GRANITES OF THE NORTHERN NEW ENGLAND OROGEN

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Introduction

The northern New England Orogen (NNEO) extends from the sedimentary cover of the Clarence-Moreton Basin in the south to the Bowen area, and west to the Bowen Basin. It contains granites of 4 main age groups: Middle to Late Devonian; mid- Carboniferous to Early Permian; Late Permian to Late Triassic; and Early Cretaceous. Common features shared by all of the granites include:

- They are overwhelmingly high temperature I-type granites with no relict zircon;
- They have low I_{Sr} ratios indicating that old continental crust was not involved in their formation; and
- They are associated with Cu-Mo-Au mineralisation.

Middle to Late Devonian

The Mount Morgan Trondhjemite (MMT) is a relatively small intrusion 20 km long and 4 km wide that is important for three reasons: it is a key to tectonic interpretations of the nNEO; it is spatially associated with the Mount Morgan orebody that produced >250 t Au and 360 000 t Cu; and it provides a reference point of 380 Ma for the age of the Middle-Late Devonian boundary.

The MMT intrudes a Lower to Middle Devonian marine sequence that includes co-magmatic volcanics, and is overlain by Upper Devonian basalts to andesites. It has no distinctive geophysical expression. Trondhjemite is the dominant rock type, consisting of equal proportions of quartz and sodic plagioclase with up to 10% hornblende. The quartz and plagioclase occur in micrographic intergrowth, indicating that it is a high level intrusion. Both pervasive and chloritic vein style alteration are widespread, and breccias with chloritic matrix occur locally. Variations are found in the northern part of the intrusion near the town of Mount Morgan, and include tonalite (typically less altered, and with minor biotite as well as hornblende), quartz diorite, and gabbro.

Geochemically the MMT is high in silica (Figure 1) and low in Al_2O_3 and K_2O, and is similar to island arc dacites and oceanic plagiogranites. Compared to trondhjemite-tonalite suites of the Late Permian-Triassic NEO granites generally interpreted as continental margin arc intrusives, the MMT has higher TiO_2, total Fe, MgO, Sc, V and Y, and lower Al_2O_3, K_2O, Ba, Rb and Sr (Figure 2). Widespread albitisation within the MMT, particularly in trondhjemites, has undoubtedly increased the Na/Ca ratio. However, the low K_2O content is not the result of post-magmatic alteration. In fact, clear evidence of addition of K_2O, rather than removal, is provided by the local replacement of plagioclase by K-feldspar.

An oceanic setting for the MMT is supported by its high Yb/Al_2O_3 and Y/Al_2O_3 ratios, and it falls entirely within the field of island arc dacites on a plot of Rb versus Sr. Messenger (1996) compared the Mount Morgan volcanic-plutonic suite with modern low-K intraoceanic island arcs such as Tonga-Kermadec. He modelled the major and trace element geochemistry of the high-silica rocks by a two-stage process involving low pressure melting of low-K basaltic andesite to produce tonalite, followed by fractional crystallisation resulting in trondhjemitic liquids. He proposed a moderately thick crust, and concluded that the setting was the incipient extensional phase of a continental island arc. However, low pressure melting of basaltic andesite has recently been suggested for the origin of widespread low-K rhyolitic volcanism in the Izu-Bonin arc (Tamura & Tatsumi, 2002), and can match the major element compositions of trondhjemites of the MMT extremely well. The nature of rhyolitic volcanism in the Izu-Bonin arc, with submarine silicic calderas producing thick pumice deposits accompanied in some cases by Au-rich Kuroko-style VHMS mineralisation, is a close analogue of the environment of formation of the Mount Morgan orebody envisaged by Messenger *et al.* (1997).

The orebody occurred in a roof pendant of Middle Devonian volcanic and sedimentary rocks in the northern part of the MMT. Although a replacement origin related to the MMT has been proposed a number of times, the most widely supported interpretation is that the orebody is a large and unusually Au-rich VHMS deposit, and that the ore fluids were a mixture of seawater and magmatic fluids. Recent Pb isotope determinations suggest that the host volcanics were not the source of the ore, and favour a composite model with elements of VHMS, porphyry and intrusive-related replacement mineralisation (Ulrich *et al*, 2002).

Mid-Carboniferous to Early Permian

Apart from some small S-type granodiorites NNW of Brisbane, that are similar in age, petrology and tectonic setting to the Hillgrove suite of New England, mid-Carboniferous to Early Permian granites and associated volcanics are restricted to the Connors and Auburn Arches along the western edge of the nNEO. An unusual and still unexplained feature of these granites is that they coincide with strong positive gravity anomalies, particularly the Auburn Arch, despite the fact that mafic intrusions make up only a small proportion of the granitoids.

The intrusions range from gabbro to granite and are dominantly granodiorite in composition (Figure 1). All are I-type. Ages of the granites appear to increase systematically from north to south. In the northern part of the Connors Arch, the oldest granitoids, the Urannah suite, have given zircon ages of 305±5 Ma, and the crosscutting Thunderbolt Granite is significantly younger at 278±6 Ma (Allen *et al.*, 1998). In the Auburn Arch and the southern part of the Connors Arch, the oldest group of granites have zircon dates of 320 to 330±5 Ma (Hutton *et al.*, 1999 and unpublished data). Similarly, Webb & McDougall (1968) noted that K-Ar ages in the Connors Arch are older from north to south, and explained this by differential uplift. An increase from north to south in the proportion of volcanics relative to intrusives supports a greater degree of uplift northwards. Possible compositional variations with age have not yet been investigated.

The intrusions of the Connors and Auburn Arches, and at least some of the associated volcanics, were regarded as the final products of Devonian-Carboniferous subduction in the nNEO, but recently have been attributed to crustal extension. Evidence from geochemistry, the sedimentary record in adjacent sedimentary basins, and dyke swarms supports an interpretation that both granites and volcanics span the transition from arc to extensional magmatism.

The granites are medium to high-K and have similar geochemistry to well known continental margin arc batholiths (Allen, 2000). They also plot within fields defined by Late Permian to

Late Triassic granites of the nNEO on major and trace element Harker diagrams, although lacking the most alkali-rich compositions of the latter group. Among the volcanic rocks, abundant mafic compositions ranging from basalt to andesite partly overlap with and are transitional between modern continental arc volcanics and rocks of the extensional phase of the Basin and Range province.

Support for formation of the granites of the Auburn Arch and the southern Connors Arch comes from the sedimentary record in the Devonian-Carboniferous forearc basin to the east. These granites can possibly be directly linked to a major change in provenance of forearc basin strata close to the Visean-Namurian boundary (327 Ma), with the appearance of granite clasts and a dramatic increase in radiometric signature. The rapid unroofing required for this provenance linkage has been documented from other continental arc-forearc basin pairs (Kimbrough *et al.*, 2001). The onset of extension at about 305 Ma formed a totally new pattern of depositional basins in which sediments and minor volcanics were laid down disconformably to unconformably on a basement of forearc basin rocks. Commencement of extension at about the Carboniferous-Permian boundary is also supported by Early Permian and younger dates on a regional NNW-trending dyke swarm that cuts the Late Carboniferous granites of the northern Connors Arch, and an age of 294±3 Ma from ignimbrite close to the base of the extensional sequence near Mackay (Allen *et al.*, 1998).

The mid-Carboniferous to Early Permian granites of the Connors Arch have I_{Sr} ratios above 0.7045, and are more radiogenic than Triassic and Early Cretaceous intrusions within or east of the arch. Allen (2000) attributed this change to Early Permian extension and crustal thinning accompanied by mafic underplating. There is no record of this event in the Auburn Arch, where I_{Sr} of 0.7040 for Carboniferous granites is actually lower than that of Late Permian intrusions to the southeast (Webb & McDougall, 1968).

Although mid-Carboniferous to Early Permian volcanics of the Connors and Auburn Arches contain significant epithermal Au mineralisation (Cracow, Mount Mackenzie, Crush Creek), granites of this age are very sparsely mineralised.

Late Permian to Late Triassic

Granites of this age form a NNW-trending belt extending north to Rockhampton, with a few scattered outcrops along the eastern side of the Connors Arch and on offshore islands. They range from multiphase batholiths to small plutons, and have very different topographic expression depending on their composition and texture. Biotite-rich granodiorites disintegrate on weathering due to expansion of biotite to hydrobiotite and vermiculite, and erode rapidly to form topographic basins. In contrast, hornblende-bearing monzogranites with micrographic groundmass are resistant to weathering and form prominent peaks. Ages range from mid-Permian (270 Ma) to the end of the Triassic (205 Ma), and a few may even extend into the Jurassic.

The range and distribution of compositions is remarkably similar to the mid-Carboniferous to Early Permian granites (Figure 1). There is also strong coincidence on Harker diagrams, both groups being medium to high-K, but the Permo-Triassic group includes a greater proportion of more alkali-rich compositions at all SiO_2 contents. Most granites are I-type, but some of the later intrusions are alkaline with sodic amphibole and A-type chemistry. It should be emphasised, however, that the Permo-Triassic group as a whole shows no systematic trend towards more evolved compositions with time. A feature is the presence of several layered gabbros generally marked by strong magnetic and positive gravity anomalies. The geophysical expression of the felsic intrusives is variable. Some are centred on deep gravity lows and must extend to considerable depths.

Many of the plutons are zoned, typically with a mafic rim intruded by a felsic core, giving them a bimodal composition. Some are associated with concentric dyke swarms and can be described as ring complexes. The scarcity of foliation, prevalence of micrographic textures, and narrow hornfels zones indicate emplacement at a high level in the crust. This is supported by the occurrence of remnants of Triassic volcanics throughout the main belt of intrusives as far north as Rockhampton. The Late Triassic volcanics have strongly bimodal compositions.

A subduction-related origin is favoured, with a transition to extensional magmatism in the Late Triassic due to slab rollback (Gust *et al.*, 1993). The chemistry of mafic volcanics is consistent with development at a convergent continental margin. The close association of mafic and felsic magmas suggests an origin involving crustal melting by mantle-derived basalts, although details of this process await further study (Gust *et al.*, 1996). A limited data set suggests that the Late Triassic granites, including those with A-type chemistry, have lower I_{Sr} ratios than older Permo-Triassic intrusives (Webb & McDougall, 1968; Stephens, 1991), requiring either a different source or a progressive change in source composition due to addition of mantle-derived mafic material.

The position of the Norfolk Rise and Lord Howe Ridge in reconstructions pre-dating the opening of the Tasman Sea (Figure 3) is a possible problem in assigning a subduction-related origin to the Permo-Triassic granites. These continental masses could not have been in the position indicated in Figure 3 in the Devonian and Carboniferous, when a classic accretionary wedge assemblage developed along the eastern edge of the present Australian continent. Either they came in contact with Australia after the Middle Triassic, or the trench associated with the postulated subduction zone must have been located several hundred kilometres east of the magmatic belt.

One interesting feature of the Permo-Triassic granites is that their age range completely overlaps that of the Hunter-Bowen Orogeny, which commenced at 267 Ma and concluded with termination of sedimentation in the Bowen Basin at 230 Ma (Fielding *et al.*, 1997). Although the Hunter-Bowen Orogeny was an episodic event with periods of WNW-directed thrusting alternating with stability and perhaps even extension, the almost continuous record of granite ages from 270 to 220 Ma indicates that in many cases emplacement must have coincided with contractional deformation.
This raises the question of how unstressed high level granites were emplaced in a contractional environment characterised by zones of thin-skinned thrusting, particularly as some intrusions extend to considerable depths. Some intrusions of the nNEO have narrow foliated contact aureoles with very steep lineations, suggesting that the mechanism of emplacement may have been similar to that proposed by Paterson & Miller (1998). They argued that downward flow of host rocks in a narrow zone surrounding plutons is the main mechanism to create space in arcs being shortened and thickened.

The proposal that some of the Torlesse terrane in New Zealand (Figure 3) was sourced from the NEO is based on the similarity of the age range of the Permo-Triassic granites to dates of detrital micas and zircons (Adams & Kelley, 1998; Pickard *et al.*, 2000). Apart from the difficulty of transporting these detrital grains to New Zealand, wherever it was located at the time, a major problem is that this correlation was initially based largely on dates from more than 100 muscovite flakes. The fact that muscovite is an extremely minor component of the Permo-Triassic granites and their metamorphosed contact rocks provides a strong argument against the NEO-Torlesse connection.

The Permo-Triassic granitoids are associated with and genetically related to a wide range of mineralisation styles. These include subeconomic porphyry Cu-Mo, base metal and magnetite skarns (Glassford, Many Peaks, Ban Ban, Biggenden), mesothermal Au-quartz veins (Eidsvold, Bouldercombe), breccia-hosted subvolcanic Au-Ag (Mount Rawdon, Mount Shamrock), shear-hosted Cu (Mount Perry), minor Mo and W, and an unusual rutile deposit near Mount Perry. Highly fractionated granites tending to A-type contain Sn mineralisation at two localities. Some layered gabbros include magnetite-ilmenite bands, and have been evaluated for PGEs (Eulogie Park, Hawkwood, Bucknalla, Wateranga). Horton (1978) showed that the porphyry Cu-Mo deposits form a narrow linear belt, consistent with a subduction-related origin. They are associated with small intrusions either within or near the margins of larger plutons. Most of the mineralising stocks are non-magnetic, although some are surrounded by a magnetic hornfels rim. The largest porphyry deposits are Moonmera, Coalstoun and Anduramba.

Early Cretaceous

Early Cretaceous granites occur between Mackay and Townsville within and on both sides of the Connors Arch. The larger plutons west of Bowen are centred on deep gravity lows and must have considerable vertical extent. A younger suite of volcanics with small subvolcanic intrusions forms the Whitsunday Islands and the adjacent mainland. These rocks have ages from 145 to 100 Ma (Allen *et al.*, 1998). Another group of Cretaceous granites, dated at about 140 Ma, occurs along the western edge of the Maryborough Basin west of Maryborough, also associated with volcanics.

Compositions range from gabbro to granite, are medium to high-K, and are bimodal (Figure 1). Allen *et al.* (1997) noted compositional differences with age of intrusions in the Bowen region. Granodiorite dominates for ages from 145 to 125 Ma, with few mafic rocks, whereas there is a broad range of mafic to felsic compositions in the younger group of granitoids, which also includes granites approaching A-type compositions. Limited analyses from the Cretaceous granites of the Maryborough Basin are intermediate between these two groups.

It is universally agreed that the younger Cretaceous intrusions and volcanics formed in an extensional environment, but whether the older granites shared this origin or were related more directly to subduction is debatable. Allen *et al.* (1997) argued on geochemical grounds that the younger intrusive and volcanic assemblage in the Bowen region represented an increase in the geothermal gradient and resultant magmatism compared to the older rocks. If subduction was involved, the associated trench must have been well to the east given the position of the Norfolk Ridge and Lord Howe Rise in the Early Cretaceous (Figure 3).

As for the Permo-Triassic, genesis of the Cretaceous intrusives involved melting and underplating of the crust by basaltic magma, with the possibility that some granites were produced directly from the mantle. Because of their more radiogenic composition, Late Carboniferous to Early Permian granites of the Connors Arch cannot have had the same source as the Cretaceous crustal melts, and could not have been a source themselves.

Mineralisation associated with the Early Cretaceous granites includes subeconomic Cu-Mo porphyry deposits (Horton, 1978), and small but rich mesothermal Au-quartz veins (Dittmer, Normandy goldfield). A unique intrusion is the mid-Cretaceous Goondicum layered gabbro east of Monto, being evaluated as a source of ilmenite and other commodities.

Conclusions

An unusual feature of the 4 age groups of granites in the nNEO is that both average compositions and the most common composition within each group become more SiO_2-rich with decreasing age (Figure 1). The Carboniferous to Permian, Permian to Triassic, and Cretaceous granites of the nNEO, considered as broad groups, include the same range of rock types (although the Cretaceous is bimodal), and have remarkably similar major and trace element geochemistry. This indicates that they shared common elements of source and process in their generation, despite variation in I_{Sr}. For all three groups, a temporal transition from subduction-related to backarc extensional magmatism has been suggested. For the Permo-Triassic and Early Cretaceous, this transition is marked by intrusion of late stage alkaline granites approaching or displaying A-type geochemistry. This does not appear to be the case for Carboniferous to Permian intrusives, suggesting a greater degree of inheritance of a subduction component in upper mantle and crust. The Middle to Late Devonian Mount Morgan Trondhjemite differs from all other granites of the nNEO, and is interpreted as an oceanic island arc trondhjemite.

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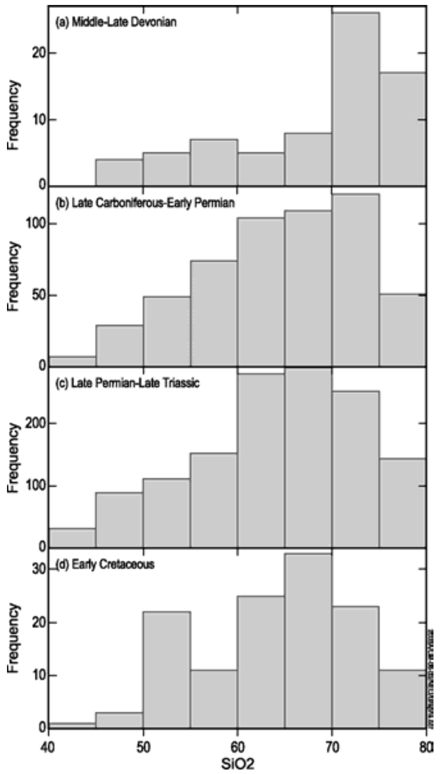


Figure 1. Histogram of SiO_2 contents of age groupings of nNEO granites.

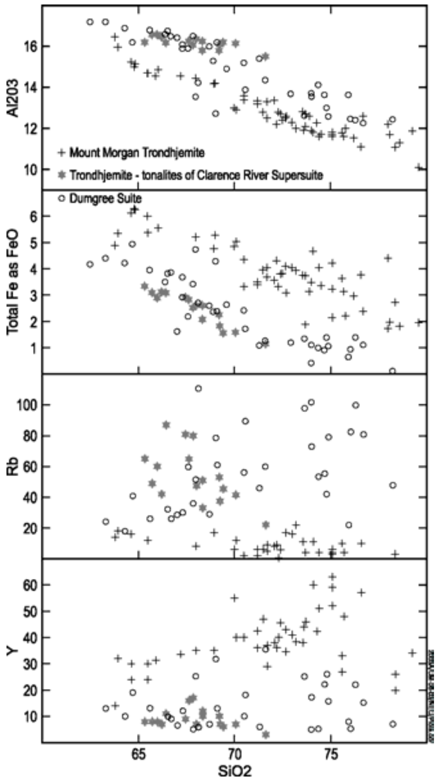


Figure 2. Harker plots showing discrimination of the Devonian Mount Morgan Trondhjemite from Permo-Triassic trondhjemitic and tonalitic rocks of the Clarence River Supersuite (Bryant *et al*, 1997) and the Dumgree suite of the nNEO.

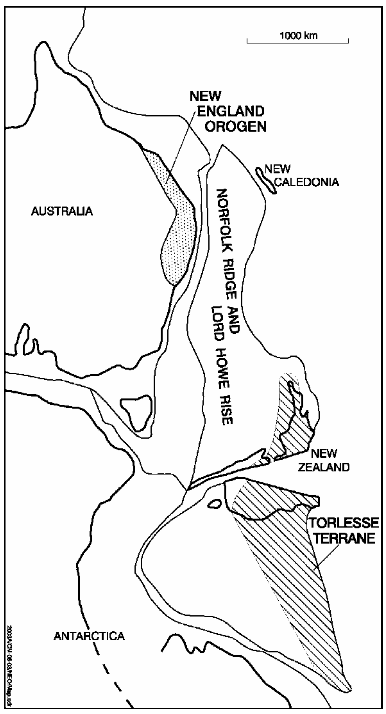
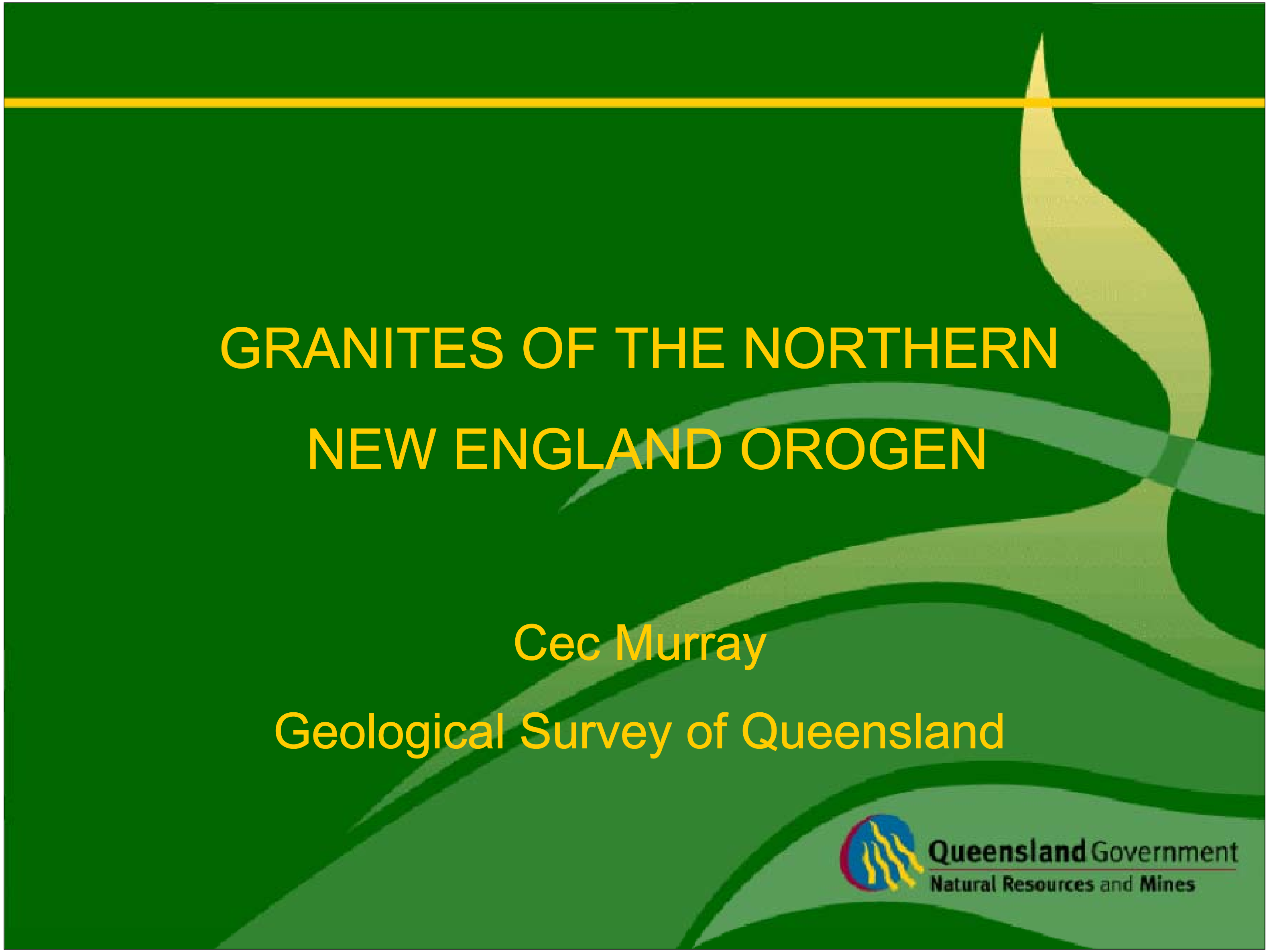


Figure 3. Reconstruction of Australia, Antarctica, Norfolk Ridge, Lord Howe Rise and New Zealand prior to commencement of opening of the Tasman Sea at 80 Ma (after Adams & Kelley, 1998).


GRANITES OF THE NORTHERN
NEW ENGLAND OROGEN
Cec Murray
Geological Survey of Queensland
Queensland Government
Natural Resources and Mines


GRANITES OF 4 MAIN AGE GROUPS
• Middle - Late Devonian (380 Ma)
• Mid-Carboniferous – Early Permian (330-280 Ma)
• Late Permian – Late Triassic (275-205 Ma)
• Early Cretaceous (145-90 Ma)
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ALL GRANITES

- Have low I_{sr} ratios indicating no input from old continental crust
- Are mainly high-temperature I-type with no relict zircon
- Are associated with co-magmatic volcanics
- Show a decrease in average and dominant SiO_2 content from oldest to youngest group
- Record repeated cycles of subduction and extension
- Are associated with Cu-Mo-Au mineralisation

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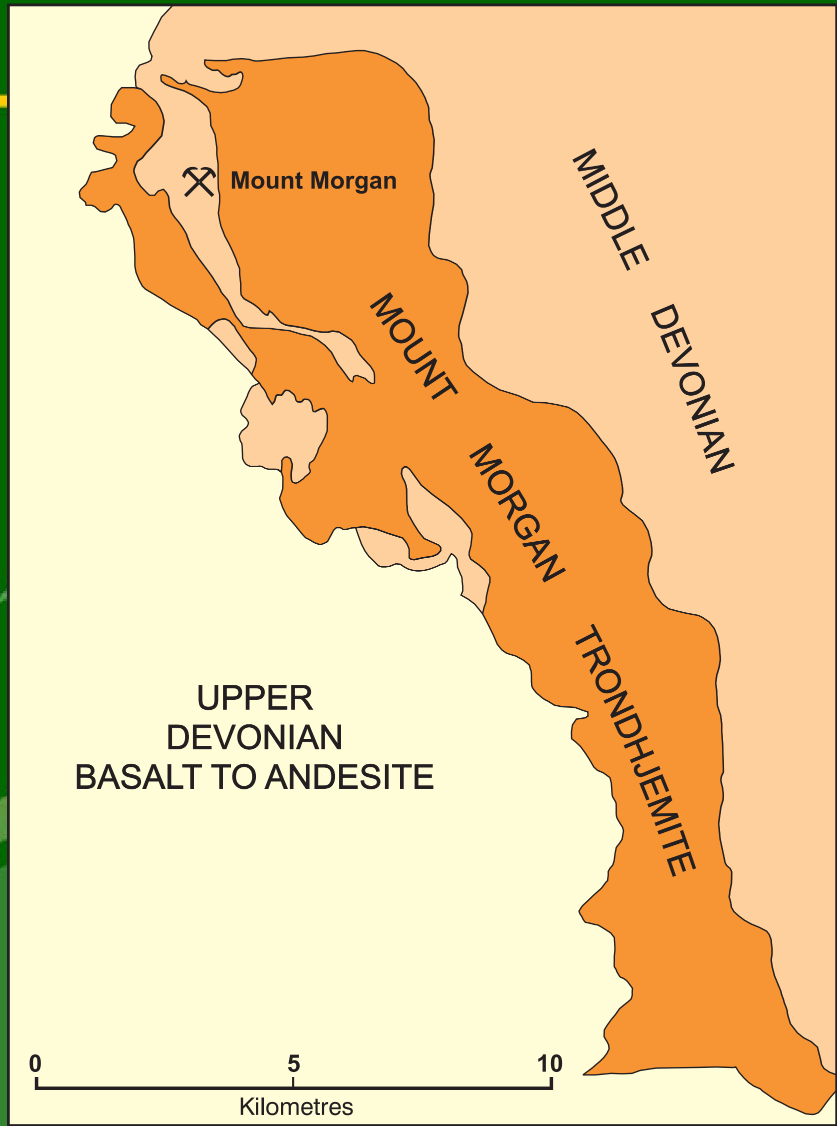
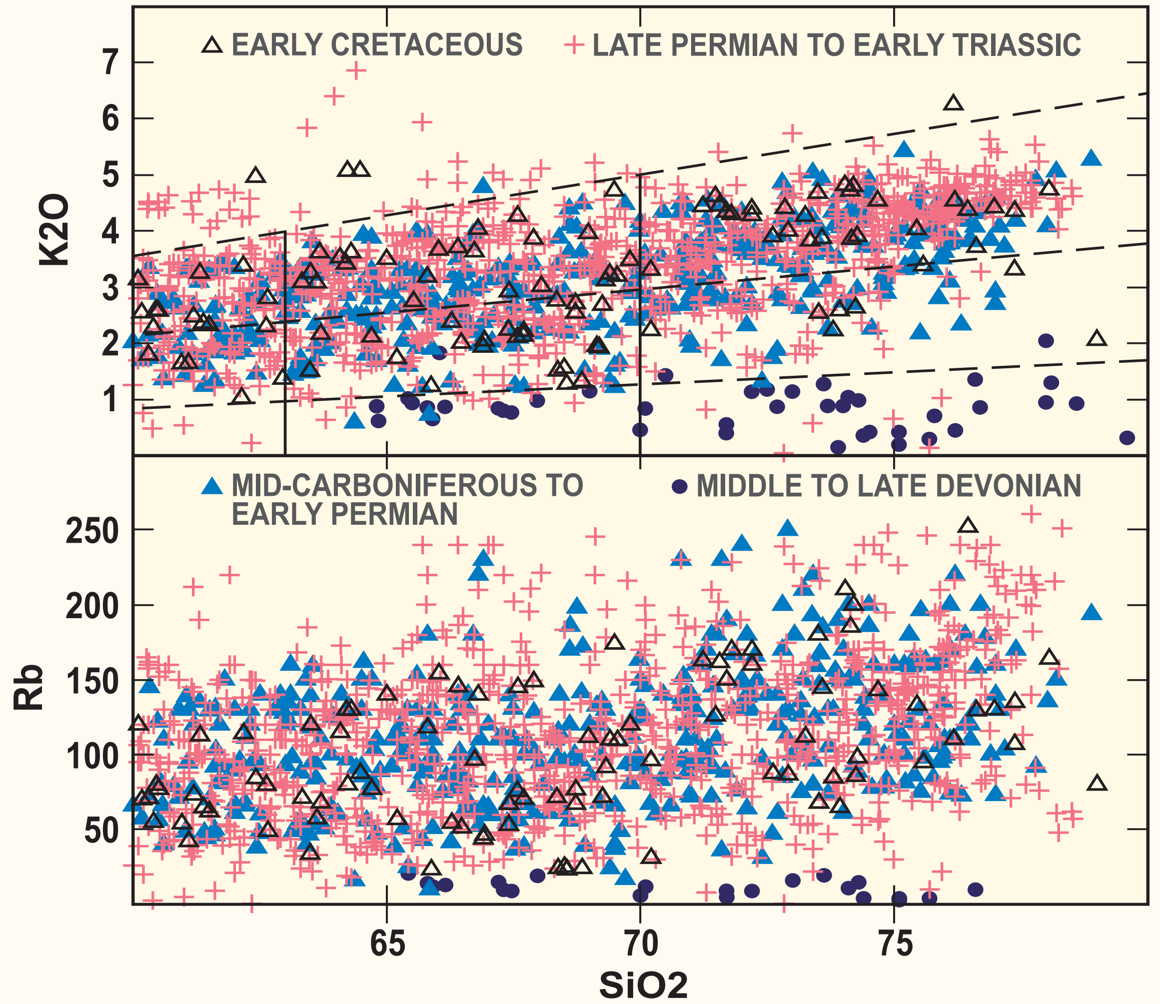
MIDDLE TO LATE DEVONIAN MOUNT MORGAN TRONDHJEMITE

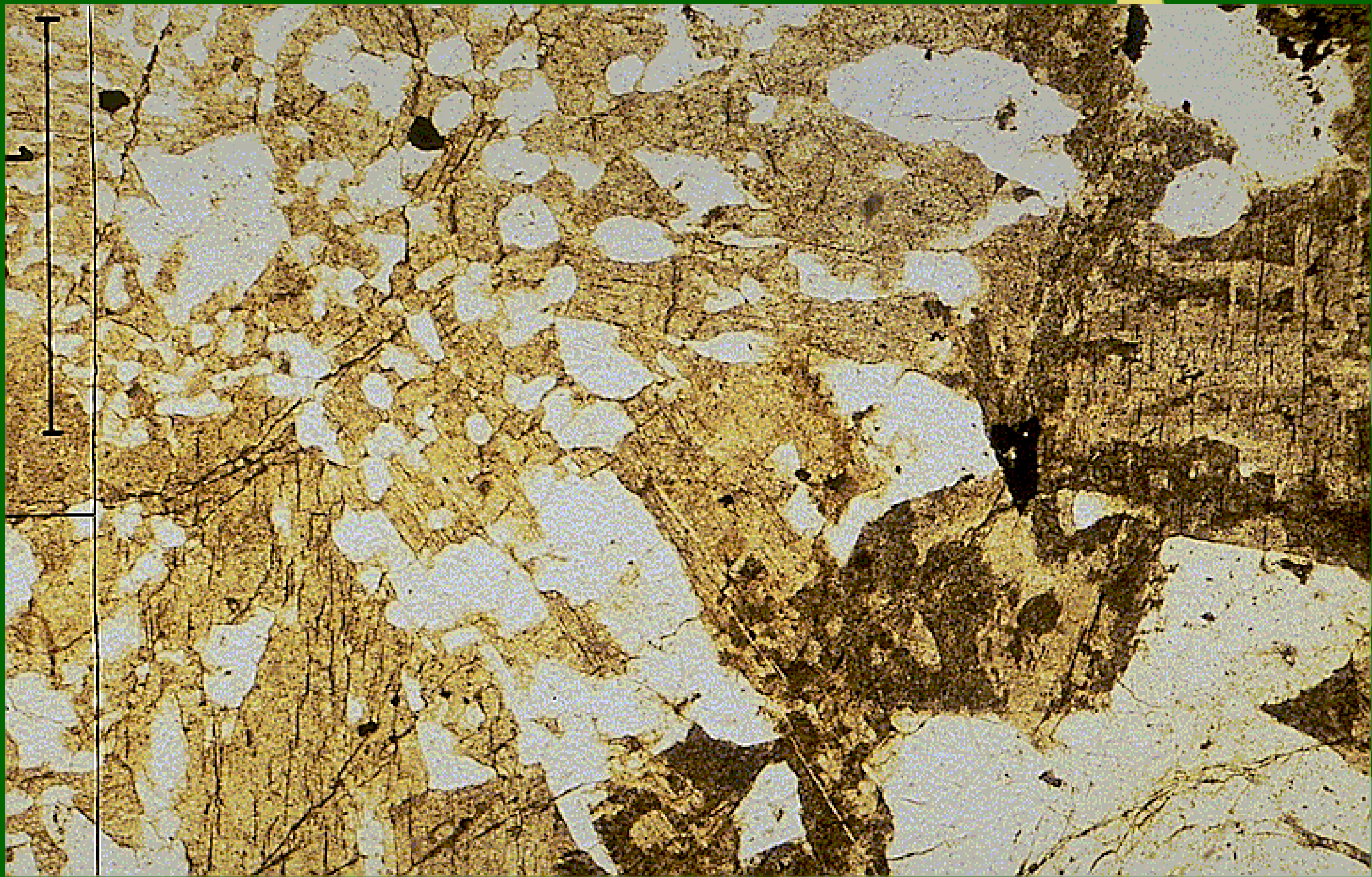
(380 Ma)



Low K_2O and Rb of Devonian Mount Morgan Trondhjemite

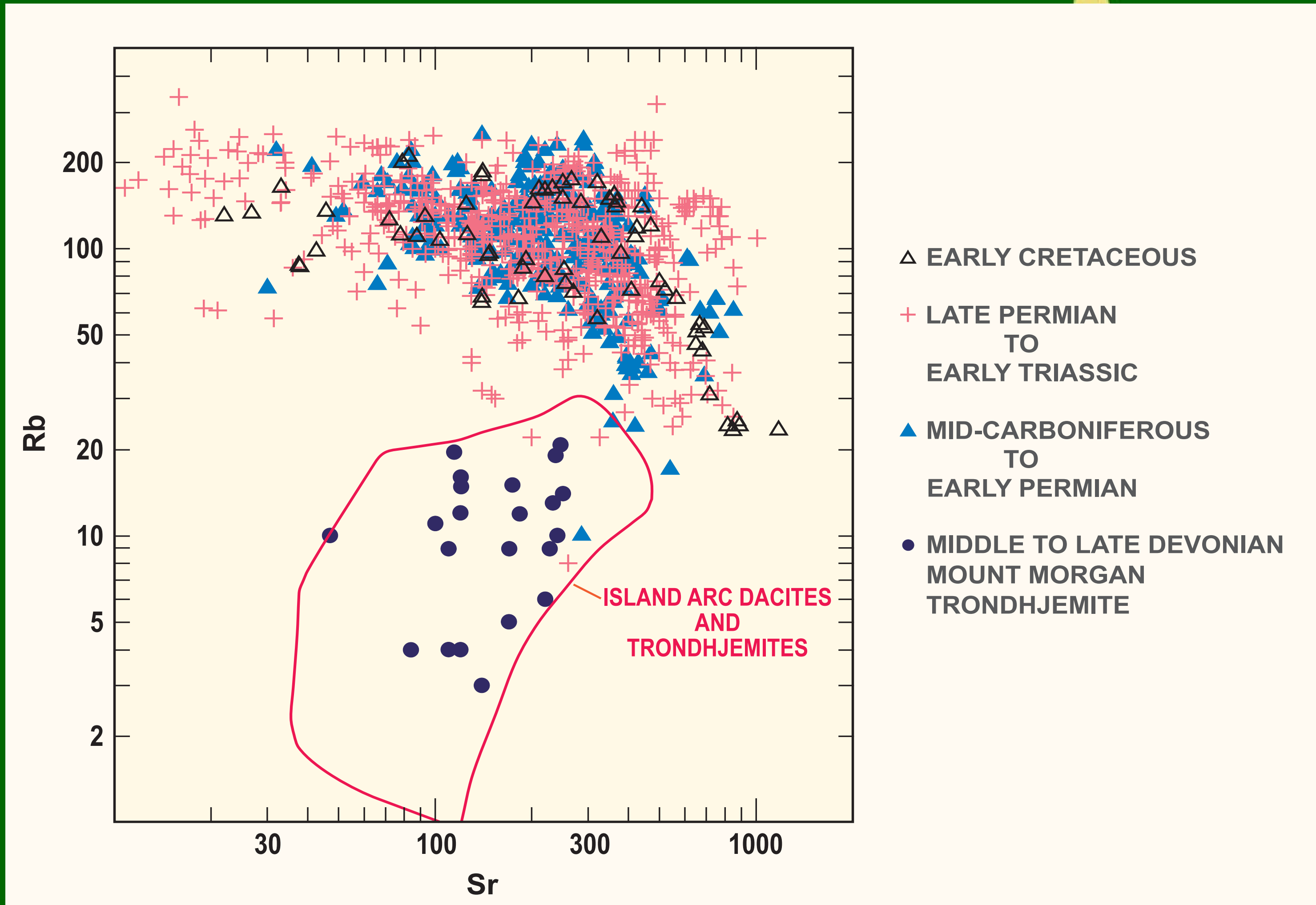


Micrographic texture and K feldspar alteration

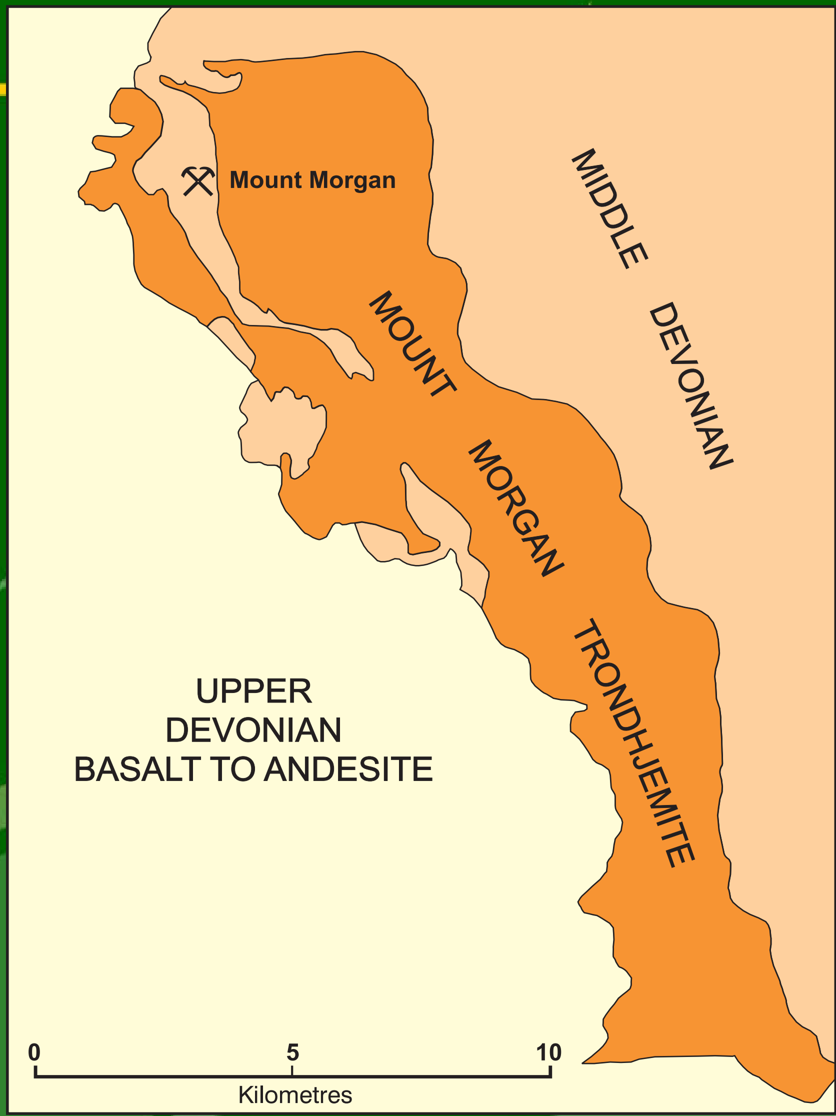


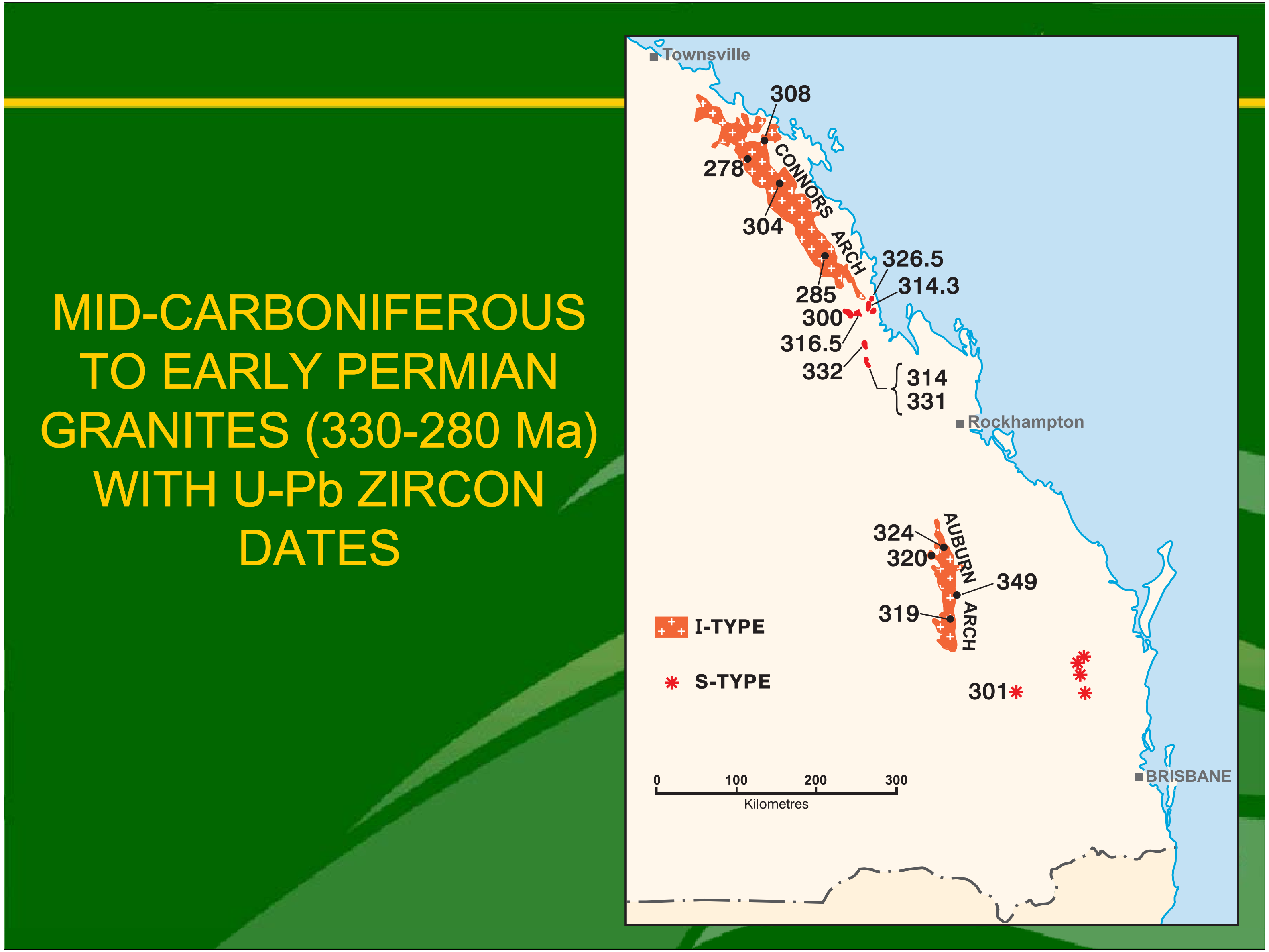
Quartz veins with chlorite alteration

Rb/Sr discrimination plot for Mount Morgan Trondhjemite (>65% SiO_2)

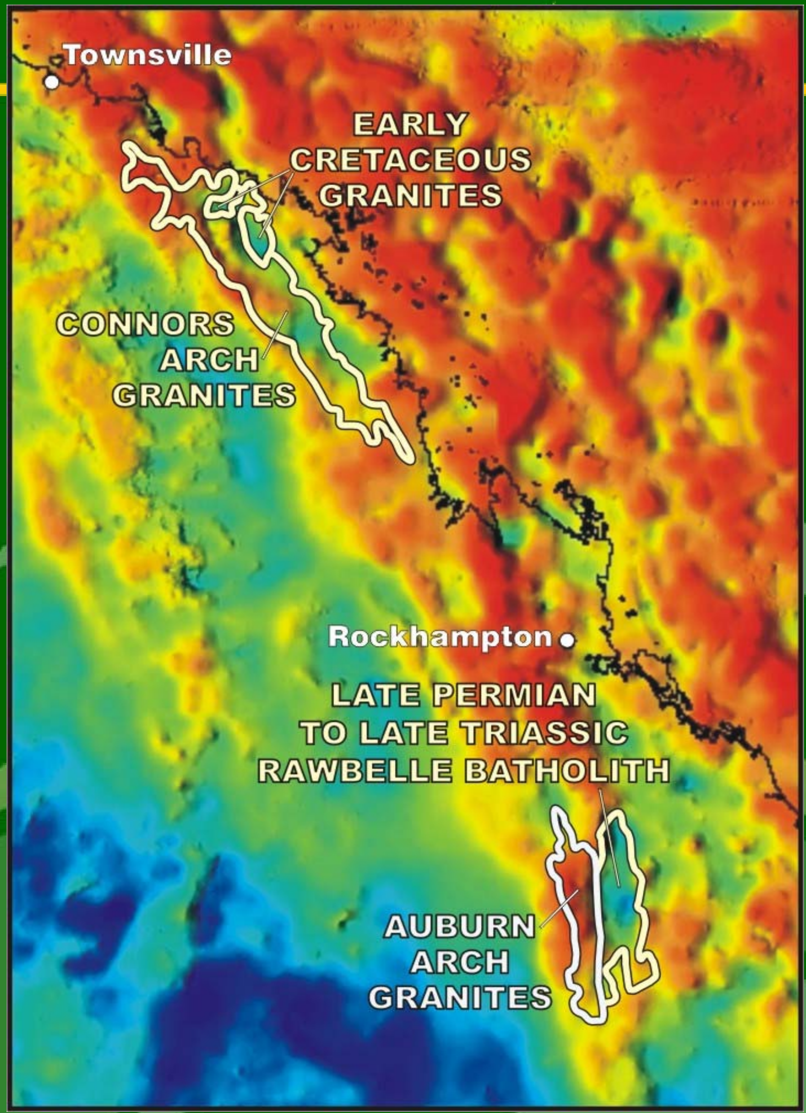


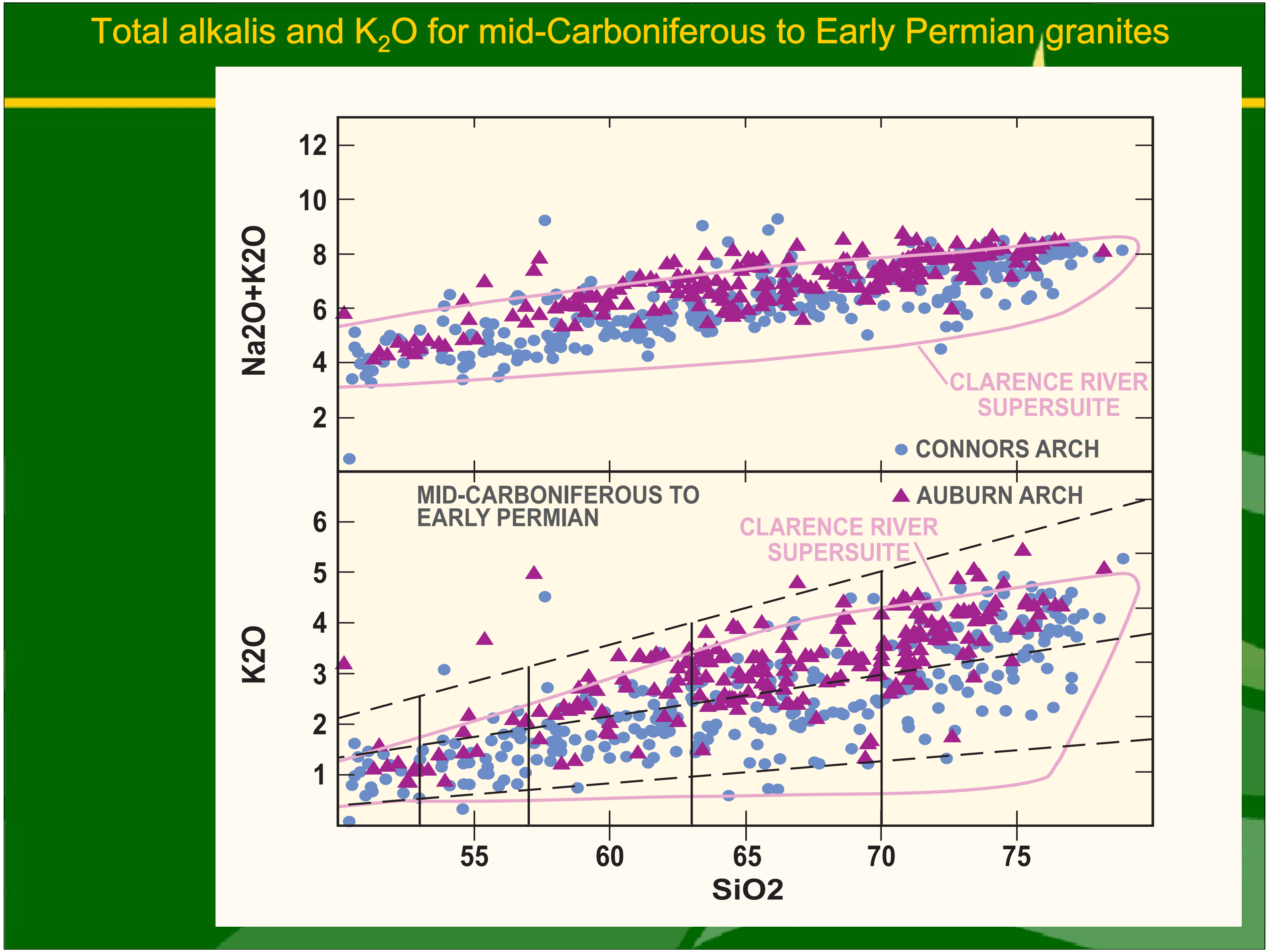
MOUNT MORGAN Au-Cu DEPOSIT IS IN ROOF PENDANT OF MINE CORRIDOR VOLCANICS WITHIN MOUNT MORGAN TRONDHJEMITE

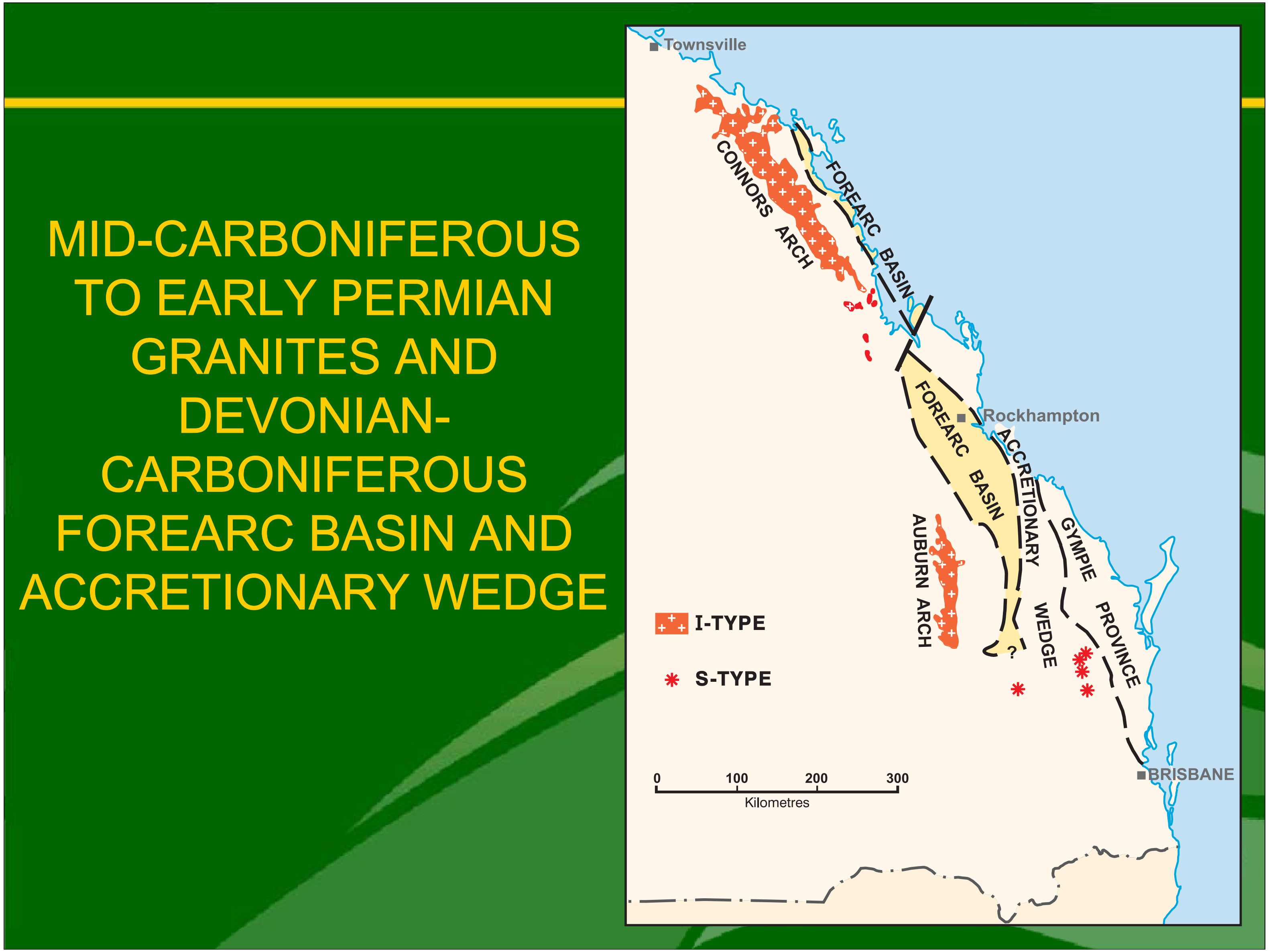



MID-CARBONIFEROUS
TO EARLY PERMIAN
GRANITES (330-280 Ma)
WITH U-Pb ZIRCON
DATES
Townsville
308
278
CONNORS
ARCH
304
326.5
314.3
285
300
316.5
332
314
331
Rockhampton
AUBURN
ARCH
324
320
349
319
I-TYPE
S-TYPE
301
0
100
200
300
Kilometres
BRISBANE

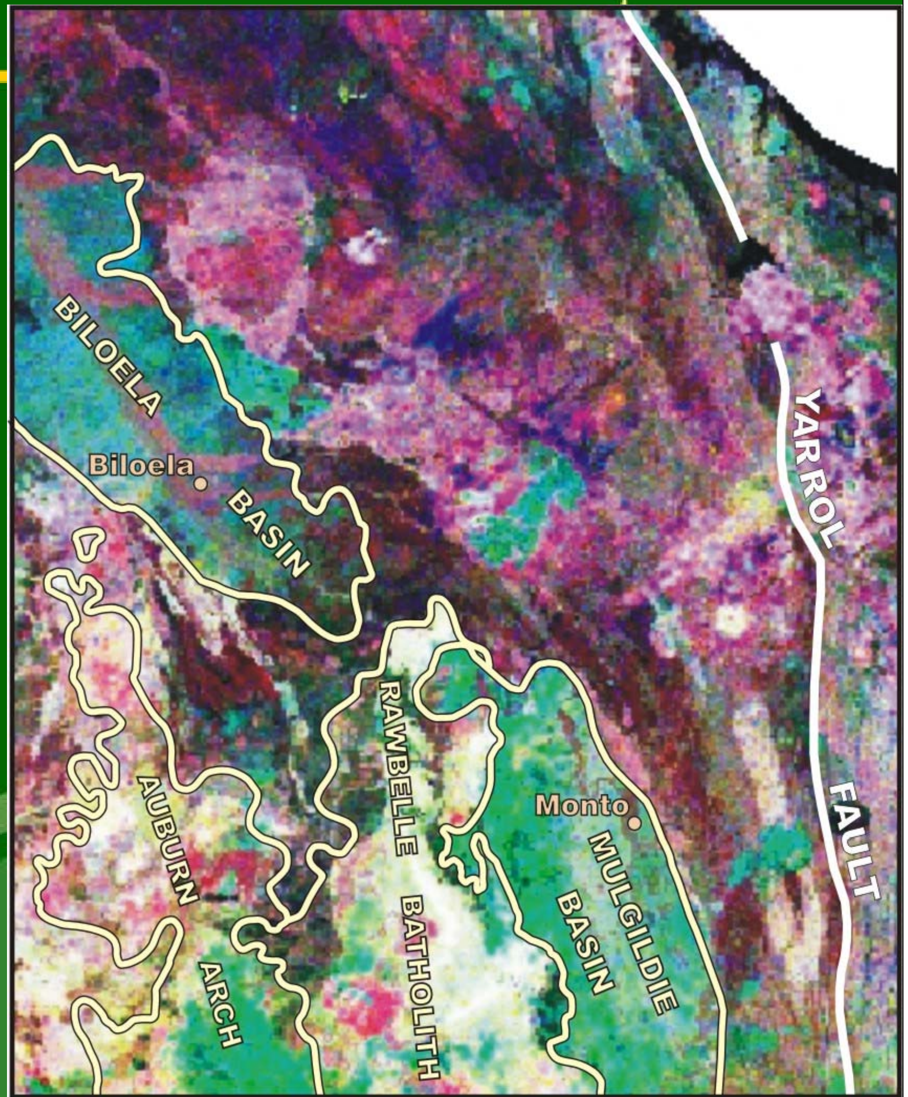
Bouger gravity image of northern New England Orogen showing strong gravity ridge along the Auburn Arch



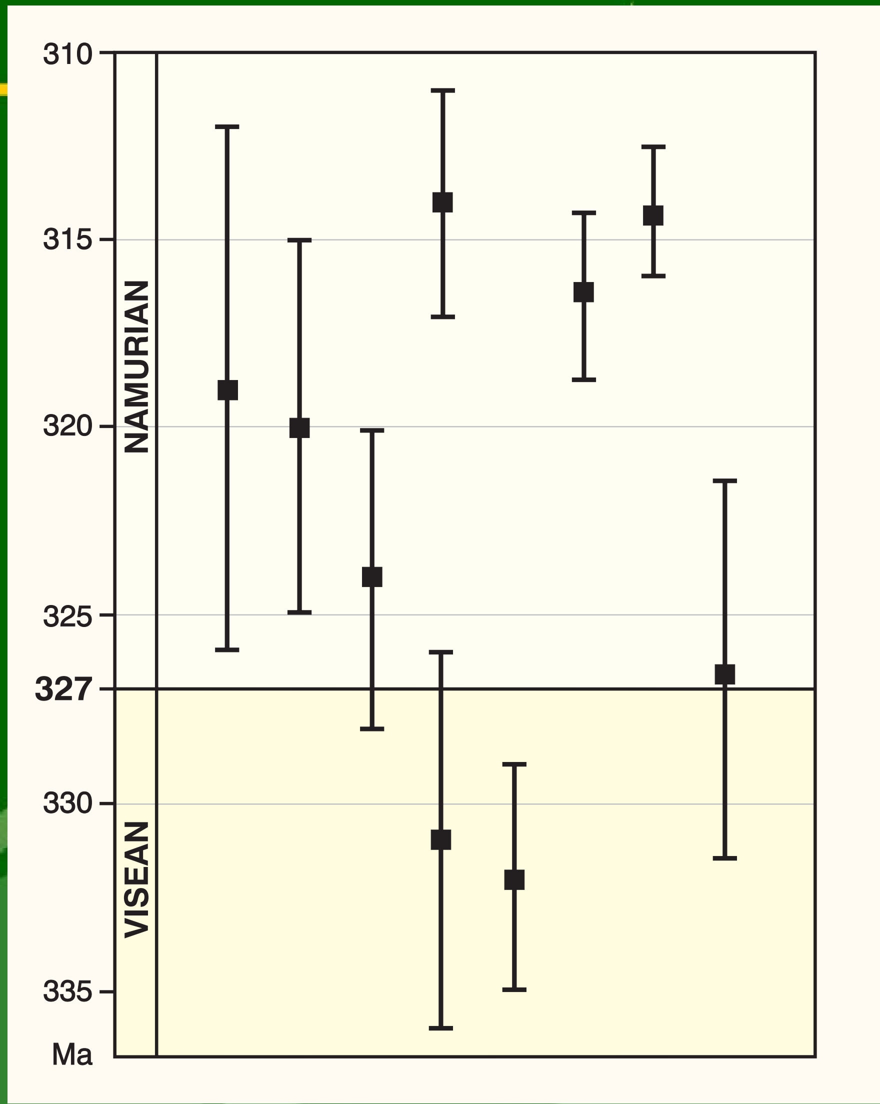

Total alkalis and K2O for mid-Carboniferous to Early Permian granites
Na2O+K2O
12
10
8
6
4
2
CLARENCE RIVER SUPERSUITE
CONNORS ARCH
AUBURN ARCH
MID-CARBONIFEROUS TO EARLY PERMIAN
CLARENCE RIVER SUPERSUITE
K2O
6
5
4
3
2
1
55
60
65
70
75
SiO2

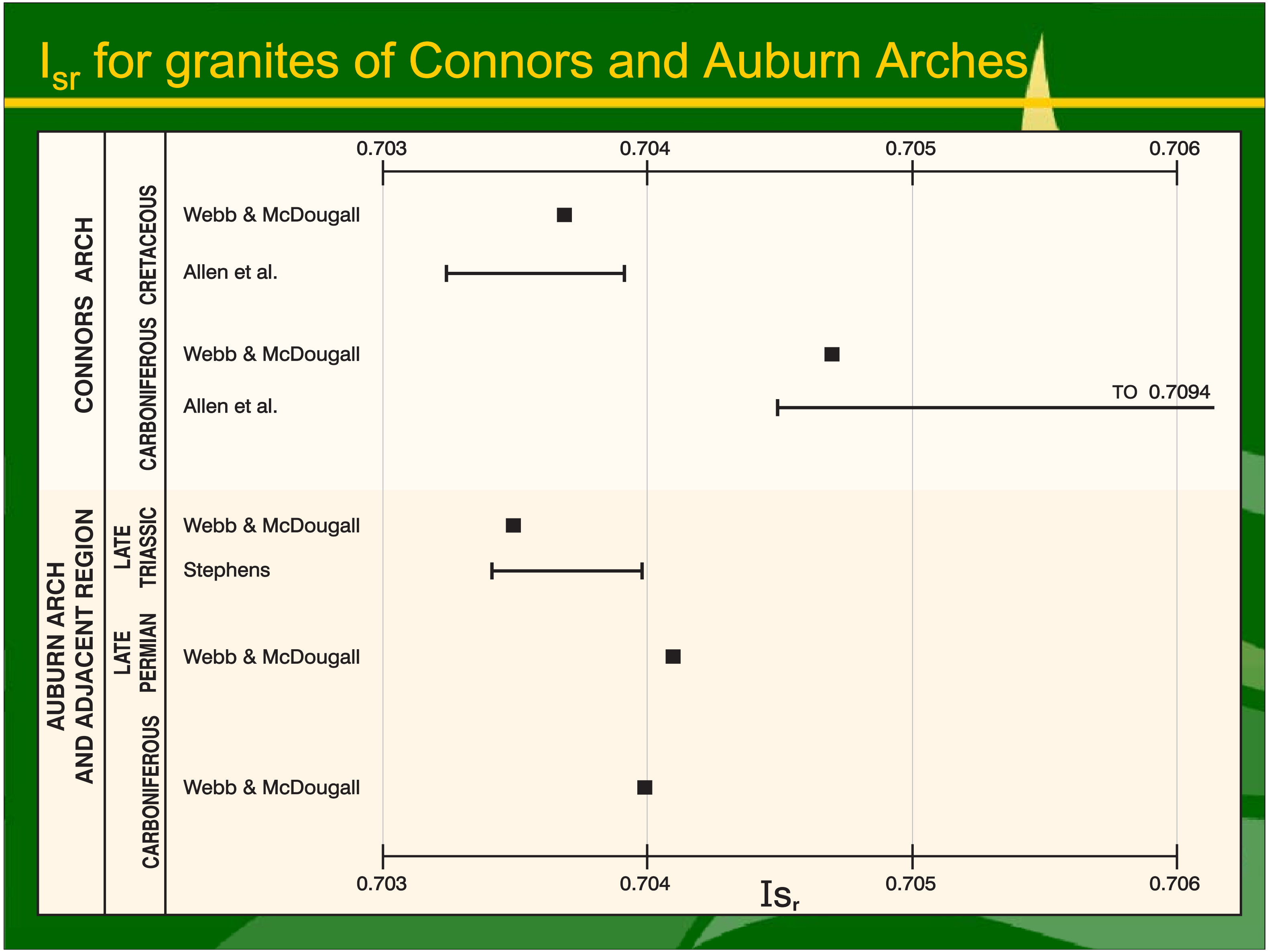

MID-CARBONIFEROUS TO EARLY PERMIAN GRANITES AND DEVONIAN-CARBONIFEROUS FOREARC BASIN AND ACCRETIONARY WEDGE
Townsville
CONNORS ARCH
FOREARC BASIN
Rockhampton
FOREARC BASIN
ACCRETIONARY WEDGE
GYMPIE PROVINCE
AUBURN ARCH
I-TYPE
S-TYPE
0 100 200 300
Kilometres
BRISBANE

Radiometric image of Yarrol Forearc Basin showing high response from Late Carboniferous sequence in the Yarrol Syncline and from latest Carboniferous to Early Permian extensional phase deposits east of the Biloela Basin



AGES OF MID-CARBONIFEROUS GRANITES OF THE AUBURN ARCH AND SOUTHERN CONNORS ARCH COMPARED TO THE VISEAN-NAMURIAN BOUNDARY

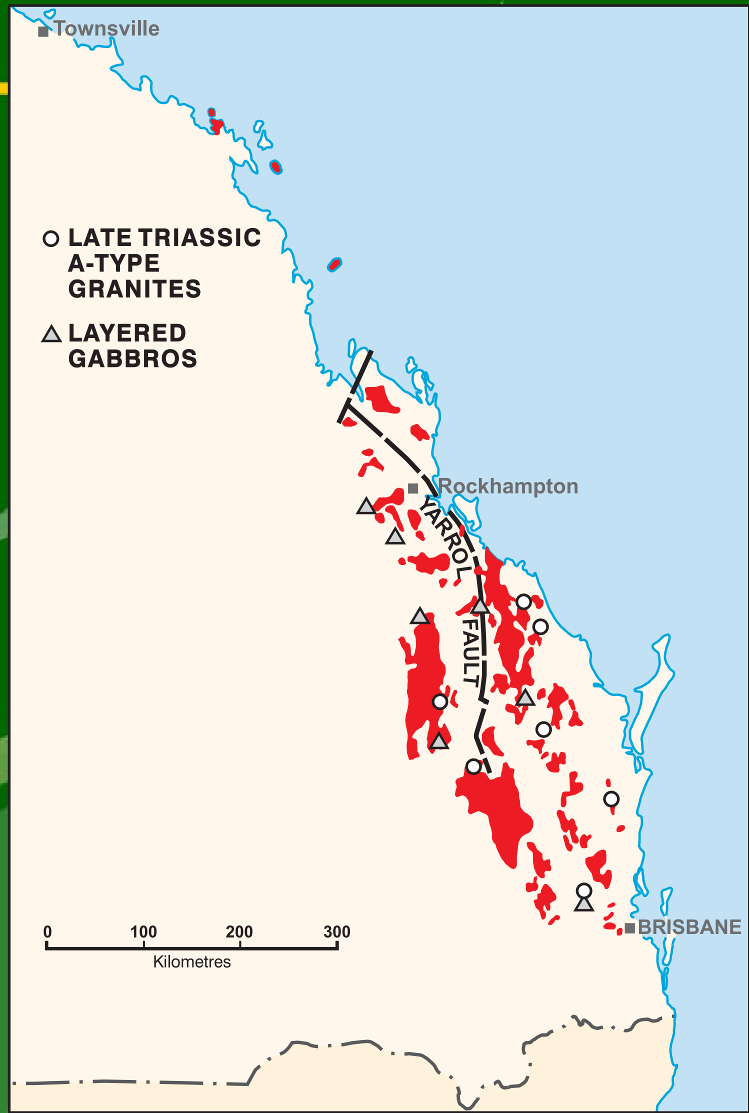




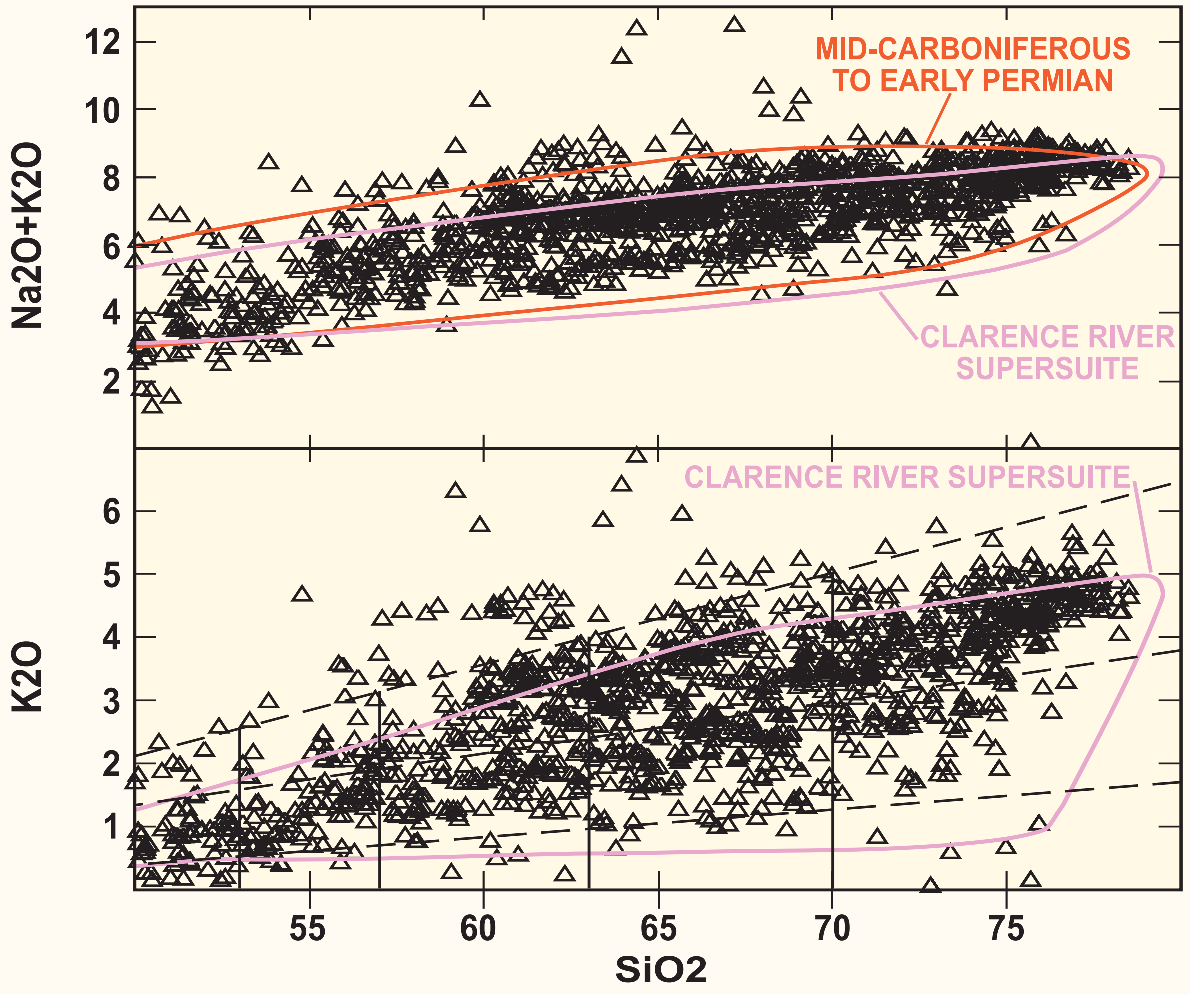
I_{sr} for granites of Connors and Auburn Arches
CONNORS ARCH
CRETACEOUS
CARBONIFEROUS
AUBURN ARCH AND ADJACENT REGION
LATE TRIASSIC
LATE PERMIAN
CARBONIFEROUS
0.703
0.704
0.705
0.706
Webb & McDougall
Allen et al.
Webb & McDougall
Allen et al.
TO 0.7094
Webb & McDougall
Stephens
Webb & McDougall
Webb & McDougall
Is_r

LATE PERMIAN TO LATE TRIASSIC GRANITES

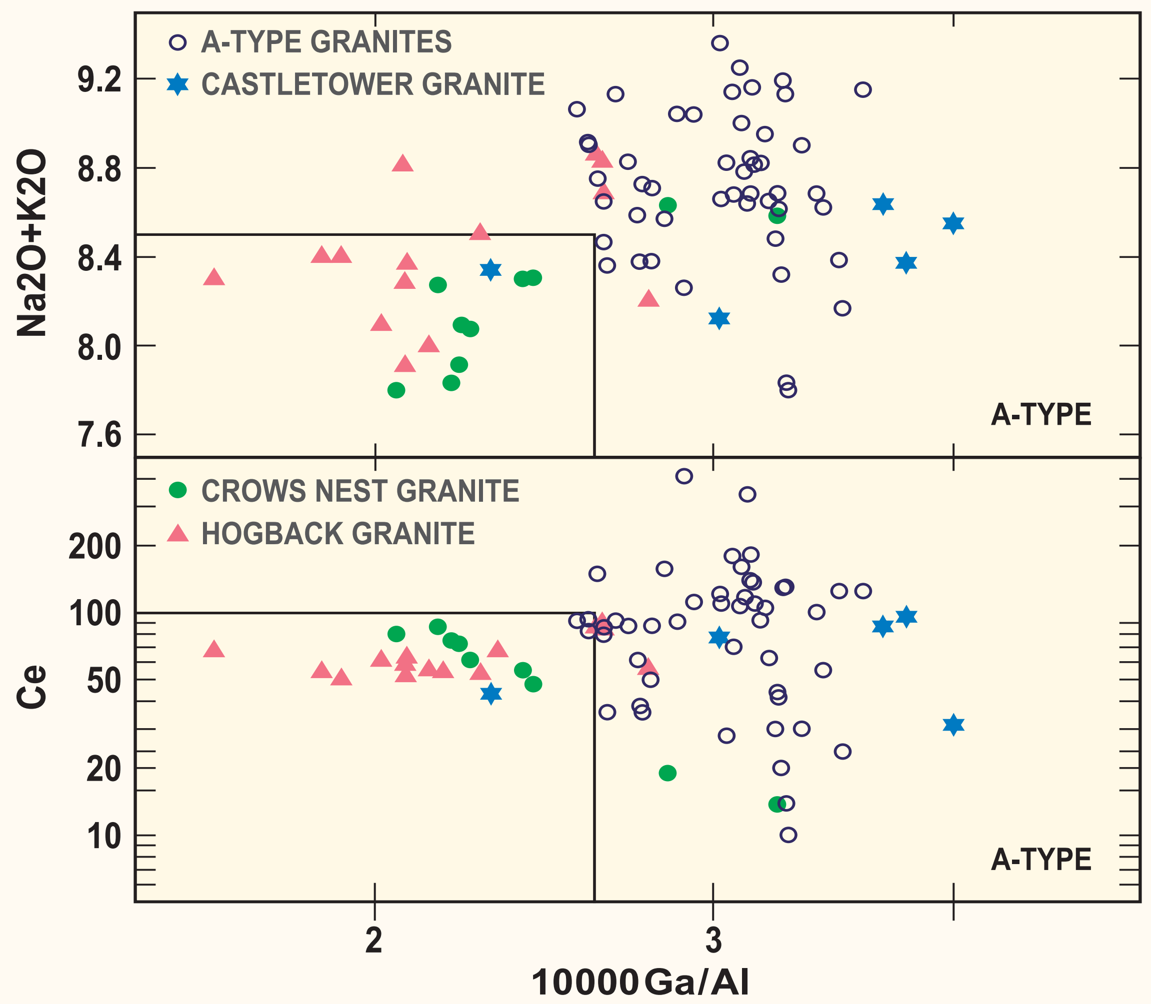
(275-205 Ma)



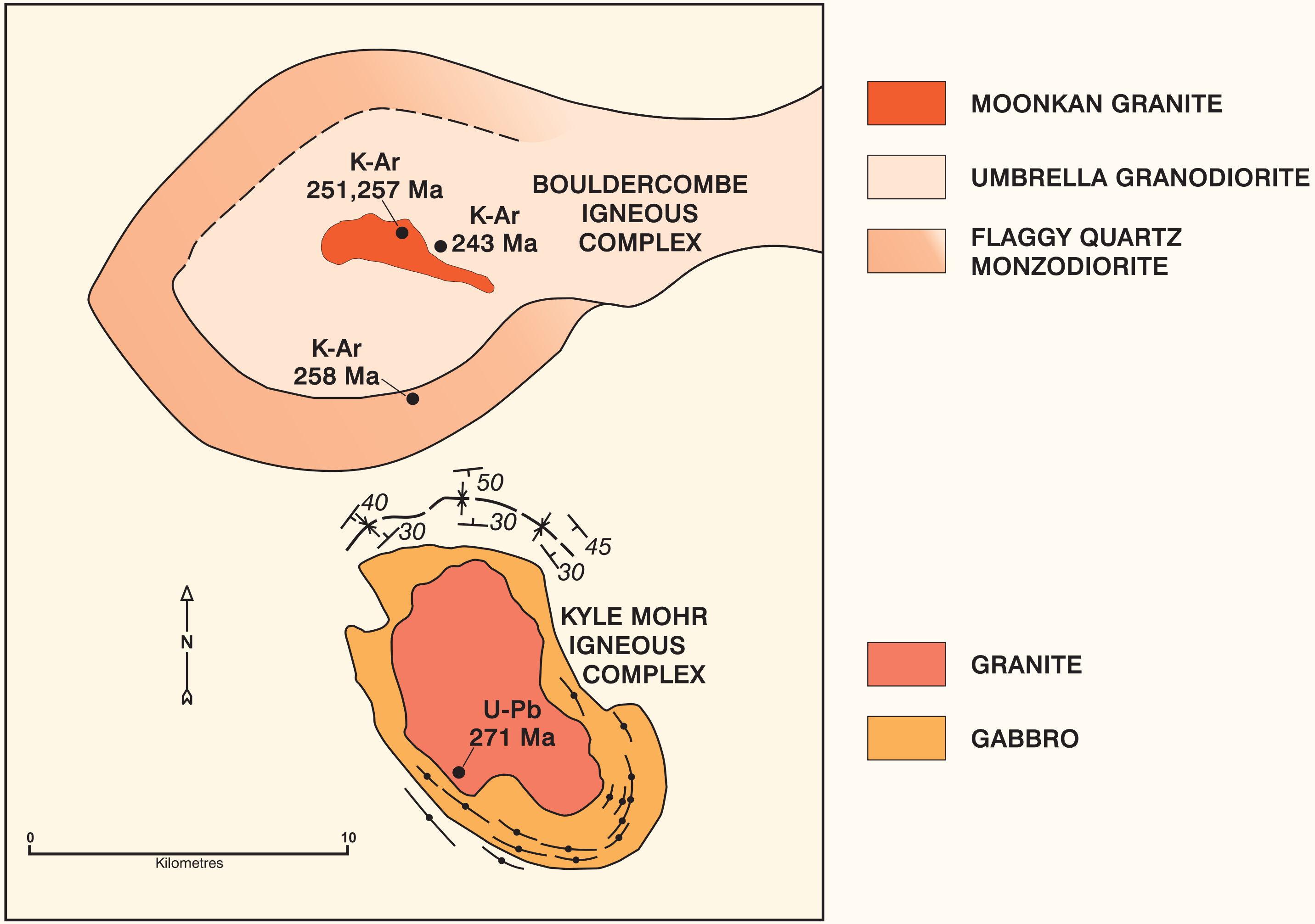
Total alkalis and K_2O for Late Permian to Late Triassic granites

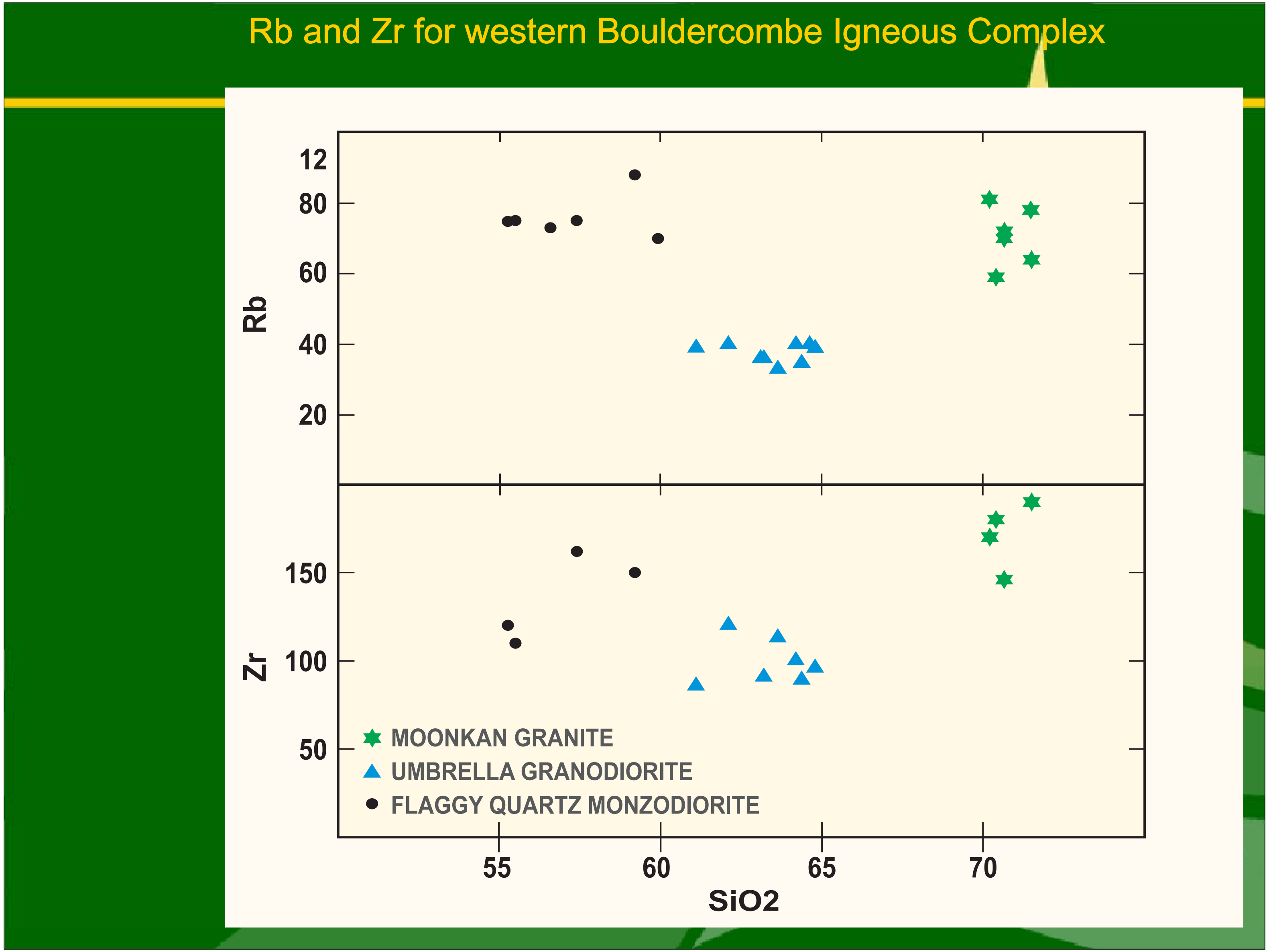


A-type and fractionated I-type granites



Kyle Mohr and western Bouldercombe Igneous Complexes

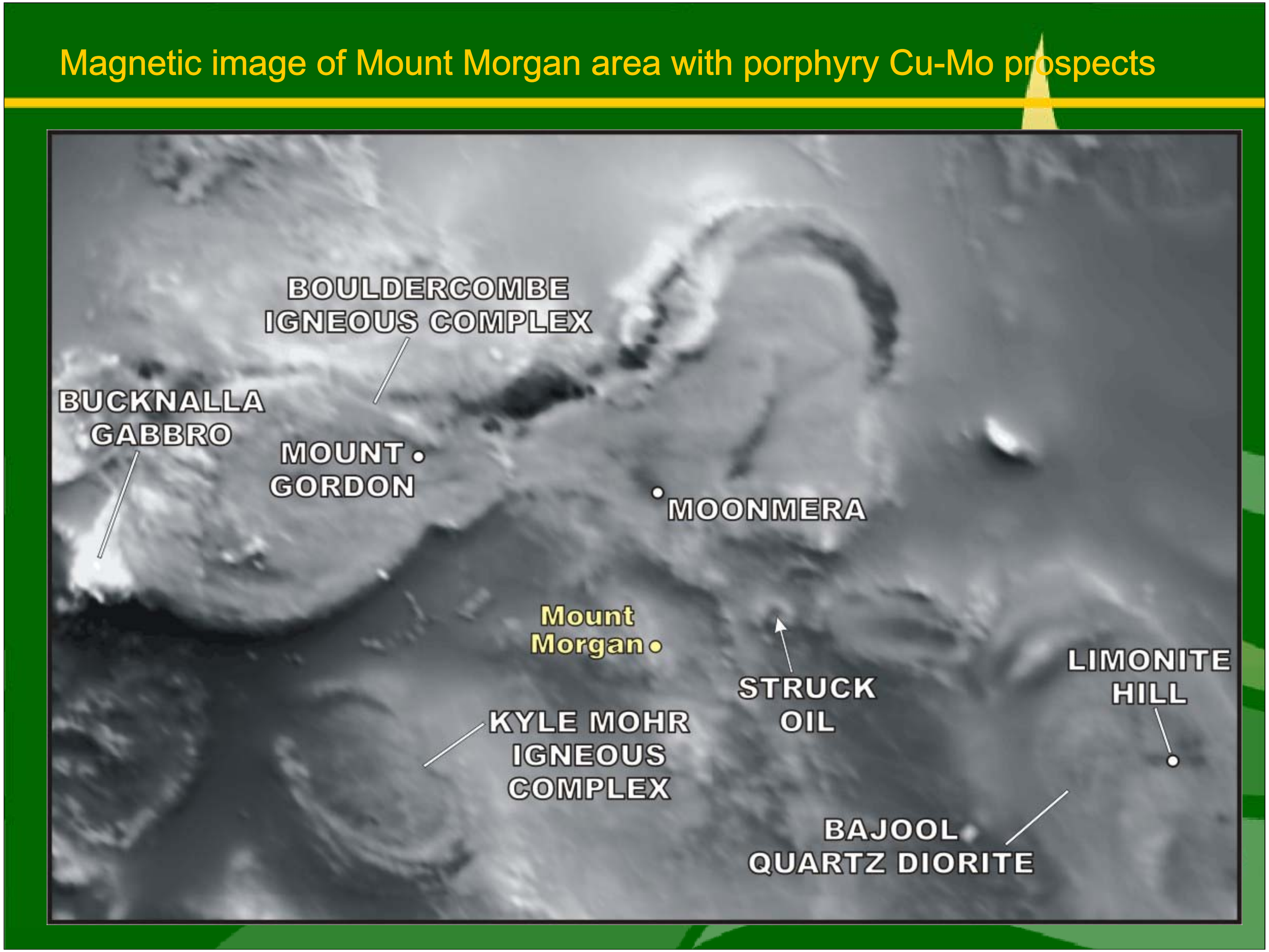




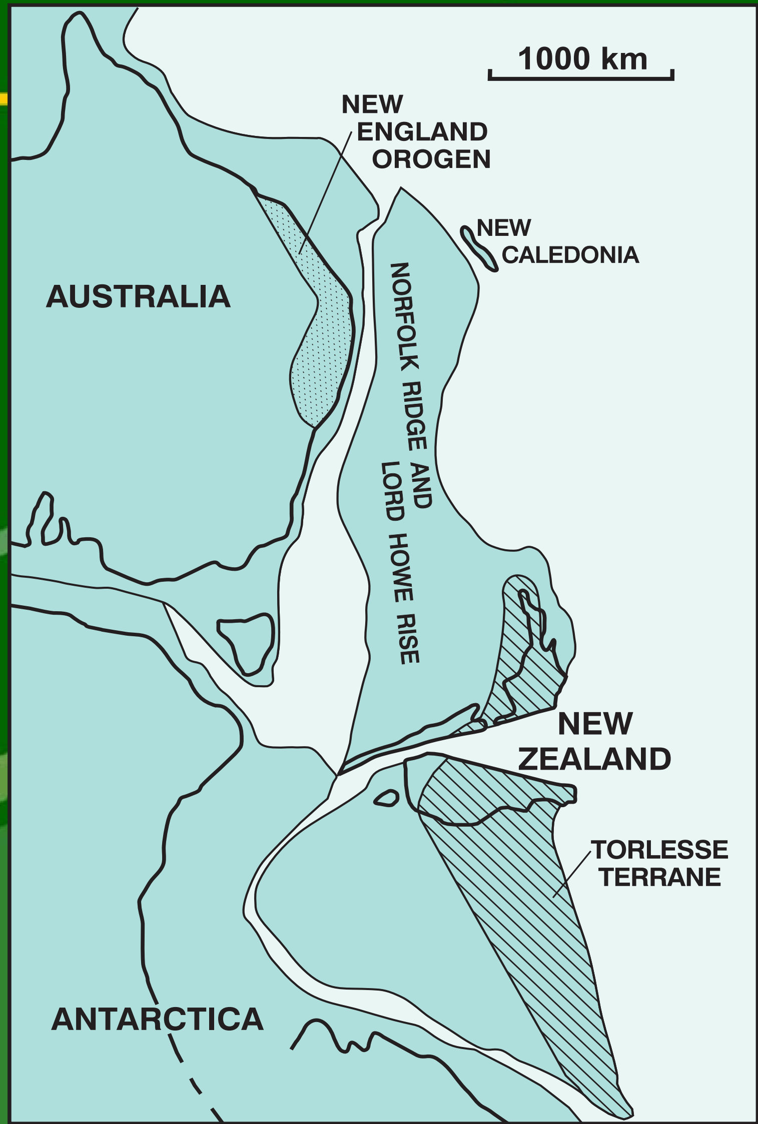
Rb and Zr for western Bouldercombe Igneous Complex
12
80
60
40
20
Rb
150
100
50
Zr
MOONKAN GRANITE
UMBRELLA GRANODIORITE
FLAGGY QUARTZ MONZODIORITE
55
60
65
70
SiO2

Foliated Flaggy Quartz Monzodiorite


Net veining of gabbro by granite, Kyle Mohr complex

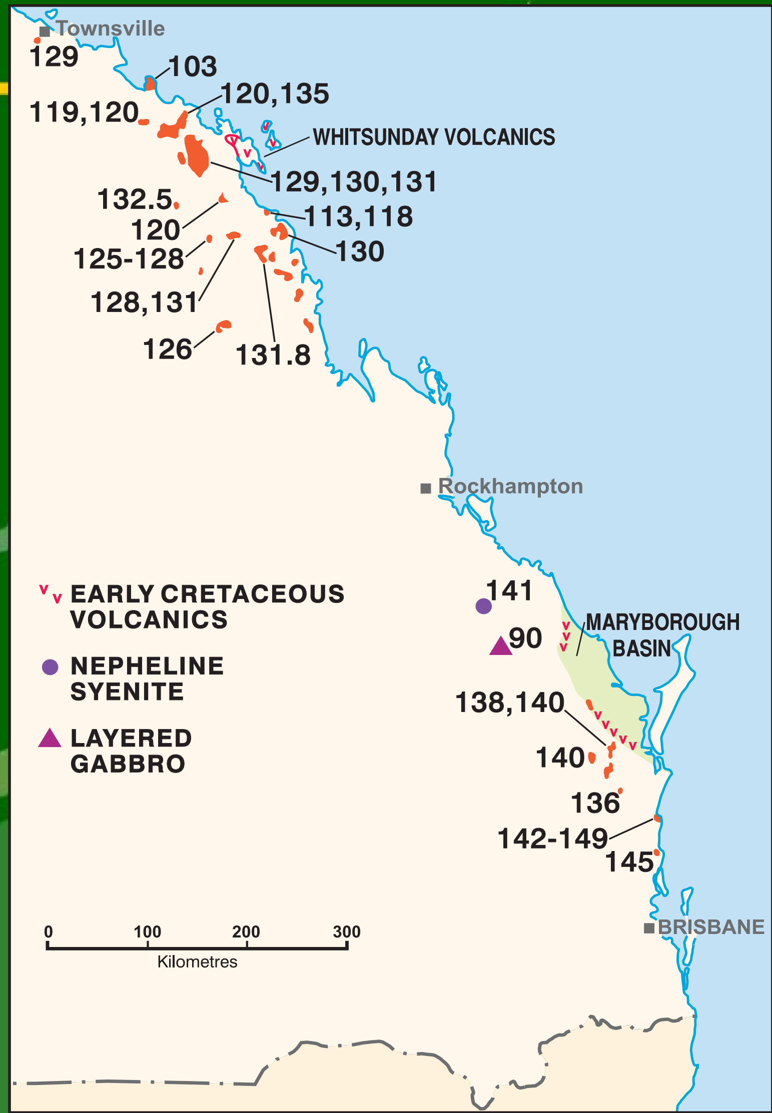

Magnetic image of Mount Morgan area with porphyry Cu-Mo prospects
BOULDERCOMBE
IGNEOUS COMPLEX
BUCKNALLA
GABBRO
MOUNT
GORDON
MOONMERA
Mount
Morgan
STRUCK
OIL
LIMONITE
HILL
KYLE MOHR
IGNEOUS
COMPLEX
BAJOOL
QUARTZ DIORITE

Reconstruction showing relationship between the New England Orogen and the Torlesse terrane of New Zealand before opening of the Tasman and Coral Seas

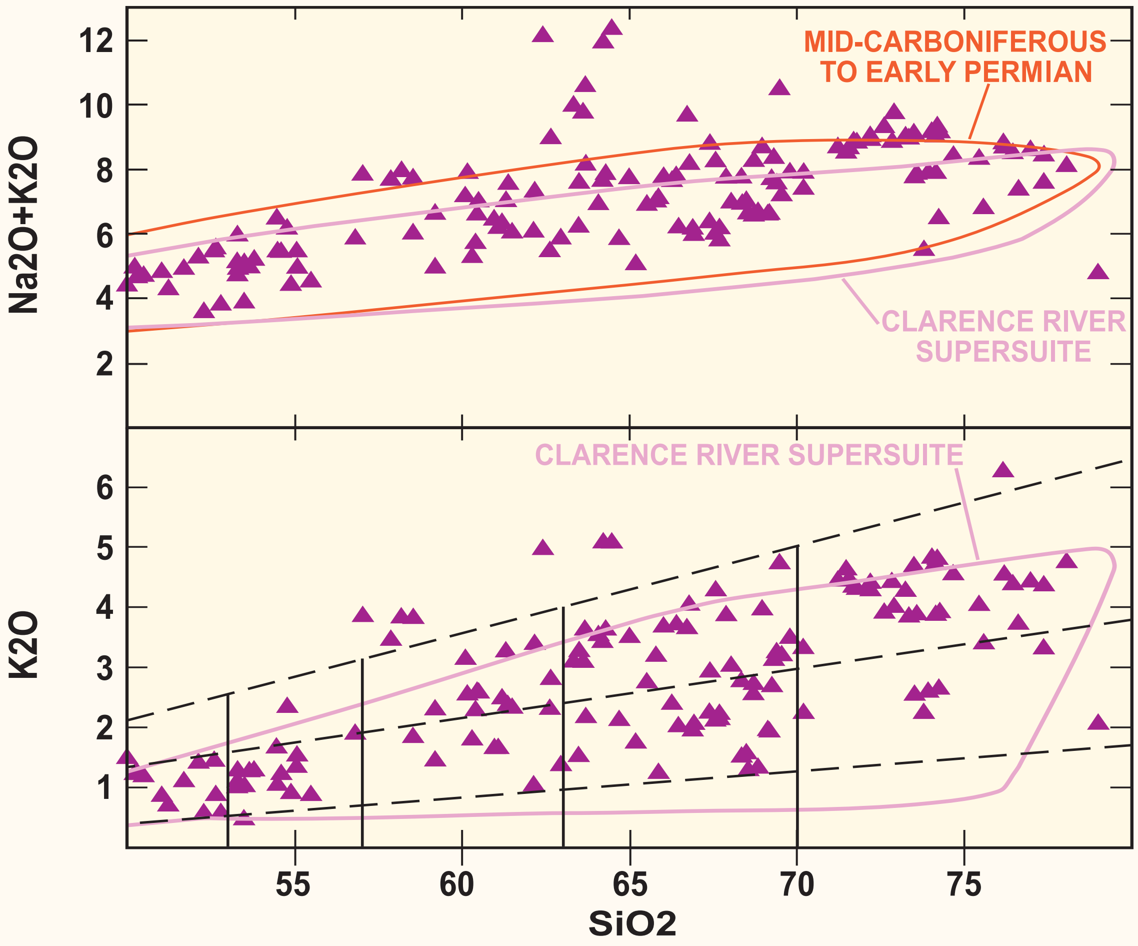


EARLY CRETACEOUS GRANITES

(145-90 Ma)



Total alkalis and K_2O for Early Cretaceous granites



CONCLUSIONS

MIDDLE TO LATE DEVONIAN

- Mount Morgan Trondhjemite formed in an oceanic island arc by dehydration melting of low-K basaltic andesite and subsequent fractionation
- Relationship of the intrusion to the Mount Morgan Au-Cu orebody is still uncertain

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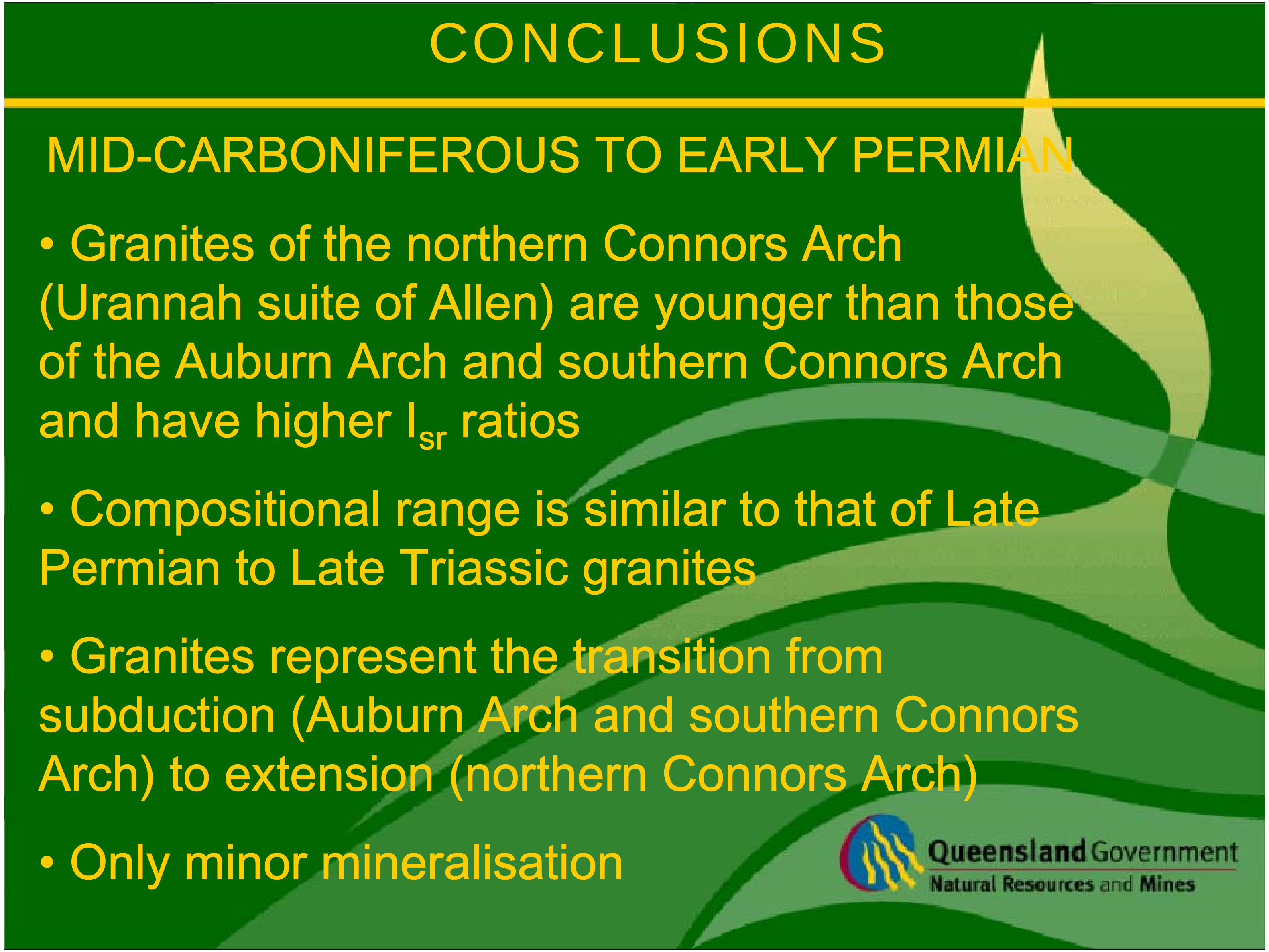
CONCLUSIONS
MID-CARBONIFEROUS TO EARLY PERMIAN
• Granites of the northern Connors Arch (Urannah suite of Allen) are younger than those of the Auburn Arch and southern Connors Arch and have higher I_{sr} ratios
• Compositional range is similar to that of Late Permian to Late Triassic granites
• Granites represent the transition from subduction (Auburn Arch and southern Connors Arch) to extension (northern Connors Arch)
• Only minor mineralisation
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CONCLUSIONS

LATE PERMIAN TO LATE TRIASSIC

- Similar range of compositions to New England Batholith, but different proportions
- No systematic compositional trends with time except for several Late Triassic A-type granites
- Subduction origin favoured, changing to extensional magmatism in the Late Triassic due to slab rollback
- Age range of intrusions completely overlaps that of the compressional Hunter-Bowen Orogeny
- Associated with a wide range of mineral deposit styles

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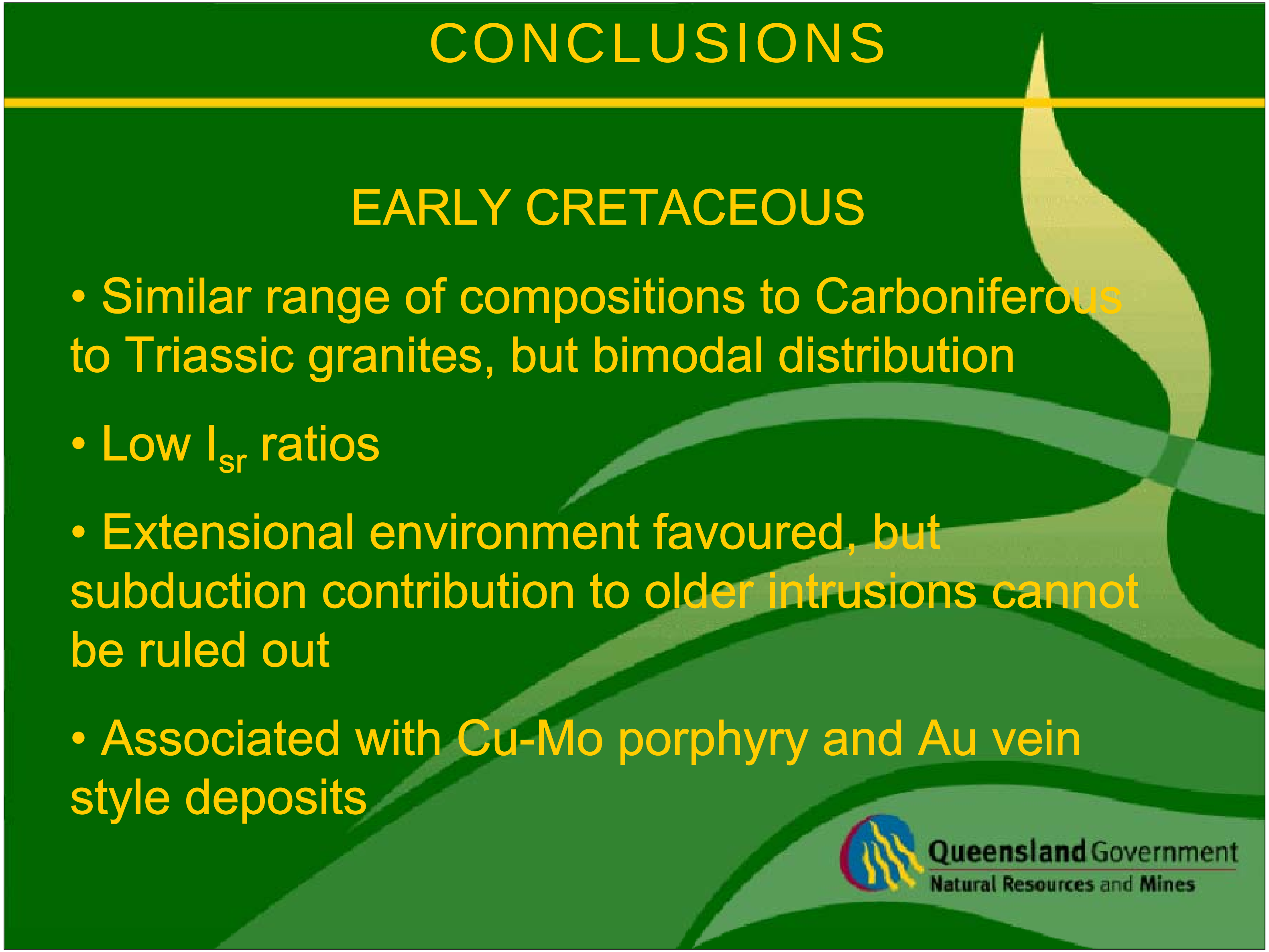
CONCLUSIONS
EARLY CRETACEOUS
• Similar range of compositions to Carboniferous to Triassic granites, but bimodal distribution
• Low I_{sr} ratios
• Extensional environment favoured, but subduction contribution to older intrusions cannot be ruled out
• Associated with Cu-Mo porphyry and Au vein style deposits
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