite and garnet, and also form zone delimiters in atoll-textured garnets. The same minor assemblage infills fractures in garnets. Pyroxene is a minor phase and occurs as disseminated, fine-grained, xenoblastic inclusions in garnet and vesuvianite. Minor scheelite is present as fine- to medium-grained anhedral and subhedral inclusions, and associated with, vesuvianite, calcite and feldspar interstitial fills between garnets.

Garnet compositions are grossular rich, with spessartine + almandine contents less than 3.1 mole percent and andradite contents less than 6.1 mole percent (Table 5; Fig. 13). No compositional variations were evident across growth zoning in the garnets. Pyroxenes are diopside rich, with hedenbergite contents of 21 to 28 mole percent and a johannsenite content of less than 2 mole percent (Table 6; Fig. 14). Vesuvianite shows little compositional variation and remains magnesium rich (Table 8; Fig. 20). Epidote-group minerals are more aluminous compared with those in the wollastonite zone, with compositions averaging Ps 14 (Table 7; Fig. 16).

Garnet-pyroxene zone

Garnet- and pyroxene-dominant assemblages are not well preserved in the Kilba Well skarns. Outcrop and drillcore exposures indicate that a possibly more extensive garnet-pyroxene zone existed at Kilba Well, but that retrograde overprinting has left only remnants. These remnants

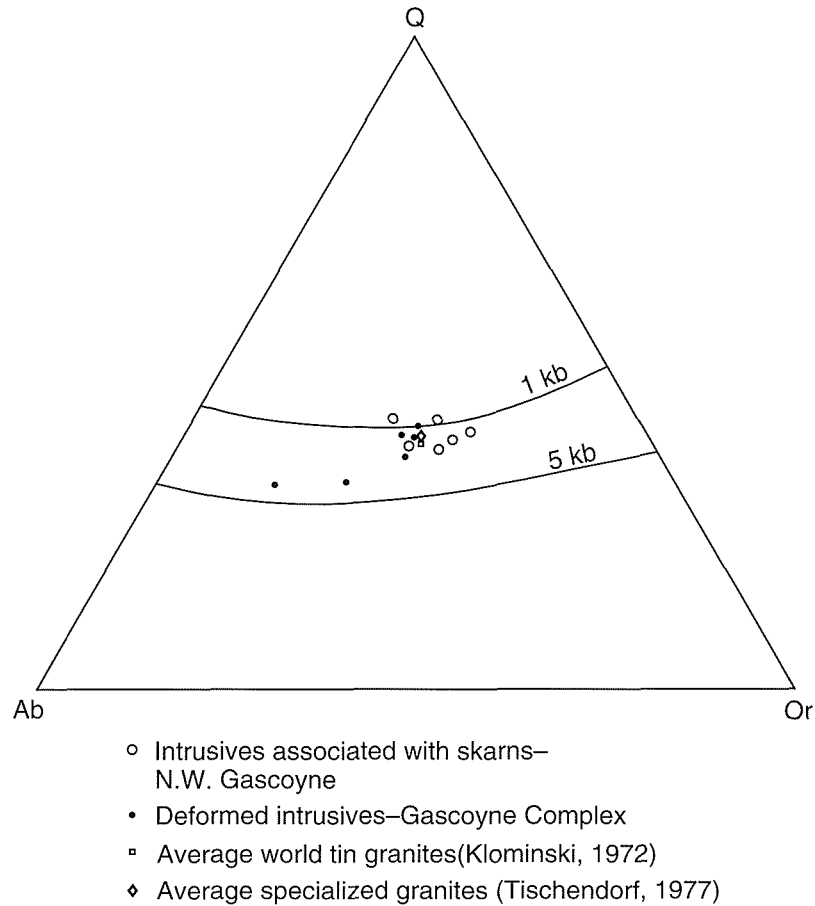
indicate an assemblage consisting of coarse garnet and fine- to medium-grained clinopyroxene. Garnet is variably anisotropic, but is typically poikiloblastic with respect to pyroxene. The latter occurs as granular xenoblasts and subidioblasts disseminated throughout the garnet. Poorly developed banding is present and is defined by alternating, discontinuous garnet and pyroxene-dominant laminae, including lenticular domains containing coarse garnet with minor calcite, pyroxene and clinozoisite. No mono-mineralic zones have been observed. Minor amounts of calcite, quartz, feldspar, epidote and clinozoisite complete the assemblage with clinozoisite, epidote, actinolite and calcite present as interstitial and vein infills. Fluorite and rare scheelite are locally present, but together with calcite and the epidote group minerals these replace the pre-existing garnet-pyroxene assemblage.

Garnet compositions are grossular rich and show a relatively restricted compositional range (Table 5) that is indistinguishable from garnets in the wollastonite and transitional zones (Fig. 13). The garnets contain less than 5 mole percent andradite and 2 mole percent almandine + spessartine. Zoning in some garnets is defined by rims being slightly more calcic than cores, expressed as a decrease in andradite content of up to 1.5 mole percent. Pyroxene compositions show a greater range and are more iron rich than those in the wollastonite or transition zones. Hedenbergite contents range between 31 and 48 mole percent (Table 6; Fig. 14), whereas johannsenite contents remain low at less than 2 mole percent. No zoning was evident within pyroxenes. Epidote-clinozoisite compositions show no significant variation and range from Ps 12 to Ps 16 (Table 7; Fig. 16).

Pyroxene zone

The pyroxene zone is best developed along footwall and hangingwall margins of the skarn bodies and is characterized by the increased proportion of pyroxene and epidote-group minerals. Textural and microstructural evidence from thin skarn bands indicate that the pyroxene zone replaces the transition skarn facies, although equivocal evidence further suggests replacement of the garnet-pyroxene facies. The facies is normally replaced by actinolite or epidote of the amphibole or epidote zones.

The assemblages representing this zone occur as a fine-grained, pale-green rock interbanded with other



BD17

29.10.97

Figure 27. Ternary Q–Ab–Or P_{H_2O} diagram comparing Gascoyne granites associated with tungsten skarns with other granitoids from the Gascoyne Complex and elsewhere. Isobars indicate emplacement depth (after Tuttle and Bowen, 1958). As used by Tischendorf (1977), ‘specialized granites’ host tin–tungsten mineralization and show distinctive minor-element abundances

zonal assemblages. The zone consists of a granoblastic intergrowth of pyroxene with epidote, clinozoisite, and minor vesuvianite, calcite, quartz, microcline, plagioclase (albite), scheelite and pyrrhotite. Garnet is a relict phase generally replaced by epidote, clinozoisite and calcite. Unaltered garnet is commonly preserved as inclusions in vesuvianite present as coarse poikiloblasts. Epidote and clinozoisite are common and locally dominate, in many places defining fine banding or lamination at outcrop and microscales. Scheelite, although rare, occurs as fine-grained anhedral inclusions in vesuvianite.

Pyroxene compositions show no significant difference from those of the garnet–pyroxene zone. They remain diopside rich with hedenbergite contents ranging from 22 to 42 mole percent. The compositional fields of this zone and that of the garnet–pyroxene field overlap (Fig. 14). Hedenbergite contents determined ranged from 22 to 42 mole percent. Epidote and clinozoisite compositions remain aluminous with a range in the pistacite component of Ps 12 to Ps 16, and averaging Ps 13.8 (Table 7). An enrichment in iron characterizes vesuvianite compositions, with Fe/(Fe+Mg) ratios

averaging 0.61 (Fig. 20). No compositional zoning was noted in any of these minerals.

Epidote zone

The epidote zone occurs as a green to cream, fine-grained granoblastic rock near the hangingwall and footwall margins of the skarn horizons. It is commonly banded with sharp boundaries against adjacent zones. The assemblage is defined by a granoblastic intergrowth of epidote and clinozoisite, variable proportions of locally dominant quartz, and minor calcite, clinopyroxene, plagioclase and sphene. No scheelite has been observed in this assemblage. Banding and lamination are defined by the relative abundances of epidote group minerals to quartz.

No major compositional variations could be distinguished in any of the primary phases in this zone when compared with equivalent phases from earlier prograde facies. Epidote-group minerals are aluminous and pyroxene compositions fall within the range indicated for pyroxenes in the pyroxene facies (Fig. 14).

Retrograde skarn zones

Amphibole zone

The amphibole zone appears as a dark-green banded zone adjacent to wallrocks, with a sharp boundary against the epidote facies. The zone varies in width, but is generally less than 5 cm wide. Fine to coarse-grained, randomly oriented actinolite laths dominate the assemblage and monomineralic zones have developed locally. Actinolite is accompanied by calcite, phlogopite, clinozoisite and epidote, with minor plagioclase, quartz, sphene, pyrrhotite and chalcopyrite. Sphene is ubiquitous and disseminated as fine- to very fine-grained idiomorphs, or as medium-grained subidiomorphs to idiomorphs. Rare inclusions of anhedral scheelite are present in actinolite.

The actinolites have Mg/(Mg+Fe) ratios averaging 0.54 (Table 9) and are compositionally distinct from those in the wallrocks, where the amphiboles are ferro-edenites with generally lower Mg/(Mg+Fe) ratios. Epidote compositions are marginally enriched in iron at Ps 15.3 (Table 7) compared with those in other prograde skarn facies.

Vesuvianite zone

The vesuvianite zone occurs as 'interbedded' units in other skarn zones, or near hangingwall and footwall margins of the thicker skarn bodies. The assemblage is defined by abundant vesuvianite and quartz, with minor calcite, epidote, clinozoisite, actinolite, pyrrhotite, plagioclase, fluorite, microcline and apatite. Vesuvianite is generally present as coarse to very coarse poikiloblasts enclosing altered pyroxene and garnet, and commonly displays well developed growth banding. This contrasts with the more massive and commonly fractured vesuvianite grains found in the garnet-vesuvianite zone. The proportion of quartz relative to vesuvianite varies greatly and in some domains dominates as coarse poikiloblasts enclosing idiomorphic vesuvianite. Many garnet grains are partially to completely replaced by epidote and calcite, and commonly occur as relict skeletal grains. Pyroxene is replaced by actinolite, calcite and clinozoisite, although relict grains are present in most sections. One section displayed intense epidotization of garnet and pyroxene adjacent to scheelite-bearing vesuvianite skarn.

Scheelite occurs as anhedral to subhedral inclusions in vesuvianite and as single grains or, particularly where fluorite is present, in aggregates in the matrix. Fluorite abundances are variable, but the mineral is generally common in this zone. Apatite is restricted to inclusions in vesuvianite, where it occurs as fine tabular subhedra.

Vesuvianite from this zone is moderately iron rich, with Fe/(Fe+Mg) ratios of between 0.51 and 0.58 (Table 8; Fig. 20). These values differ from those present in the garnet-vesuvianite zone, which have Fe/(Fe+Mg) ratios greater than 0.58, and from those in the wollastonite facies where ratios are much less than 0.51. No systematic variations in Ti contents were noted for vesuvianite in this zone. The relict garnets are calcic (approaching grossular) in composition and

pyroxenes are diopside rich. The compositions of garnet and pyroxene are similar to those recorded from the garnet-pyroxene and transition zones. Epidotes are aluminium rich with a typical compositional range of Ps 1 to Ps 13 (Table 7; Fig. 16) and are thus better classified as clinozoisites.

Hydrosilicate zone

The spatial relationships of this zone, relative to those described above, is unclear owing to incomplete exposure of the skarn system. Hydrosilicate assemblages pervasively replace the prograde garnet-pyroxene and garnet-vesuvianite zones, and are present in selvages adjacent to veins in these zones. Observed exposures show that this zone is most intensely developed along the footwall and hangingwall margins of the skarn bodies. The identification of similar assemblages in many of the prograde and retrograde zones indicates that a large volume of skarn was affected by the fluids responsible for the formation of this zone.

The assemblages that define the hydrosilicate zone are highly variable (Table 11). Several sub-assemblages can be recognized, all containing amphibole: quartz-rich, amphibole rich, and phlogopite bearing. These are accompanied in varying proportions by quartz, calcite, phlogopite, epidote, vesuvianite, fluorite, scheelite, plagioclase, alanite, sphene, pyrrhotite, chalcopyrite and sphalerite. Pyroxene is present as relict grains, and fluorite and medium- to coarse-grained idiomorphic sphene are common. Scheelite distribution is irregular, but where present is coarse grained and anhedral to subhedral. It has only been observed intergrown with plagioclase, which is typically highly sericitized, calcitized and locally epidotized (clinozoisite). Sulfide minerals are intergrown with the amphibole and phlogopite.

Intense epidote, actinolite and calcite alteration of garnet occurs adjacent to veins in the garnet-pyroxene zone. Scheelite is common in these alteration selvages.

Amphibole compositions vary considerably and cover the range from actinolite through ferro-actinolitic hornblende to ferro-edenite. Actinolite is dominant, usually occurring as coarse-grained laths up to 3 mm in length. The greatest compositional variability is found where alteration has occurred at wallrock boundaries. This reflects the variable assemblages and rapidly changing bulk composition of the rocks in these locations. Distinctive amphibole zonation results where a progression occurs from ferro-edenitic amphiboles in the wallrocks to actinolitic amphiboles in the altered skarn. This zonation is reflected by the broad range in Mg/(Mg+Fe) ratios, which vary from 0.48 to 0.73 (Table 9). Phlogopite compositions are relatively consistent with Mg/(Mg+Fe) ratios in the quartz-rich domains ranging between 0.67 and 0.69. This ratio varies considerably where amphibole dominates the assemblage and the phlogopites become magnesium rich. In the latter case, ratios in the order of 0.78 to 0.80 are common (Table 10; Fig. 23). Epidote is somewhat more enriched in iron with an average composition of Ps 16 (Table 7; Fig. 16). Epidotization of plagioclase in amphibole-

dominant domains results in iron-rich epidotes with compositions typically averaging Ps 20.

Mineralization in Kilba Well skarns

The complexity of the skarn system in the Kilba Well area results from the overprinting of bimetasomatic skarn by exoskarn. This makes it difficult to place constraints on the distribution and timing of scheelite mineralization. The data suggest that scheelite deposition took place during the late prograde and retrograde periods of exoskarn development. The distribution of mineralized skarn is highly variable at all scales and no particular sites appear to be favoured.

Prograde-stage mineralization appears to have been limited. Scheelite is irregularly distributed in what remains of prograde zones, although it is uncommon to rare in most. Assemblages associated with scheelite in some of the prograde zones may reflect the effects of very localized retrograde alteration.

The bulk of scheelite mineralization (and the higher tungsten grades) is found in retrograde zones, particularly in the hydrosilicate zone. The geometric complexity of the retrograde zone relative to that of the prograde zones results in variable scheelite distribution patterns within the skarn bodies. In the hydrosilicate zone, scheelite occurs as fine- to coarse-grained anhedral to subhedral grains intergrown with an assemblage characterized primarily by one, or a combination of, vesuvianite, fluorite, plagioclase, phlogopite and epidote-clinozoisite. The association of fluorite with scheelite is typical in the Kilba Well skarns as it is for the Mount Alexander skarns, particularly for higher grade mineralization. The distribution of scheelite in the hydrosilicate zone itself is somewhat patchy, and the continuity of grade within retrograde zones on larger scales is not known. The irregular distribution of mineralization resulting from the 'interlayering' of retrograde alteration causes problems in defining the limits of mineralization within any or all of the skarns at Kilba Well.

Summary

Intrusives

The northwestern part of the Gascoyne Complex contains several scheelite-bearing skarns that are related to porphyritic monzogranitic and granodioritic intrusives. The intrusives are present in stocks and batholithic complexes that are, for the most part, tectonically undeformed. They are characterized by weak to intense greisen-style alteration which is fracture controlled and restricted to the peripheries of the intrusives. Pervasive sericitic and intense greisen alteration is best developed in the Kilba Well granodiorite stock. The absence of deformation and the presence of greisenous and sericitic alteration set these intrusives apart from those of similar composition elsewhere in the Gascoyne Complex, and coincide with a lower grade of regional metamorphism in country rocks in the northwestern Gascoyne Complex.

Metasedimentary rocks immediately surrounding intrusives and skarns are intruded by swarms of unaltered, coarse- to very coarse-grained pegmatite dykes containing tourmaline and garnet. Pegmatites occur throughout the Gascoyne Complex, but the frequency and density of their occurrence in the Mount Alexander and Kilba Well areas appear to be unique.

Intrusives associated with the scheelite skarns are highly differentiated and characterized by high SiO₂, B, Li and Rb and are also generally enriched in Na₂O, K₂O, Sr, Th, and Nb. The overall compositions indicate a metaluminous to slightly peraluminous character, which contrasts with the moderately peraluminous intrusives elsewhere in the Gascoyne Complex. A definitive classification of the skarn-related intrusives in terms of the S and I types of Chappell and White (1974) is not possible, as both mineralogical and chemical data indicate that the Mount Alexander and Kilba Well intrusives are transitional between the two. It is likely that crustal contamination has modified an initial I-type magma.

Exoskarns

Exoskarns at Mount Alexander and Kilba Well are characterized by distinctive mineralogical zoning that developed during two stages of metasomatic activity. The zones reflect progressive changes in the composition of the metasomatic fluid. The general sequence is for prograde assemblages to be more calcium rich than retrograde assemblages (Table 4). This is reflected in the presence of wollastonite and grossular-rich garnets in the outer zones and subcalcic garnets and assemblages generally more iron rich in the main skarn zones.

At Mount Alexander, the prograde stage consists of three distinct zones that are dominated by a banded garnet-pyroxene skarn assemblage containing only low-grade mineralization. High-grade mineralization took place during a second, later stage in which scheelite deposition accompanied retrograde alteration of prograde assemblages. This was characterized by the replacement of anhydrous phases such as garnet and pyroxene by hydrous assemblages that included vesuvianite, fluorite, calcite, actinolite, biotite, phlogopite, epidote and clinozoisite. Three zones have been recognized within the retrograde phase; these are confined to areas close to the source intrusives and along footwall and hangingwall margins of the skarn bodies.

The Kilba Well skarns are more complex than those at Mount Alexander. A large proportion of the observed calc-silicate assemblages have a bimetasomatic origin, and result from the thermal metamorphism of impure carbonate rocks during emplacement of the Kilba Well monzogranite. Mineralogical zones in these skarns are also recognizable, but their distribution is commonly parallel to bedding, unlike the irregular and transgressive zone-boundary geometry found at Mount Alexander. Early bimetasomatic skarns at Kilba Well were overprinted by exoskarn, which resulted in a complex mix of the two skarn types that cannot always be differentiated. Because of this complexity, the physical dimensions of

the exoskarn bodies developed at Kilba Well are not known. The data indicate that the retrograde phase was a major event in the metasomatic history of the Kilba Well skarns and this contrasts with the Mount Alexander skarns, where this phase appears to have been less well developed. Overprinting of prograde zones by retrograde alteration adds further complexity to the Kilba Well skarns.

Scheelite is the only tungsten mineral recognized in the skarns at Mount Alexander and Kilba Well. Sulfides are present in minor proportions in the retrograde zones, particularly in the hydrosilicate zone at Kilba Well. The hydrothermal system in both areas is both iron and sulfur poor and the low proportions of sulfide minerals is a feature of the skarns. Where present, pyrrhotite is the dominant sulfide species, although minor pyrite and trace amounts of chalcopyrite and sphalerite are also present.

Little zoning in the minerals is evident from either the Mount Alexander or the Kilba Well skarns. Some garnets display a cyclic zonation, but the range is less than 4 mole percent of the main end-member component. No significant compositional zoning was detected in pyroxenes or amphiboles.

Bimetasomatic and prograde exoskarns are characteristically highly fractured and commonly show incipient to advanced alteration near retrograde skarn zones. This microscale crackle brecciation indicates the presence of a highly active hydrothermal environment during retrograde mineralizing events. The large volumes of prograde skarn that have been replaced at Kilba Well indicate that permeability must have been high during the retrograde stage.

All skarns in the Mount Alexander and Kilba Well areas can be assigned to the reduced class of scheelite-bearing skarns, a class essentially defined by the presence of subcalcic garnets. This class encompasses virtually all of the major and minor tungsten skarns that have been, or are presently being mined in the world. The King Island scheelite skarn, however, belongs to the oxidized class.

Discussion

Granitoids related to tungsten skarns

The physical and mineralogical nature of intrusive phases associated with tungsten mineralization in general, and skarn-hosted tungsten mineralization in particular, is well documented. However, in many cases, compositional data, particularly for trace elements, are lacking and attempts to characterize the intrusives using such data are difficult. Given the inability to concisely characterize 'tin granites', even with large amounts of data available (Taylor, 1979) and the close relationships exhibited by tin and tungsten mineralization, it is unlikely that granitoids related to tungsten deposits will be satisfactorily characterized.

Despite the limited data, however, some generalizations can be made, although the problems with inter-province comparisons remain.

Tungsten skarns are typically associated with granodiorite as well as monzogranite (or 'granite' as used in the general sense by Streckeisen (1976)), but are also associated with suites ranging in composition from diorite to granite. In the latter case, the skarns are most closely associated with the more felsic members.

Granitoid fabrics

Intrusives associated with tungsten-bearing skarns are, by contrast with those associated with porphyry-copper deposits (Einaudi, 1981) and tin deposits (Taylor, 1979), relatively unfractured and unaltered. This is the single most important physical characteristic of tungsten-related granitoids. The Mount Alexander and Kilba Well examples are also relatively unfractured, but where fracturing has occurred, it is restricted to marginal zones and developed late in the emplacement history. There are no extensive fracture systems in the metasedimentary rocks surrounding the intrusives such as those that surround some higher level porphyry-copper intrusives. The absence of these features suggests emplacement of tungsten granitoids at a greater depth than tin or copper porphyry-related granitoids.

The development of an aureole foliation is also characteristic of tungsten-related intrusives. Examples occur in the central Sierra Nevada region of California (Bateman, 1965; Nokleberg and Kistler, 1980) and adjacent to the monzogranite stock at the Cantung deposit in Canada (Blusson, 1986). The aureole fabrics suggests forceful emplacement of these intrusives, possibly by a ballooning diapir mechanism (Bateman, 1985). The absence of a penetrative fabric in the Mount Alexander and Kilba Well skarns indicates that emplacement preceded skarn development. The general absence of tectonic deformation within the plutons in all tungsten skarn provinces, including the northwest Gascoyne, indicates that emplacement was probably post-tectonic. The weakly developed fabric in the Kilba Well stock and in the marginal zones of the Mount Alexander batholith, are probably magmatic using the criteria of Paterson et al. (1989).

Myrmekitic zones and associated domains of inter-connecting, fine-grained, anastomosing granoblastic zones, have been reported from some of the granites spatially related to tungsten skarns (e.g. Vitaliano, 1944; Hotz and Willden, 1964; Bateman, 1965; Brock, 1972; Newberry, 1982). These features suggest deformation within the intrusive at, or close to, granite solidus temperatures, and further suggests that solid-state deformation processes are involved (Vernon et al., 1983; Simpson, 1985; Paterson et al., 1989). In the Gascoyne, myrmekite is most common in monzogranite occurring near the skarns and is clearly associated with the interconnecting, fine-grained anastomosing granoblastic zones described above. The primary implication of this deformation is that zones of high permeability were formed within the intrusive at a time when the

metalliferous water-rich fluids were evolving. The presence of such features could be interpreted to be favourable when assessing potential source granites during an exploration program.

Alteration

Sericitization and greisenization

Apart from alteration at the contact between skarn and intrusive, alteration in the main granitoid bodies is, in general, poorly documented. The available literature on granitoids associated with tungsten-bearing skarns does, however, show that pervasive alteration is present in many associated intrusives.

In the northwestern Gascoyne Complex, alteration is present as dyke-like zones of variable and commonly intense, sericitization and greisenization. These zones are fracture controlled and are confined to the contact zone of the relevant intrusive, although not necessarily at the immediate contact between the skarn and the intrusive. The alteration within the granodiorite of the Osgood Mountain Stock, Nevada, is typically greisenous, consisting primarily of muscovite and quartz with some hydrobiotite and apatite (Hotz and Willden, 1964). In this example, the greisen zones are present as pockets 30 cm to several metres in the longest dimension, or narrow, elongate fracture-controlled bodies up to several tens of metres long and 10 cm wide. Both are located close to the contact, with some veining extending outwards into the country rock for 6 m or more. Most of these veins contain some scheelite mineralization and a few have been worked. The monzogranite adjacent to the Tem Piute mine, also in Nevada, has undergone patchy, intense to pervasive sericitic alteration in which feldspar and primary biotite are partially replaced by white mica (Buseck, 1967). Alteration is most intense near the contacts of the stock, where it commonly contains pyrite. Alteration outside the immediate contact zone in the Pine Creek mine is restricted to a discontinuous development of scheelite-bearing quartz veins and accompanying local silicification along the contacts between the intrusive and country rocks (Bateman, 1965). For the same mine, Newberry (1982) describes a biotite-quartz-chalcopyrite alteration of the quartz monzonite (monzogranite) up to a distance of 5 m from the contact between it and the retrograde skarn. In the Gascoyne intrusives, similar scheelite-bearing veins were mapped during exploration in the non-carbonate country rocks immediately adjacent to the monzogranite stock at Kilba Well.

Sericitic or greisen alteration is also present in the monzogranites and granodiorites associated with the W-Cu skarns in the northern Cordillera, USA. The alteration is peripheral to quartz veins as well as pervasive in zones of unknown dimensions (Dick, 1979; Dick and Hodgson, 1982). This is similar to the geometry and occurrence of alteration in the Kilba Well monzogranite, where pervasive sericitization is present on the western and southern margins of the stock. The intensity of the alteration at Kilba Well varies, but tends to increase as the contacts are approached. Restriction of the most obvious alteration to the marginal zones of intrusives is

also apparent in the granitoids associated with scheelite skarns in the Fairbanks (Alaska) area (Newberry and Swanson, 1986).

Five distinguishable zones of intensely greisenized rock occur in the marginal parts of the Dolcoath granite underlying the F-Sn-W skarn deposit at Moina in Tasmania (Kwak and Askins, 1981b). This deposit is unusual in that scheelite and cassiterite occur together in 'wrigglite' (Kwak and Askins, 1981a). The least-altered granite consists primarily of quartz, white mica, K-feldspar and plagioclase. With increasing alteration feldspar is replaced, and at the contact the granite consists mainly of quartz, muscovite, fluorite and pyrite. Like those in the Gascoyne and elsewhere, the greisen at Moina contains no topaz.

It is clear that patchy, pervasive greisen and/or sericitic alteration of plutons related to tungsten skarns is more common than was previously thought. This style of alteration tends to be restricted to the marginal zones of the intrusive and intensities vary considerably, although are generally weak. The most common style of alteration is where sericitization with silicification, or greisenization, of the enclosing granitoid occurs adjacent to linear, vein-controlled zones also located at or near the margins of the intrusive. In some areas these may extend into the country rock, for example around the Osgood Mountain stock, but this appears to be uncommon.

Other alteration

At the Clea deposit in the northern Cordillera (USA), intense tourmalinization occurs locally within the associated monzogranite stock (Dick, 1979). Tourmaline is present as an accessory in the granitoids around the Mount Alexander and Kilba Well deposits, and is very common in the pegmatites that are closely associated with the skarn bodies. Intense tourmalinization of wallrocks adjacent to some of these pegmatites has been observed near the Aladdins Skarn south of Mount Alexander. Intense tourmalinization also prevails alongside pegmatites intruding the metasedimentary rocks, and in the monzogranite adjacent to quartz veins in the Kilba Well area.

Granitoid geochemistry

A review of the nature of granitoids associated with tungsten-bearing skarns was published by Newberry and Swanson (1986), although Kwak and White (1982) previously attempted to differentiate between those associated with scheelite skarns and Sn(-W-F) skarns in Australia.

The majority of intrusives associated with tungsten-bearing skarns are compositionally similar to 'tin' granites. Reviews of such granites in Taylor (1979) and Tischendorf (1977) showed that they were characterized by higher contents of SiO₂ and K₂O and by lower contents of TiO₂, Fe₂O₃, MgO and CaO than granites not associated with mineralization. The effects of differentiation and subtle, pervasive alteration may have contributed to the geochemical signatures of some of these granitoids,

particularly those associated with tin mineralization (Pollard and Taylor, 1986).

The trends outlined for the tungsten-related granitoids in the northwestern Gascoyne Complex are typical of most of those associated with tungsten skarns elsewhere. The monzogranites generally have high to very high SiO_2 and K_2O contents, show little variation in $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, and are marginally peraluminous. The granodiorites also show elevated SiO_2 contents relative to the average granodiorite of Nockolds (1954), although they have lower values compared with the average composition of muscovite-biotite and biotite granodiorite (Nockolds, 1954). They are universally enriched in K_2O and marginally in MnO , but lower in Al_2O_3 and Na_2O .

The combination of mineralogical and chemical data does not point unequivocally to either an S-type or I-type character for the Gascoyne intrusives. The data suggest a predominantly S-type affiliation with normative corundum generally higher than 1%, although the presence of magnetite, sphene and possibly magmatic muscovite indicates a transitional nature, possibly due to contamination of an I-type magma by sedimentary material. Contamination was suggested by Sawkins (1984) as being critical to the formation of tungsten skarns and this is in part supported by investigations of several Sierra Nevada intrusives by Ague and Brimhall (1987). If most of these were derived from an I-type magma, then the role of hornblende fractionation in producing the observed assemblages and compositional variations may be important. This process has been demonstrated by Frey et al. (1978) to have caused the compositional variations in some central Sierra Nevada plutons, some of which are directly related to significant tungsten-skarn systems. Thus, the absence of hornblende is noteworthy in the Mount Alexander batholith and in other batholiths in the region, such as the Boolaloo Granodiorite, Wongida Creek Granodiorite, and the Mount Danvers Granodiorite (Daniels, 1965). Hornblende is also absent from intrusives associated with major tungsten-skarn systems elsewhere, such as in the Selwyn Basin area (Anderson, 1983).

High differentiation indices coupled with the meta-luminous to peraluminous chemistry is a feature of many tungsten-related plutons and indicates a strong S-type character despite the bulk of analyses from associated intrusives indicating I-type primary magmas. This suggests that significant modification occurred in certain plutons, and it was those that were subsequently associated with tungsten-skarn formation. However, an S-type character could be caused by pervasive alteration of a pluton. It is therefore possible that the intrusives associated with the Gascoyne scheelite skarns represent fractionated and differentiated or altered I-type magmas, resulting in compositions that have an S-type character. Investigation of Cordilleran (USA) intrusives associated with scheelite-bearing skarns suggests that the bulk of these were initially I-types that were subsequently and significantly modified by fractionation and differentiation (Newberry and Swanson, 1986), and by contamination (Ague and Brimhall, 1987). Newberry and Swanson (1986) point to the potential problems in sampling

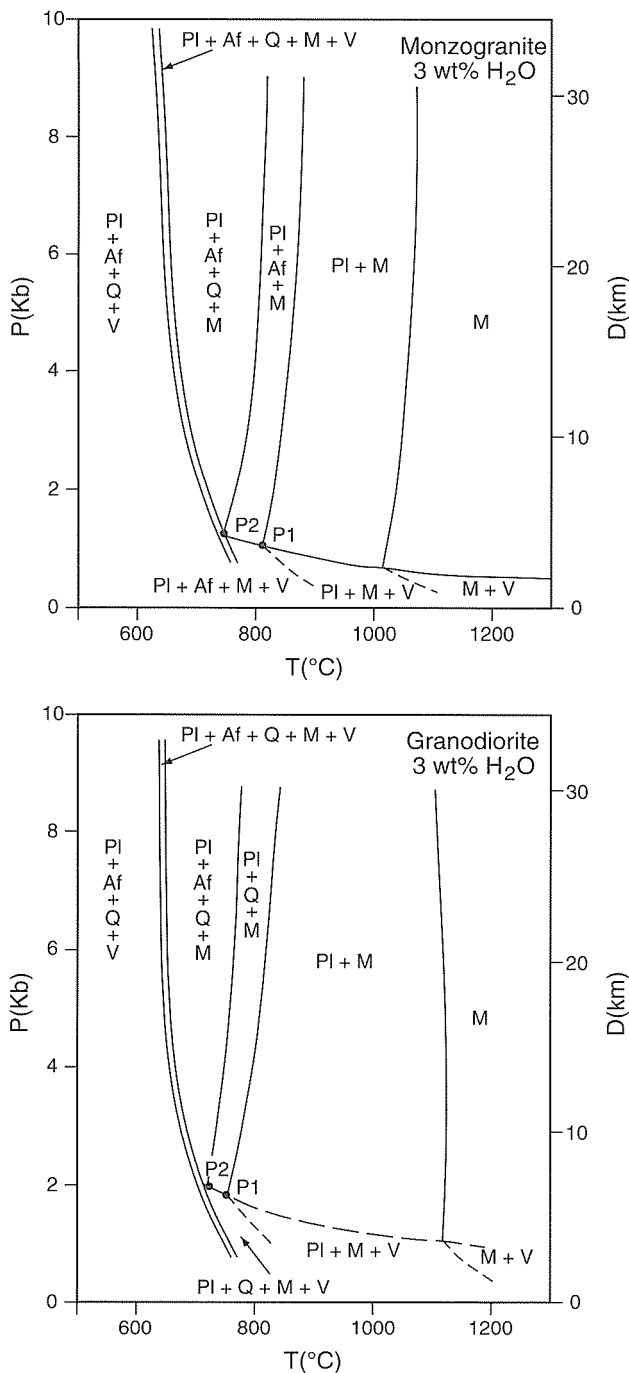
resulting from the tendency for the skarns to develop adjacent to the most highly differentiated zones in the pluton. Care is therefore needed when sampling and in subsequent interpretation of analytical results.

The limited amount of data available for the tungsten-skarn-related intrusives means that the above interpretations of their origins and evolution should be regarded with some caution. Until more major- and minor-element, REE and isotope data become available for these and other intrusives, definitive conclusions regarding primary magma types and their evolution cannot be reached.

Depth of, and conditions during, magma emplacement

Emplacement of intrusives associated with scheelite-bearing skarns occurred at pressures greater than those for other skarn types and are typically in the range 1 to 2 kb (Einaudi et al., 1981; Newberry and Swanson, 1986). This contrasts with an average pressure of less than 0.5 kb for the formation of Cu skarns (Einaudi et al., 1981). The increased depth of emplacement indicated for tungsten-skarn-related intrusives is reflected in the absence of major brecciation within the intrusive and surrounding country rocks, an absence that characterizes plutons associated with porphyry-copper and related Cu skarn deposits (Burnham, 1979; Einaudi, 1981). Fracturing in the plutons in the northwest Gascoyne is minor and its restriction to the marginal zones suggests that emplacement of the Mount Alexander batholith and associated intrusives occurred at pressures of greater than about 1 kb (Fig. 27). Support for this is derived from the experimental studies of Whitney (1975a,b) on synthetic monzogranite and granodiorite with a water content of 3 weight percent. These studies indicate that fluid exsolution does not take place until the solidus of the melt is approached and confining pressure increases above 1.0 kb (Fig. 28). The water content used in the modelling is supported by the data of Burnham (1979), which indicate that the water contents of such granitoids are probably in the order of 2 to 4 weight percent. Whitney's (1975a,b) results also provide a basis for explaining the limited development of pervasive alteration throughout most of the plutons associated with the tungsten skarns.

The porphyritic texture and late crystallization of biotite in the intrusives, including those in the northwestern Gascoyne Complex indicate that crystallization probably took place under vapour-undersaturated conditions (Swanson, 1977). Despite an inherent undersaturation with respect to water, the presence of phaneritic rocks (i.e. pegmatites) associated with the intrusives suggests that water was retained by the magmas until late in their crystallization histories. Moreover, the absence of aphanitic phases, such as occur in porphyry-copper systems, indicates that the rate of water loss from the magma, when it did occur, was relatively slow. This is further evidence for the interpretation that the confining pressures at the final level of emplacement were sufficient to inhibit major fracturing of the overlying rocks, and therefore rapid water loss from the cooling plutons.



BD18

30.10.97

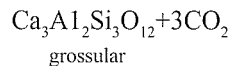
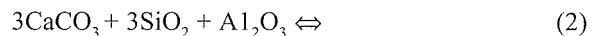
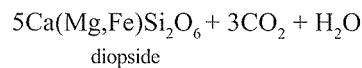
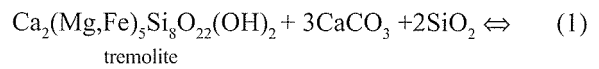
Figure 28. P–T phase diagrams for synthetic granitoid compositions. At higher emplacement pressures (e.g. P2), an aqueous phase does not appear until just above the solidus. The higher degree of crystallization concentrates W in the residual melt from which it partitions strongly into the aqueous fluid and maximizes concentration (Manning and Henderson, 1984). At lower confining pressures (e.g. P1), the degree of W partitioning and potential concentration in an aqueous fluid are lower. Diagrams and data from Whitney (1975a,b). PI = plagioclase, Af = alkali feldspar, Q = quartz, M = silicate melt, V = aqueous vapour

The presence of transgressive, anastomosing vein-like zones of fine-grained quartz and plagioclase in the Mount Alexander and Kilba Well intrusives, and similar features and relationships elsewhere (Newberry, 1982), indicate the existence of zones of relatively high porosity and permeability late in the cooling history of the magmas. It is possible that these zones represent fracturing due to some overpressuring at the time of water release.

Conditions during bimetasomatic skarn formation

Zoning within bimetasomatic skarns in both areas reflects an increase in Ca and decreases in Fe and Mg in the non-carbonate wallrock.

The pressure–temperature conditions of bimetasomatic skarn formation can be estimated from the following reactions, based on observed phase relations in the bimetasomatic skarns in the Mount Alexander region.



These two reactions have been studied by Metz and Winkler (1963) and Mill and Kalinin (1966) respectively. Tremolite and calcite are the common constituents of the host marbles prior to skarn formation. Reaction (1) will proceed at temperatures of between 500° and 550°C at $P_{\text{total}}=1$ kb if X_{CO_2} is greater than 0.1. Reaction (2) normally attains equilibrium between 550° and 600°C at 1.5 kb, although temperatures can decrease if excess calcite is present. These values are in good agreement with those determined for contact metamorphism, which indicates that contact metamorphism and bimetasomatic skarn development occurred at around 500–550°C and 1.5 kb.

Significance of bimetasomatic skarns

The Kilba Well skarn system contains large volumes of barren, iron-poor bimetasomatic skarns. While large volumes of such calc-silicates are apparently absent from the Mount Alexander area, they are a common feature of other tungsten skarn districts (Bateman, 1965; Einaudi et al., 1981; Nokleberg, 1981).

The origin of these barren calc-silicate units in tungsten provinces remains unclear. They have been considered to be related to a period of aluminium–magnesium metasomatism that preceded the main period of tungsten-bearing skarn formation. A metamorphic origin has also been suggested in which their presence or absence has been related to the purity of the host carbonates. In the latter case, those with the least amount

of impurity do not develop the iron-poor calc-silicate units, whereas they do in hosts containing high levels of argillaceous impurities. At Kilba Well, the host carbonates appear to be variably argillaceous, which suggests that the impurity content of the hosts was the controlling factor governing the development of the barren calc-silicate units. If this interpretation is correct, then it follows that the bulk of the calc-silicate units have a contact metamorphic origin and therefore preceded exoskarn formation.

The barren calc-silicate units lack the distinctive lateral zoning sequences that are characteristic of the exoskarns. Bedding-parallel banding caused by bimetasomatic skarn formation within the banded to laminated impure marble host at Kilba Well are characteristic of many parts of the exoskarns. The distribution of these zones therefore relates directly to the variations in bulk composition of the host. Overprinting of these bimetasomatic skarn bands by prograde and retrograde stages of the exoskarns caused the complex geometrical and mineralogical relationships observed in this area.

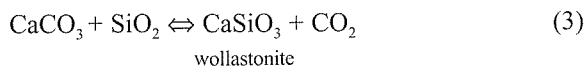
Conditions during exoskarn formation

Prograde skarn

Prograde skarn formation is estimated to have occurred late during the crystallization period of the source intrusives. Phase relationships indicate that at the onset of prograde skarn formation temperatures did not exceed 550°C and were probably in the range 500° to 535°C. The maintenance of temperatures close to those of contact metamorphism suggests that local thermal gradients were still high following regional metamorphism and granite emplacement. From contact metamorphic data, the ambient pressure immediately prior to the onset of skarn formation was approximately 1.5 kb.

The release of fluids from the source intrusives following emplacement was slow. This suggests that temperatures during the initial stages of skarn formation may have been marginally lower than those estimated from contact assemblages. Initial temperatures at King Island have been estimated as low as 350°C (Kwak, 1978) based on fluid-inclusion and thermochemical data, although an estimate of between 400° and 710°C for this deposit has also been suggested (Large, 1971).

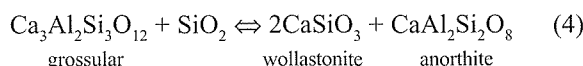
The presence of wollastonite-bearing rocks in the Mount Alexander and Kilba Well skarns suggests a much higher temperature than for King Island.



The reaction should proceed to the right at a maximum temperature of 725°C and $X_{\text{CO}_2} = 1.0$ (Greenwood, 1967) and at lower temperatures as the CO_2 content in the fluid decreases. While the formation of wollastonite is dependent on the $X_{\text{H}_2\text{O}}/X_{\text{CO}_2}$ ratio in the

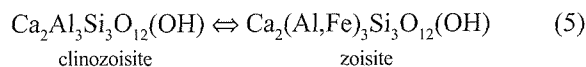
fluid, its presence indicates a low mole fraction for CO_2 at the temperatures indicated for contact metamorphism in the Mount Alexander and Kilba Well skarns. A maximum value of X_{CO_2} of 0.15 has been suggested for such systems (Greenwood, 1967). The development of the transition zone in the Mount Alexander skarns, in which wollastonite is replaced by calcite and quartz, probably reflects an increase in X_{CO_2} in the fluid resulting from the replacement of calcite by wollastonite, garnet and pyroxene during prograde skarn development. The Gascoyne data suggest a range in X_{CO_2} values of 0.06–0.10 (Metz and Winkler, 1963; Mill and Kalinin, 1966) during prograde skarn development. An increasing CO_2 content and the subsequent instability of wollastonite suggests that there was no escape for the fluids and that they were not buffered with respect to CO_2 . The absence of veining in the silicate wallrocks provides some evidence for the inability of skarn-forming fluids to escape the marble hosts.

An estimate of the upper limit for temperature during the formation of the garnet–pyroxene zone in the Mount Alexander skarns can be derived from the garnet–quartz assemblages which were stable in this zone. The reaction

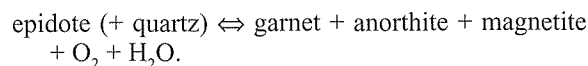


takes place at 600°C at 2 kb (Newton, 1966). The higher temperature assemblage is not present in any of the skarns and this temperature is therefore assumed to represent the maximum possible for the formation of the garnet–pyroxene zone. A lower pressure reduces this temperature and the presence of iron and manganese extends the stability field for garnet–quartz assemblages (Newton, 1966; Taylor and Liou, 1978). Although lower pressures are possible, it is unlikely that a significantly increased stability field for garnet–quartz pairs was achieved because prograde garnets have low iron and manganese contents.

An upper temperature limit for assemblages containing epidote-group minerals can be determined from the presence of clinozoisite-rich epidotes. Their stability is governed by the reaction



The intersection of the phase boundaries for reactions 4 and 5 defines a maximum temperature of 545°C for garnet–epidote(–clinozoisite)–quartz assemblages. A similar temperature can be deduced from the pair epidote–quartz, whose stability is limited by the complex reaction:



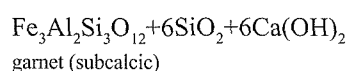
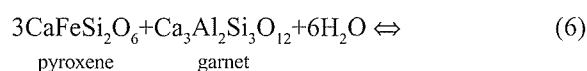
Epidote compositions of Ps 25 or less indicate low oxygen fugacities at or below those of the Ni–NiO (NNO) buffer. Under these conditions the equilibrium boundary for the reaction is crossed at about 535°C at 1.5 kb and 557°C at 2 kb (Liou, 1973). As none of the products of the epidote breakdown reaction have been observed in either the Mount Alexander or Kilba Well systems, these

temperatures represent maxima for prograde skarn development.

In conclusion, the absence of major fracturing and brecciation associated with the emplacement of the intrusives suggests a depth corresponding to pressures in the range of 1 to 2 kb. This conforms with interpretations made by other workers for other intrusives related to scheelite skarns. Interpretation of contact metamorphic assemblages confirms that the depth estimate for the Mount Alexander and Kilba Well intrusives is realistic and that an initial temperature of between 450° and 550°C existed at the time of emplacement. Further confirmation of these conditions is derived from the phase relationships and equilibrium data for mineral assemblages in the bimetasomatic skarns.

Retrograde skarn

Temperatures during the retrograde stages were lower than in prograde times. The conditions under which subcalcic garnets formed containing substantial proportions of almandine and spessartine components have not yet been defined. However, several studies show that nearly complete solid solution exists at relatively low temperatures and pressures (Ackermann et al., 1972; Ito and Frondel, 1968; Shimazaki, 1977; Newberry, 1983). Calcium-depleted fluids required for the formation of subcalcic garnets were present during the initial stages of retrograde skarn formation (Newberry, 1983). Low aca^{2+} in the fluids responsible for retrograde alteration was probably the result of the formation of vesuvianite and fluorite. Any initial increase in aca^{2+} was probably the result of reaction between these fluids and the prograde pyroxenes and garnets, such as via the reaction



The calcium ions in solution are represented by hydroxide complexes, although in the fluids associated with the Gascoyne skarns, they may also have been present as CaCl_2 or CaF^+ complexes, based on the assemblages observed in those zones.

The stability of vesuvianite is broad at the pressures interpreted for skarn formation. However, the thermal stability of vesuvianite is shifted to considerably lower temperatures in the presence of quartz (Hochella et al., 1982). Quartz is abundant in the vesuvianite zone and the synthesis work of Hochella et al. (1982) indicates that stable coexistence of these phases will occur only at temperatures below 400°C and $X_{\text{CO}_2} = 0.015$ at $P_{\text{fluid}} = 2$ kb. By graphical extrapolation of Hochella's data, the temperature would be less than about 360°C and $X_{\text{CO}_2} < 0.015$ at $P_{\text{fluid}} = 1.5$ kb. An upper temperature limit of 400°C is therefore interpreted for the early stages of retrograde alteration in both Mount Alexander and Kilba Well skarns.

The presence of abundant epidote in many of the retrograde assemblages allows an interpretation of the minimum temperature for retrograde skarn formation. Seki (1972) estimates that the minimum temperature for epidote stability is about $220 \pm 50^\circ\text{C}$, subject to oxygen fugacity. It is probable that the actual minimum temperature was higher in the Gascoyne skarns, although a realistic estimate is difficult to make. The assemblages do, however, suggest that a significant drop in temperature marked the change from prograde to retrograde events.

Although precise estimates of temperatures at the time of deposition cannot be deduced from the presence of fluorite, it is evident from the work of Richardson and Holland (1979a,b) and the review of Holland and Malinin (1979) that the solubility of fluorite is relatively low at the salinities expected for the retrograde fluids. Slight changes in the aca^{2+} in the fluid would lead to deposition of fluorite under these conditions. Fluorite is absent from the wollastonite, transition and garnet–pyroxene zones of the skarns, but is common in the late retrograde zones such as the hydrosilicate zone at Kilba Well. Its rare occurrence in the early retrograde assemblages suggests that temperatures were too high for fluorite deposition. With decreasing temperature below about 250°C, there is a rapid decrease in solubility of fluorite, due to decreases in the solubility of CaF^+ , MgF^+ and NaF complexes in the presence of NaCl and CaCl_2 . The actual temperature of deposition is governed by the salinity of the fluid, but even at relatively high concentration, the solubility decreases rapidly below about 350°C. It can therefore be interpreted that temperatures were decreasing as retrograde alteration was taking place. This temperature is in broad agreement with those determined from microthermometric measurements in other tungsten skarn deposits (Kwak, 1978).

In summary, retrograde skarn formation occurred late in the evolution of the skarn system, coinciding with an overall decrease in the ambient temperature of the host rocks and that of the hydrothermal fluids. Temperatures within the system at this stage are not known but, based on mineral equilibrium data presented above, are interpreted to fall in the range 300° to 400°C.

Scheelite mineralization

The distribution of scheelite in skarns varies considerably. In most deposits, such as those at the Mactung, Cantung, Strawberry, Elgfall, Tem Piute, Sandong and King Island mines, scheelite is common in the main garnet–pyroxene skarns (Ohlsson, 1979; Buseck, 1967; John, 1963; Large, 1971; Dick and Hodgson, 1982; Nokleberg, 1981). The overall scheelite distribution in the Kilba Well and Mount Alexander skarns appears to be one in which there are only low to moderate tungsten grades in the prograde zones of the skarn. The highest grades are found in assemblages related to retrograde alteration. This suggests that either the concentration of tungsten in solution was initially low and did not reach a maximum until the later stages of hydrothermal activity, or deposition of scheelite in the outer zones of the skarns was initially greater, but

most was lost through subsequent reactions involving changing calcium contents in the skarn fluids. This possible recycling of tungsten within the skarn system has been suggested for the deposits at Mactung (Dick and Hodgson, 1982) and King Island (Kwak and Tan, 1981).

Scheelite solubility is effectively controlled by fluid composition, particularly the calcium concentrations. At the outer margins of the advancing metasomatic front, the a_{Ca} in fluids would vary considerably as they reacted with the marble. Assuming that conditions are essentially isothermal during the formation of a given skarn zone, the deposition of scheelite will probably be a function of the $a_{Ca}/a_{\text{introduced components}}$ ratio in the fluid, as well as pH. Calcium activities in the tungsten-bearing fluid reacting with the marble would be high enough for the solubility product of scheelite to be exceeded and deposition to occur. Calcium chloride is a common component in hydrothermal fluids reacting directly with carbonates, and this has been demonstrated through fluid-inclusion work in skarn and other carbonate replacement environments (Mathieson and Clark, 1984; Davies, 1985; Roedder, 1984). Subsequent reaction of scheelite with $CaCl_2$ -poor and $NaCl$ - KCl -bearing fluids during the formation of the transition and garnet-pyroxene zones probably resulted in the dissolution of scheelite, an interpretation supported by the limited work on scheelite solubility by Foster (1977). In the transition zone at Mount Alexander, in which garnet and pyroxene proportions are increasing, the characteristically ragged grain boundaries of scheelite indicate instability as this zone formed. The interpretation for the skarns in the northwest Gascoyne Complex is that scheelite mineralization probably began during the early period of exoskarn development and that its general absence in the other prograde zones reflects the low a_{Ca} in these fluids.

Deposition of scheelite in prograde skarn zones is common in many deposits. In the Pine Creek skarns, significant amounts of scheelite replaced calcite during the formation of the outer vesuvianite-wollastonite-bearing zone (Newberry, 1982). This has also been recognized in the King Island skarns where the first period of scheelite deposition is interpreted to have occurred during fluid boiling in the prograde stage (Kwak and Tan, 1981). Some early scheelite is preserved as inclusions in garnets and was therefore protected from subsequent reactions. Unprotected scheelite was dissolved during reactions with retrograde fluids and reprecipitated during the formation of the retrograde zones.

Dick and Hodgson (1982) suggested that in systems where fluids have high concentrations of tungsten, scheelite would be concentrated in the lower temperature skarn zones that are characterized by hydrous mineral assemblages. In all of the Mount Alexander skarns, significant scheelite concentrations are found within the prograde zones where partial hydration of the anhydrous assemblages has occurred.

Hydration of the more calcic early assemblages would increase the $a_{Ca^{2+}}$ in the fluids and the potential for the formation of scheelite and fluorite would thereby be enhanced. Evidence for this exists in the scheelite-bearing subcalcic garnet-vesuvianite-fluorite assemblages present

in the early calcic prograde phase in the Mortgage and White Lightning skarns. Scheelite is, however, absent from late-stage veins, which suggests that scheelite could not have been deposited directly from those fluids and therefore must have required an increase in $a_{Ca^{2+}}$ through reaction with early prograde calcic assemblages before it would be deposited. The increase in scheelite grades in the late retrograde assemblages can be similarly explained. Only in the marginal amphibole and, locally, the vesuvianite zones, was the activity of calcium generally too low for scheelite to be deposited. Scheelite morphology and textural data from the northwestern Gascoyne Complex skarns indicate that cyclic leaching and redeposition of scheelite occurred during skarn formation.

Potential for more skarn mineralization

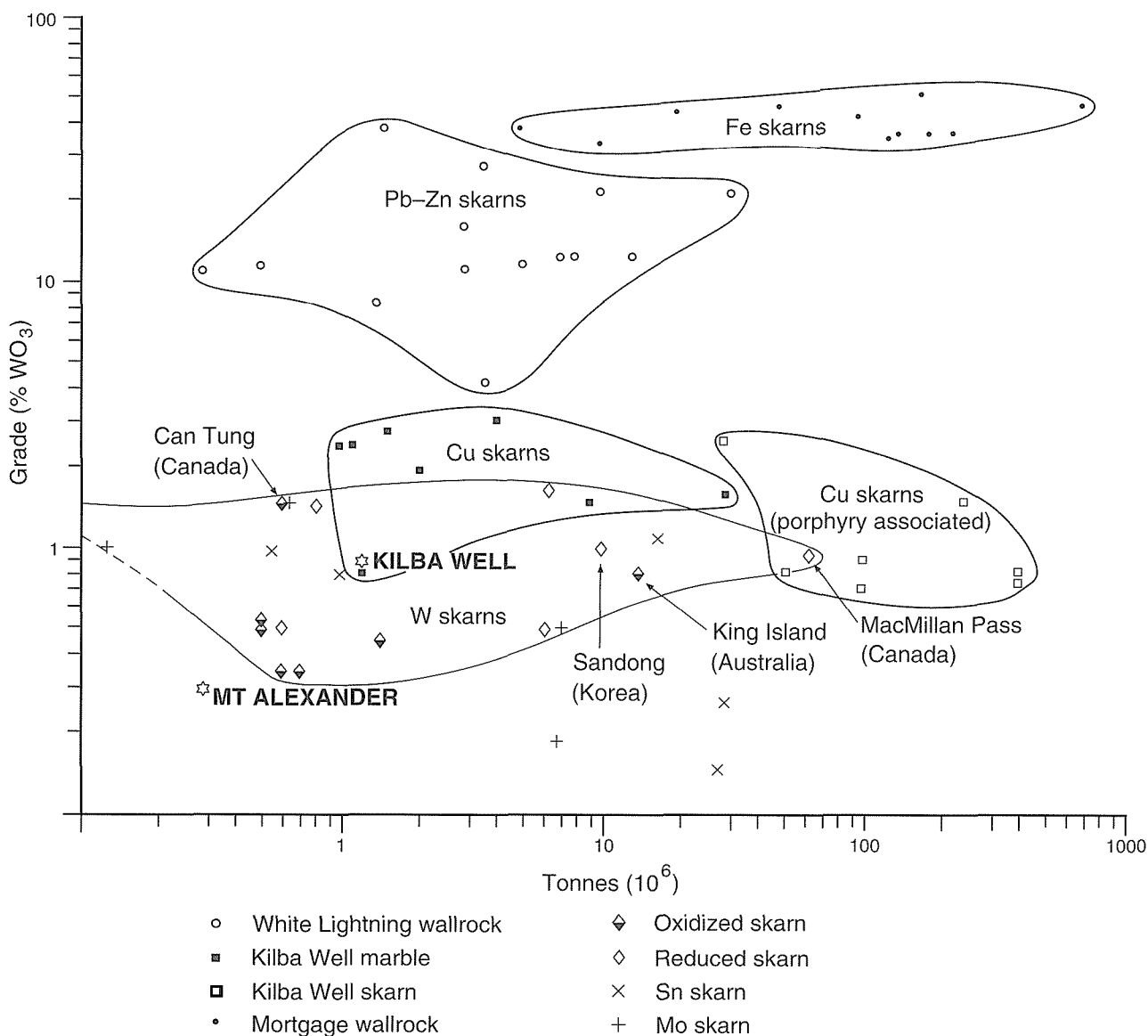
Evaluation of these systems would involve a substantial amount of drilling. At Mount Alexander, the focus of previous exploration has been in the prograde zones, which are the better exposed and easier to access. The presence of scheelite in these zones encouraged this exploration strategy. However, the data derived from this study indicate that better and probably more consistent grades could be present in retrograded parts of the skarn. These are either poorly developed at Mount Alexander, or have not been tested, as they are most likely to be developed close to the unexposed intrusive contacts. Of prime importance is the mapping of skarn assemblages to provide an indication of the skarn environment intersected, and ultimately vectors to the more prospective retrograde zones.

It is possible that the carbonate that hosts the Mortgage skarn may be stratigraphically equivalent to that hosting the White Lightning skarn. If the two skarns are equivalent, then a very large volume of carbonate was replaced during a single period of exoskarn formation. This being the case, which could be confirmed only through drilling, then there is a substantially increased tonnage potential.

The highly active hydrothermal system associated with the retrograde stages at Kilba Well has resulted in relatively widespread scheelite mineralization. However, the complex overprinting relationships described above need to be understood, and careful mapping of these would be required if further exploration were undertaken. There are several untested skarn systems surrounding the Kilba Well monzogranite. The approach for evaluation remains the same, with careful mapping of assemblages used to focus on the most intensely altered parts of the systems.

Potential for tungsten skarns elsewhere in the Gascoyne Complex

None of the granodiorite and monzogranite intrusives elsewhere in the Gascoyne Complex is known to be



BD20

29.10.97

Figure 29. Grade-tonnage relationships between various skarn deposits. Resource estimates for Mount Alexander and Kilba Well skarns are approximate. Data for other skarn deposits are from Einaudi et al. (1981)

associated with skarn mineralization. However, a number of calc-silicate units reportedly containing minor scheelite have been mapped in the Mount Phillips area (Williams et al., 1983), and potential remains for scheelite mineralized skarns. These calc-silicate bodies contain calcite, forsterite, clinohumite and clinopyroxene, with minor actinolite, serpentine and trace scheelite, and are consistent with the overall higher grade of regional metamorphism in the central Gascoyne Complex. It is not known whether these calc-silicate units represent bimetasomatic rocks, exoskarn, or a combination of these. The presence of scheelite in these bodies was not confirmed during the current study, and its identification in addition to other minerals common to the exoskarns in the Mount Alexander region is required prior to any judgement on their prospectivity. Minnie Creek

batholith (Williams et al., 1979), the largest of its kind within the Gascoyne Complex, has component members which form a single suite that ranges in composition from biotite tonalite through monzogranite to biotite-poor muscovite granite. Unlike those in, and associated with, the Mount Alexander batholith, many are deformed and have undergone some degree of metamorphism and recrystallization. However, no alteration of the kind described above for the Mount Alexander batholith and elsewhere has yet been identified.

Figure 29 shows grade-tonnage relationships for different kinds of mineralized skarns, including scheelite skarns of both 'reduced' and 'oxidized' classes. It is apparent from this that in order to sustain a small mining

operation, a scheelite skarn requires a grade and tonnage well in excess of 1.0% WO_3 and 2 million tonnes. These figures should be regarded as a guide only, as other factors relating to the economics of a deposit can influence its viability. It is probable that a significantly greater reserve would be necessary in order to justify exploitation, given that the bulk of world tungsten production has been derived from a small number of deposits each containing more than ten million tonnes of ore. These deposits include Sandong (Korea), King Island (Tasmania), Canada Tungsten (Northwest Territories, Canada), MacMillan Pass (Yukon Territories, Canada), and Pine Creek (California).

In assessing the potential for the discovery of other tungsten skarns in the Gascoyne Complex, something of their tectonic setting should be known. All of the major and smaller well-documented deposits occur along active plate margins. The most extensive development of this mineralization occurs in and along the Cordillera of North America where the deposits are considered to be broadly arc-related (Newberry and Einaudi, 1981). In the northern Cordillera, scheelite skarns occupy a spatially distinct band relative to tin and base-metal skarns. Other deposits, such as the King Island skarns, occur in a continent-continent collision setting rather than a subduction setting, although active margins are again involved.

Assessment of the central and southern Gascoyne Complex in terms of tungsten skarn potential requires an interpretation of the likely tectonic environment in existence during its formation. Williams (1986) invoked an intracontinental diapiric tectonic model in which crustal arching was followed by heating and the emplacement of gneiss domes and later granite diapirs. It is now accepted that the development of the Gascoyne Complex is related to a collision between the Pilbara and Yilgarn Cratons (Thorne, 1986; Tyler and Thorne, 1990; Myers, 1993). The latter model is favoured by the results derived from the present study, particularly because of the observed association between all other tungsten skarns and active margins. Further support comes from the association between calc-alkaline magmatism and the northwestern Gascoyne skarns. These intrusives have compositional features that are transitional between I and S types, which may in part reflect contamination by pre-existing crustal material, as for granites in central and southern California (Ague and Brimhall, 1987). This is significant as the Californian granites also occur adjacent to an active plate margin and are related to many significant scheelite-skarn deposits.

It is thought that the potential for significant tungsten-skarn deposits is low in the central and southern parts of the Gascoyne Province. This conclusion is based, firstly, on an interpretation which considers the rock in these regions to be part of an exposed metamorphic core complex, and those in the northwest as part of a higher crustal level. Mineralization that may have been present at a higher level has since been lost through erosion. Forsterite in marble from the central Gascoyne, as well as widespread migmatization in the same region, indicates high-temperature metamorphism,

conditions unfavourable for scheelite-skarn development.

Secondly, the granitic rocks in the central and north-west Gascoyne can be contrasted structurally and compositionally. Solid-state deformation fabrics suggest synkinematic intrusive activity. The undeformed granitic rocks found in association with skarns in the northwest are interpreted to represent a younger intrusive episode that occurred at the end of, or following, major periods of deformation and metamorphism. If this was the case, the absence of similarly undeformed granitic rocks elsewhere would indicate a significantly decreased potential for scheelite-skarn mineralization. The highly evolved character of the northwestern intrusives, as well as fracture-related greisen-style alteration, is not found in granitic intrusives elsewhere in the Gascoyne Complex. The alteration can be considered to be a good indication of high-level emplacement.

Conclusions

Evaluation of granitoids as source rocks for scheelite skarn deposits in the Gascoyne Complex

Criteria considered to be important in the planning of an exploration program are listed below. In compiling this list it is assumed that carbonate rocks are known to exist in the area of interest.

- Monzogranite and granodiorite are the target intrusive compositions.
- Whole-rock analyses should indicate high SiO_2 , K_2O and possibly Na_2O , and low total Fe and TiO_2 . Trace elements should be expected to show some variation, although positively anomalous B and Li would be encouraging. The degree of deformation and metamorphism will affect trace-element contents, and interpretations as to the prospectivity of a particular intrusive based on these should be assessed with this in mind. Note that F is a common component in members of the Minnie Creek batholith and can probably not be relied upon as an indicator. Similarly, the major-element trends just mentioned are evident in some intrusives in the Gascoyne Complex that are not associated with mineralization, and again some care should be taken in deriving conclusions from the data.
- Sericitic or greisenous alteration could be expected to be present, particularly near contacts. The alteration should not be expected to be pervasive, rather it should take the form of narrow, discontinuous dyke-like zones that are commonly at high angles to the contact. Care should be taken during mapping, as the relative volume of alteration will probably be low and therefore initially difficult to distinguish from unaltered granitoid.
- The sericitic alteration is geochemically characterized by very high SiO_2 , low CaO and low Na_2O .

Anomalous B, Li and Rb define the trace-element signature, with F contents variable, but generally high. Muscovite-rich greisenous alteration displays variable major-element contents, but can be considered in general terms to contain lower SiO₂ and higher Al₂O₃, CaO and K₂O. The trace-element signature is similar to that of the sericitic alteration facies, with the exception of Sn, which was present in the muscovite greisen at Kilba Well.

- Intrusives associated with tungsten skarns in the northwestern part of the Gascoyne are undeformed, which, together with the undeformed skarns, indicates that emplacement of the intrusives and mineralization occurred late in the tectonic history of the Gascoyne Complex. Although this suggests that target plutons should also be undeformed, care should be exercised as emplacement-related deformation may be present, particularly in contact zones.

Mineralized exoskarns

On the basis of the work carried out during this study, the following conclusions can be drawn.

- The tungsten occurrences comprise a series of mineralized skarn bodies in contact with small stocks. Carbonate rocks adjacent to the batholiths are recrystallized and contain thin bands of unmineralized bimetasomatic skarn. No exposures of the contact between either skarn types and adjacent intrusives have been observed in the Mount Alexander or Kilba Well areas.
- Scheelite-bearing skarns in the Gascoyne Complex are related to highly evolved, undeformed, calc-alkaline granitic intrusives, primarily porphyritic granodiorite and monzogranite.
- Fracture-related, greisen-style and weaker pervasive sericitic alteration is a feature of the intrusives associated with skarns. This alteration is restricted to marginal zones of the intrusives.
- The scheelite-bearing skarns belong to the 'reduced' class of tungsten skarns, and are characterized by the presence of subcalcic garnets. This class includes virtually all major and minor scheelite skarn deposits in the world.
- All of the skarns display well developed mineralogical zoning patterns. For the prograde stage these are, from the marble contact inwards: a wollastonite zone, characterized by the presence of wollastonite with

garnet, pyroxene and locally vesuvianite; a transition zone, marked by the disappearance of wollastonite; a garnet–pyroxene zone, massive to banded garnet and pyroxene rock with minor quartz and possibly vesuvianite. For the retrograde stage the assemblages vary, but are characterized by the common presence of hydrous minerals. The retrograde stage overprints the prograde stage by the successive replacement of prograde zones. The assemblages include vesuvianite, which is typically very abundant and locally massive, epidote–clinozoisite, fluorite, calcite, amphibole, phlogopite, and scheelite, which is generally abundant in this stage.

- Little mineralization occurs in the prograde zones of the skarns. High-grade mineralization normally accompanies the low-temperature retrograde stage of skarn formation, with the highest scheelite contents being in vesuvianite–epidote–clinozoisite–calcite–fluorite–quartz-dominated assemblages. Sulfide contents are low in the northwestern Gascoyne Complex skarns, but this may not be the case in other areas.
- Exploration of known skarns in the Kilba Wells and particularly the Mount Alexander areas may reveal the presence of further mineralization. Targets should be the retrograde parts of the skarns and careful mapping of these would provide vectors to mineralization.
- Data collected during this study and current knowledge of the geology of the Gascoyne suggest low potential for significant scheelite-skarn mineralization in the central and southern Gascoyne Complex.

Acknowledgements

The author would like to gratefully acknowledge the invaluable assistance of Rick Rogerson, whose reviews greatly improved this report. Jim Graham, Bruce Robinson and Robert Walker of CSIRO Perth are thanked for providing access to microprobe facilities. The diligent and good humoured assistance of Peter Boner in the field is also gratefully acknowledged. Richard Davy is thanked for a review of an early draft of this report. Whole-rock analyses were performed at the Chemistry Centre (W.A.).

References

- ACKERMAND, D., KARL, F., and RAASE, P., 1972, Granate mit zusammensetzungen zwischen Almandin und Grossular aus den westlichen Hohen Tauern, Osterreich: Contributions to Mineralogy and Petrology, v. 37, p. 29–38.
- AGUE, J. J., and BRIMHALL, G. H., 1987, Granites of the batholiths of California: Products of local assimilation and regional-scale crustal contamination: *Geology*, v. 15, p. 63–66.
- ANDERSON, R. G., 1983, Selwyn plutonic suite and its relationship to skarn mineralization: Canadian Geological Survey, Current Research Paper 83-1B, p. 151–163.
- BATEMAN, P. C., 1965, Geology and tungsten mineralization of the Bishop District California: United States Geological Survey, Professional Paper, no. 470, 208p.
- BATEMAN, R., 1985, Aureole deformation by flattening around a diapir during in situ ballooning: The Cannibal Creek Granite: *Journal of Geology*, v. 93, p. 293–310.
- BAXTER, J. L., 1978, Molybdenum, tungsten, vanadium and chromium in Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 11, 140p.
- BLUSSON, J. A., 1986, Geology and tungsten deposits near the headwaters of Flat River, Yukon Territory and southwestern district of MacKenzie, Canada: Canadian Geological Survey, Paper 67–22, 77p.
- BROCK, K. J., 1972, Genesis of Garnet Hill skarn, Calaveras County, California: *Geological Society of America Bulletin*, v. 83, p. 3391–3404.
- BUNTING, J. A., 1986, Geology of the eastern part of the Naberu Basin, Western Australia: Western Australia Geological Survey, Bulletin 131, 130p.
- BURNHAM, C. W., 1979, Magmas and hydrothermal fluids, in *Geochemistry of hydrothermal ore deposits (2nd edition)* edited by H.L. BARNES: New York, Wiley Publications, p. 71–136.
- BURT, D. M., 1982, Skarn deposits — historical bibliography through 1970: *Economic Geology*, v. 77, p. 755–763.
- BUSECK, P. R. 1967, Contact metasomatism and ore deposition: Tem Piute, Nevada: *Economic Geology*, v. 62, p. 331–353.
- CHAPPELL, B. W., and WHITE, A. J. R., 1974, Two contrasting granite types: *Pacific Geology*, v. 8, p. 173–174.
- COOKE, B. J., and GODWIN, C. I., 1984, Geology, mineral equilibria, and isotopic studies of the McDame tungsten skarn prospect, north-central British Columbia: *Economic Geology*, v. 79, p. 826–847.
- DANIELS, J. L., 1965, Proterozoic granites of the Ashburton region, North-west Division: Western Australia Geological Survey, Annual Report 1964, p. 31–34.
- DANIELS, J. L., 1970, Wyloo, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.
- DANIELS, J. L., 1975, Gascoyne Province, in *Geology of Western Australia*: Western Australian Geological Survey, Memoir 2, p. 107–114.
- DAVIES, B. M., 1985, The nature and mechanism of stratabound mineralization in the Renison Mine, Tasmania: James Cook University, PhD thesis (unpublished).
- DICK, L. A. 1979, Tungsten and base metal skarns in the northern Cordillera: Canada Geological Survey, Paper 79-1A, p. 259–266.
- DICK, L. A., and HODGSON, C. J., 1982, The Mactung W-Cu(Zn) contact metasomatic and related deposits of the northeastern Canadian Cordillera: *Economic Geology*, v. 77, p. 845–867.
- EINAUDI, M. T., 1981, Skarns associated with porphyry plutons. I. Description of deposits, southwestern North America II. General features and origin, in *Advances in geology of the porphyry copper deposits of southwestern North America* edited by S. R. TITLEY: Tucson, University of Arizona Press, p. 139–183.
- EINAUDI, M. T., and BURT, D. M., 1982, Introduction, terminology, classification, and composition of skarn deposits: *Economic Geology*, v. 77, p. 745–754.
- EINAUDI, M. T., MEINERT, L. D., and NEWBERRY, R. J., 1981, Skarn deposits: *Economic Geology 75th Anniversary Volume*, p. 317–391.
- FOSTER, R. P., 1977, Solubility of scheelite in hydrothermal chloride solutions: *Chemical Geology*, v. 20, p. 27–43.
- FREY, F. A., CHAPPELL, B. W., and ROY, S. D., 1978, Fractionation of rare-earth elements in the Tuolumne intrusive series, Sierra Nevada Batholith, California: *Geology*, v. 6, p. 239–242.
- GEE, R. D., 1979, Structure and tectonic style of the West Australian shield: *Tectonophysics*, v. 58, p. 327–369.
- GEE, R. D., 1986, Explanatory notes on the Peak Hill 1:250,000 geological sheet, Western Australia (2nd edition): Western Australia Geological Survey, Record 1986/11, 47p.
- GEE, R. D., 1990, Naberu Basin, in *Geology and mineral resources of Western Australia*: Western Australia Geological Survey, Memoir 3, p. 202–210.
- GORDON, T. M., and GREENWOOD, H. J., 1971, The stability of grossularite in H₂O-CO₂ mixtures: *American Mineralogist*, v. 56, p. 1674–1688.
- GREENWOOD, H. J., 1967, Wollastonite: stability in H₂O-CO₂ mixture and occurrence in a contact-metamorphic aureole near Salmo, British Columbia, Canada: *American Mineralogist*, v. 52, p. 1669–1680.
- HELLINGWERF, R. H., and BAKER, J. H., 1985, Wall rock alteration and tungsten and molybdenum mineralization associated with older 1.8–1.9 Ga granites in W. Bergslagen, Sweden, in *GUA Papers of Geology, Series 1*, no. 21-1985: University of Amsterdam, p. 123–145.
- HESS, F. L., 1919, Tactite, the product of contact metamorphism: *American Journal of Science*, v. 48, p. 377–378.
- HOCELLA, M. F. Jr., LIOU, J. G., KESKINEN, M. J., and KI, H. S., 1982, Synthesis and stability relations of magnesium idocrase: *Economic Geology*, v. 77, p. 798–808.
- HOLLAND, H. D., and MALININ, S. D., 1979, The solubility and occurrence of non-ore minerals, in *Geochemistry of hydrothermal ore deposits (2nd edition)* edited by H. L. BARNES: New York, Wiley Publishing, p. 461–508.
- HOTZ, P. E., and WILLDEN, R., 1964, Geology and mineral deposits of the Osgood Mountains quadrangle, Humboldt County, Nevada: United States Geological Survey, Professional Paper no. 431, 128p.

- ITO, J., and FRONDEL, C., 1968, Synthesis of the grossular-spessartite series: *American Mineralogist*, v. 53, p. 1036–1038.
- ITO, K., 1962, Zoned skarn of the Fujigatani Mine, Yamaguchi Prefecture: *Japan Journal of Geology and Geography*, v. 33, p. 169–190.
- JOHN, Y. W., 1963, Geology and origin of Sandong tungsten mine, Republic of Korea: *Economic Geology*, v. 58, p. 1285–1300.
- KERRICK, D. M., 1977, The genesis of zoned skarns in the Sierra Nevada, California: *Journal of Petrology*, v. 18, p. 144–181.
- KLOMINSKI, J., 1972, The Heemskirk Granite massif, western Tasmania — a study of chemical variability within plutonic rocks: University of Tasmania, PhD thesis (unpublished).
- KORZHINSKII, D. S., 1970, Theory of metasomatic zoning: New York, Oxford Clarendon Press, 162p.
- KWAK, T. A. P., 1978, The conditions of formation of the King Island scheelite contact skarn, King Island: *American Journal of Science*, v. 278, p. 969–999.
- KWAK, T. A. P., and ASKINS, P. W., 1981a, The nomenclature of carbonate replacement deposits, with emphasis on Sn-F-(Be-Zn) “wrigglite” skarns: *Journal of the Geological Society of Australia*, v. 28, p. 123–136.
- KWAK, T. A. P., and ASKINS, P. W., 1981b, Geology and genesis of the F-Sn-W (-Be-Zn) skarn (wrigglite) at Moina, Tasmania: *Economic Geology*, v. 76, p. 439–467.
- KWAK, T. A. P., and TAN, T. H., 1981, The geochemistry of zoning in skarn minerals at the King Island (Dolphin) mine: *Economic Geology*, v. 76, p. 468–497.
- KWAK, T. A. P., and WHITE, A. J. R., 1982, Contrasting W-Mo-Cu and W-Sn-F skarn types and related granitic rocks: *Kozan Chishitsu*, v. 32 (174), p. 339–351.
- LARGE, R. R., 1971, Metasomatism and scheelite mineralization at Bold Head, King Island: *Australasian Institute of Mining and Metallurgy, Bulletin* 38, p. 31–45.
- LIBBY, W. G., de LAETER, J. R., and MYERS, J. S., 1986, Geochronology of the Gascoyne Province: *Western Australia Geological Survey, Report* 20, 31p.
- LIOU, J. G., 1973, Synthesis and stability relations of epidote, $\text{Ca}_2\text{Al}_2\text{FeSi}_3\text{O}_{12}(\text{OH})$: *Journal of Petrology*, v. 14, p. 381–413.
- MANNING, D. A. C., and HENDERSON, P., 1984, The behavior of tungsten in granitic melt-vapor systems: *Contributions to Mineralogy and Petrology*, v. 86, p. 286–293.
- MATHIESON, G. A., and CLARK, A. H., 1984, The Cantung E zone scheelite skarn orebody, Tungsten, Northwest Territories: a revised genetic model: *Economic Geology*, v. 79, p. 883–901.
- METZ, P., and WINKLER, H. G. F., 1963, Experimentelle Gesteinsmetamorphose, VI1, Die Bildung von Talk aus Kieseligen Dolomit: *Geochimica et Cosmochimica Acta*, v. 27, p. 431–457.
- MILL, V. B., and KALININ, D. V., 1966, Lower temperature limit of garnet formation in the skarn process (experimental data): *Doklady Akademiyi nauk S.S.R.*, v. 167(3), p. 84–86.
- MUHLING, P. C., and BRAKEL, A. T., 1985, Geology of the Bangemall Group: *Western Australia Geological Survey, Bulletin* 128, 266p.
- MYERS, J. S., 1990, Capricorn Orogen, in Geology and mineral resources of Western Australia: *Western Australia Geological Survey, Memoir* 3, p. 197–202.
- MYERS, J. S., 1993, Precambrian history of the West Australian Craton and adjacent orogens: *Annual Review of Earth and Planetary Sciences*, v. 21, p. 453–485.
- NEWBERRY, R. J., 1979, Systematics in W-Mo-Cu skarn formation in the Sierra Nevada: an overview: *Geological Society of America, Abstracts with Programs*, v. 12, p. 492.
- NEWBERRY, R. J., 1982, Tungsten bearing skarns of the Sierra Nevada. 1. The Pine Creek Mine, California: *Economic Geology*, v. 77, p. 823–844.
- NEWBERRY, R. J., 1983, The formation of sub-calcic garnet in scheelite bearing skarns: *Canadian Mineralogist*, v. 21, p. 529–544.
- NEWBERRY, R. J., and EINAUDI, M. T., 1981, Tectonic and geochemical setting of tungsten skarn deposits in the cordillera: *Arizona Geological Society Digest*, v. 14, p. 99–112.
- NEWBERRY, R. J., and SWANSON, S. E., 1986, Scheelite skarn granitoids: an evaluation of the roles of magmatic source and process: *Ore Geology Reviews*, v. 1, p. 57–81.
- NEWTON, R. C., 1966, Some calcisilicate equilibrium relations: *American Journal of Science*, v. 264, p. 204–222.
- NOCKOLDS, S. R., 1954, Average chemical compositions of some igneous rocks: *Geological Society of America Bulletin*, v. 65, p. 1007–1032.
- NOKLEBERG, W. J., 1981, Geologic setting, petrology, and geochemistry of zoned tungsten bearing skarns at the Strawberry Mine, central Sierra Nevada, California: *Economic Geology*, v. 76, p. 111–133.
- NOKLEBERG, W. J., and KISTLER, R. W., 1980, Paleozoic and Mesozoic deformations in the central Sierra Nevada, California: *United States Geological Survey, Professional Paper*, no. 1154, 24p.
- OHLSSON, Lars-G., 1979, Tungsten occurrences in central Sweden: *Economic Geology*, v. 74, p. 1012–1034.
- PATERSON, S. R., VERNON, R. H., and TOBISCH, O. T., 1989, A review of criteria for the identification of magmatic and tectonic foliations in granitoids: *Journal of Structural Geology*, v. 11, p. 349–363.
- POLLARD, P. J., and TAYLOR, R. G., 1986, Progressive evolution of alteration and tin mineralization: controls by interstitial permeability and fracture related tapping of magmatic fluid reservoirs in tin granites: *Economic Geology*, v. 81, p. 1795–1800.
- RICHARDSON, C. K., and HOLLAND, H. D., 1979a, The solubility of fluorite in hydrothermal solutions — an experimental study: *Geochimica et Cosmochimica Acta*, v. 43, p. 1313–1325.
- RICHARDSON, C. K., and HOLLAND, H. D., 1979b, Fluorite deposition in hydrothermal systems: *Geochimica et Cosmochimica Acta*, v. 43, p. 1327–1335.
- RICKWOOD, P. C., 1968, On recasting analyses of garnet into end-member molecules: *Contributions to Mineralogy and Petrology*, v. 18, p. 175–198.
- ROEDDER, E., 1984, Fluid inclusions: *Mineralogical Society of America, Reviews in Mineralogy*, v. 12, 644p.
- SATO, K., 1980, Tungsten skarn deposit of the Fujigatani mine, southwest Japan: *Economic Geology*, v. 75, p. 1066–1082.
- SAWKINS, F. J., 1984, Metal deposits in relation to plate tectonics: New York, Springer Verlag, 461p.
- SEKI, Y., 1972, Lower grade stability limit of epidote in the light of natural occurrences: *Journal of the Geological Society of Japan*, v. 78, p. 405–413.
- SEYMOUR, D. B., THORNE, A. M., and BLIGHT, D. F., 1988, Wyloo, W.A. (2nd edition): *Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes*, 36p.
- SHIEH, Y. N., and TAYLOR, H. P., Jr., 1969, Oxygen and hydrogen isotope studies of contact metamorphism in the Santa Rosa Range, Nevada and other areas: *Contributions to Mineralogy and Petrology*, v. 20, p. 306–356.
- SHIMAZAKI, H., 1977, Grossular-spessartine-almundine garnets from some Japanese scheelite skarns: *Canadian Mineralogist*, v. 15, p. 74–80.
- SIMPSON, C., 1985, Deformation of granitic rocks across the brittle-ductile transition: *Journal of Structural Geology*, v. 7, p. 503–511.

- SOLER, P., 1980, Geologie due gisement de Salau: Bureau Rescherches Geologie et Mineraux, Memoir 99, p. 205–216.
- STRECKEISEN, A., 1976, To each plutonic rock its proper name: *Earth Science Reviews*, v. 12, p. 1–33.
- SWANSON, S. E., 1977, Relation of nucleation and crystal growth rate to the development of granitic textures: *American Mineralogist*, v. 62, p. 966–978.
- TAYLOR, B. E., and LIOU, J. G., 1978, The low temperature stability of andradite in C-O-H fluids: *American Mineralogist*, v. 63, p. 378–393.
- TAYLOR, R. G., 1979, Geology of tin deposits: *Developments in Economic Geology*, 11: Amsterdam, Elsevier, 543p.
- THOMPSON, A. B., 1975, Calcsilicate diffusion zones between marble and pelitic schist: *Journal of Petrology*, v. 16, p. 314–346.
- THORNE, A. M., 1986, The depositional history of the 2 Ga Wyloo Group, southern Pilbara, Western Australia: Geological Society of Australia, 8th Geological Convention, Adelaide, Abstracts, no. 15, p. 189.
- THORNE, A. M., 1990, Ashburton Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 210–221.
- THORNE, A. M., and SEYMOUR, D. B., 1991, Geology of the Ashburton Basin: Western Australia Geological Survey, Bulletin 139, 141p.
- TISCHENDORF, G., 1977, Geochemical and petrographic characteristics of silicic magmatic rocks associated with rare-element mineralization, *in* Metallization Associated with Acid Magmatism (MAWAM Symposium), Volume 2 *edited by* M. STEMPROK, L. BURNOL, and G. TISCHENDORF: Czechoslovakia Geological Survey, Prague, p. 41–96.
- TURNER, F. J., 1968, *Metamorphic petrology. Mineralogical and field aspects*: New York, McGraw-Hill, 403p.
- TUTTLE, O. F., and BOWEN, N. L., 1958, Origin of granite in the light of experimental data in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O : Geological Society of America, Memoir 74, 153p.
- TYLER, I. M., and THORNE, A. M., 1990, Structural evolution of the northern margin [of the Capricorn Orogen], *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 223–232.
- VERNON, R. H., 1983, Restite, xenoliths and microgranitoid enclaves in granites: Royal Society of New South Wales, *Journal*, v. 116, p. 77–103.
- VERNON, R. H., WILLIAMS, V. A., and D'ARCY, W. F., 1983, Grainsize reduction and foliation development in a deformed granitoid batholith: *Tectonophysics*, v. 92, p. 123–145.
- VIDALE, R. J., 1969, Metasomatism in a chemical gradient and the formation of calcsilicate bands: *American Journal of Science*, v. 267, p. 857–874.
- VITALIANO, C. J., 1944, Contact metamorphism at Rye Patch, Nevada: *Geological Society of America Bulletin*, v. 55, p. 921–950.
- WARE, N. G., 1981, Computer programs and calibration with the PIBS technique for quantitative electron probe analysis using a lithium-drifted silicon detector: *Computers and Geoscience*, v. 7, p. 167–184.
- WHITNEY, J. A., 1975a, Vapor generation in a quartz monzonite magma: A synthetic model with application to porphyry copper deposits: *Economic Geology*, v. 70, p. 346–358.
- WHITNEY, J. A., 1975b, The effects of pressure, temperature, and $\text{X}_{\text{H}_2\text{O}}$ on phase assemblages in four synthetic rock compositions: *Journal of Geology*, v. 83, p. 1–31.
- WILLIAMS, I. R., 1990, Bangemall Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 308–324.
- WILLIAMS, S. J., 1986, The geology of the Gascoyne Province, Western Australia: Western Australia Geological Survey, Report 15, 85p.
- WILLIAMS, S. J., WILLIAMS, I. R., CHIN, R. J., MUHLING, P. C., and HOCKING, R. M., 1979, Explanatory notes on the Mount Phillips 1:250 000 geological sheet, Western Australia: Western Australia Geological Survey, Record, 1978/13, 61p.
- WILLIAMS, S. J., WILLIAMS, I. R., CHIN, R. J., MUHLING, P. C., and HOCKING, R. M., 1983, Mount Phillips, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 29p.

Appendix 1

Specimen locations

No.	Locality	Company	Depth (m)	No.	Locality	Company	Depth (m)
48229	MA Camp skarn			90435	MA Mortgage skarn MP5	AMAX	60.0
48239	MA White Lightning skarn			90438	MA Mortgage skarn MP7	AMAX	88.6
48244	MA Mortgage skarn			90439	MA Mortgage skarn MP7	AMAX	91.4
48255	MA Mortgage skarn			90440	MA Mortgage skarn MP7	AMAX	93.5
48257	MA Mortgage skarn			90449	Central Gascoyne Complex, Mick Well: 24°52'45"S, 116°02'00"E		
90301	KW DDH 7	ANZECO	24.7	90477	Central Gascoyne Complex, O'Connor Well: 24°29'15"S, 116°27'30"E		
90302	KW DDH 7	ANZECO	26.4	90490	Kilba Well monzogranite: AMG 03504007480400		
90304	KW DDH 7	ANZECO	29.3	90491	Kilba Well monzogranite: AMG 035061007480700		
90304	KW DDH 7	ANZECO	29.3	90492	Kilba Well monzogranite: AMG 03502007480500		
90306	KW DDH 7	ANZECO	39.6	90493	Kilba Well monzogranite: as for 90492		
90311	KW DDH 7	ANZECO	54.9	90496	Pegmatite (tourmaline), altered, western margin of Kilba Well monzogranite		
90312	KW DDH 7	ANZECO	56.3	90497	Kilba Well monzogranite, greisen: as for 90490		
90314	KW DDH 7	ANZECO	48.4	90498	Kilba Well monzogranite, greisen: as for 90490		
90315	KW DDH 7	ANZECO	57.0	90609	Pegmatite (tourmaline), Zone 11, costean T10: as for 90492		
90316	KW DDH 7	ANZECO	59.2	90610	KW, Zone 11, costean T10: as for 90492		
90317	KW DDH 7	ANZECO	60.0	90613	KW, Zone 11, costean T10		
90319	KW DDH 7	ANZECO	62.2	90617	KW, Zone 11, 50m SW of costean T8		
90327	KW DDH 11	ANZECO	57.2	90634	West-northwest margin of Kilba Well monzogranite		
90334	KW DDH 12	ANZECO	66.7	90635	West-northwest margin of Kilba Well monzogranite		
90341	KW DDH 12	ANZECO	85.2	90641	MA Mortgage skarn, main costean		
90351	KW DDH 1	ANZECO	110.9	90642	MA Mortgage skarn, main costean		
90352	KW DDH 12	ANZECO	115.5	90643	MA Mortgage skarn, main costean		
90360	KW DDH 13	ANZECO	21.2	90644	MA Mortgage skarn, main costean		
90364	KW Kilba Well monzogranite; DDH13	ANZECO	70.24	90645	MA Mortgage skarn, main costean		
90372	KW DDH 14	ANZECO	61.5	90646	Mount Alexander batholith: AMG 03517007488500		
90373	KW Zone 11 DDH 15	ANZECO	65.6–67.7	90647	Mount Alexander batholith: as for 90646		
90376	KW DDH 15	ANZECO	62.3	90649	MA Camp skarn: AMG 03498007493000		
90381	KW DDH 15	ANZECO	147.0	90651	200m north of Roses Find (Fig. 1)		
90382	MA WLP 1	AMAX	4.0	90652	Mortgage granite: AMG 03495007491400		
90383	MA WLP 1	AMAX	6.2	90653	Mortgage granite: as for 90652		
90385	MA WLP 1	AMAX	60.5	90654	Alladins granite: AMG 03580007492100		
90386	MA WLP 1	AMAX	60.8–61.0	90655	Alladins granite: as for 90654		
90387	MA WLP 1	AMAX	61.5	90658	White Lightning granite: AMG 03496007490200		
90390	MA WLD 1	AMAX	1.5				
90392	MA WLD 1	AMAX	24.6				
90397	MA WLD 1	AMAX	27.6				
90406	MA White Lightning skarn; WLD1	AMAX	34.9				
90407	MA White Lightning skarn; WLP1	AMAX	35.4				
90413	MA Mortgage skarn MD1	AMAX	92.4				
90414	MA Mortgage skarn MD1	AMAX	106.5				
90420	MA Mortgage skarn MP3	AMAX	28.0				
90424	MA Mortgage skarn MP3	AMAX	29.9				
90429	MA Mortgage skarn MP3	AMAX	32.3				
90434	MA Mortgage skarn MP5	AMAX	58.9				

MA: Mount Alexander

KW: Kilba Well

AMG references taken from WYLOO 1:100 000 geological sheet