thorium and their daughter products inside of the plutons.

Recent studies suggest that the gold mineralisation is related to a mixing of fluids, which produce distinctive fluid inclusions in quartz associated with the gold mineralisation (Sheppard et al., 1991). The gold mineralisation has a distinctive geochemical association, which in combination with the fluid inclusion data provides a preliminary method of assessing the economic potential of anomalous mineralisation. The fluid inclusion and geochemical studies both implicated a significant input from a granite source during mineralisation. Two studies were then commissioned to assess the role of granites belonging to the Cullen Batholith had in the formation of ore deposits in the Pine Creek Geosyncline; especially gold mineralisation. The main aims of the study were to provide a set of criteria that could be used to prioritise exploration targets in the Pine Creek Geosyncline and possibly in other Precambrian terrains.

The Cullen Batholith in the Pine Creek Province is associated with a very broad scale of hydrothermal deposits showing contrast in spatial distribution and style, temperature and timing of the mineralisation (Fig. 2). The association of the mineralisation with the granites and their thermal aureole suggests that many of the mineral deposits were formed during the initial intrusive and the following cooling phase of the Batholith. In particular, deposits characterised by relatively high-medium formation temperatures such as the tin and gold mineralisation must have been associated with these stages. There exists, however, evidence that other deposits were formed at significantly later times than the original intrusions (eg uranium and epithermal lead mineralisation).

The majority of the granites in the Cullen Batholith have a concentration of radioactive elements significantly above that typical of granites (Plant et al. 1985). As a consequence, they are characterised by unusually high heat production and heat flow rates. Because they also are in an advanced state of fracturing and weathering, these granites are potential sites for post-magmatic hydrothermal convection in response to radioactive heat production.

The Cullen Batholith is associated with radioactive heat generation between $4.02–9.96 \pm \mu W/m^3$ or 9.6–23.9 HGU ($1\ HGU = 0.417 \pm \mu W/m^3 = 3.16\ cal/m^3/year$) generated by approximately 12 ppm U, 40 ppm Th and 4 % K. With the average heat production value of $5.79 \pm \mu W/m^3$ (13.9 HGU or 44 $cal/m^3/year$) the Cullen Batholith is over two times higher than the average granite heat production at $2.5 \pm \mu W/m^3$ (equivalent to 19 $cal/m^3/year$).

As discussed above granitoids and their contact halos appear to be important in the genesis of most if not all mineral deposits in the Pine Creek Geosyncline. This may be due to heat input, fluid input or gold source. Field observations indicate that gold deposits occur within or just outside the contact metamorphic halos of granites. Regional structure, particularly regional anticlines associated with duplex thrust fault systems, appear to be the main control on mineralisation. However the reasons for this association are not clear and this will be addressed in this study.

2. Regional Geology, Stratigraphy and Geochemistry

2.1. Geology and Stratigraphy

The Pine Creek Geosyncline is an Early Proterozoic inlier of approx. 66 000 km^2 in area (Needham et al., 1980 and Stuart Smith et al., 1993). The geosyncline comprises a supracrustal sequence that consists predominantly of fine grained clastic sediments, BIF's, minor evaporites and platform carbonates, acid volcanics and basic intrusive rocks which overlay granite migmatite complexes of Archaean age (ca 3300–2400 Ma using Sm-Nd age dating, Rb-Sr whole rock ratios and zircon U-Pb ion microprobe zircon ratios as dating methods). Sedimentation and volcanism occurred between 2 000 to 1870 Ma forming an intracratonic basin, approximately 10 kilometres thick, by crustal extension of the predominantly Archaean granitic basement. This was followed by the intrusion of dolerite sills, complex multiple deformation, regional metamorphism and granitoid intrusion with associated contact metamorphism. The intrusion of granitoids was accompanied by the extrusion of felsic volcanic rocks in the Katherine region. These volcanics rest unconformably on the Early Proterozoic metasediments as do the largely undeformed Middle and Late Proterozoic, Palaeozoic and Mesozoic strata as well as Cainozoic sediments and laterite.

The stratigraphy of the Pine Creek Geosyncline is summarised in Table 1. The age of basement granitoids in the Nanambu Complex and the intrusive Nimbuwah Complex confine the depositional age of the strata between 2470 Ma and 1870 Ma (Stuart Smith et al., 1993). Age determinations from a tuffaceous unit in the Mt. Bonnie formation gave 1885 ± 2 Ma, which constrains the depositional environment between 2000 Ma and 1880 Ma.

The oldest unit preserved locally is the Namoona Group, which contains the Masson Formation and Stag Creek Volcanics. A broad two fold stratigraphic sequence has been recognised in the Masson Formation with a lower unit of shale and siltstone with rare dolomite interbeds and an upper carbonaceous shale and siltstone sequence. About a fifth of the formation comprises quartz-feldspar sandstone and pebble conglomerate similar to the Mundogie Sandstone.

The Noonamah Group also contains minor tuff, tuffaceous siltstone and greywacke of the Stag Creek Volcanics. These are poorly exposed and deeply weathered. Clastic and minor chemical sediments of the Mount Partridge Group either unconformably or disconformably overlie the Noonamah Group units. This group consists of the Mundogie Sandstone and the Wildman Siltstone. The Mundogie Sandstone ranges in thickness from less than 300 metres east of the Mary River to 1200 metres in the Mt. Masson area. The unit comprises an interbedded sequence of psammite and minor conglomerate and pelite. Over 50 % of the formation comprises coarse to pebbly feldspathic quartz sandstone and arkose. The remainder of the formation comprised of siltstone and rare pyritic shale. The Wildman Siltstone is

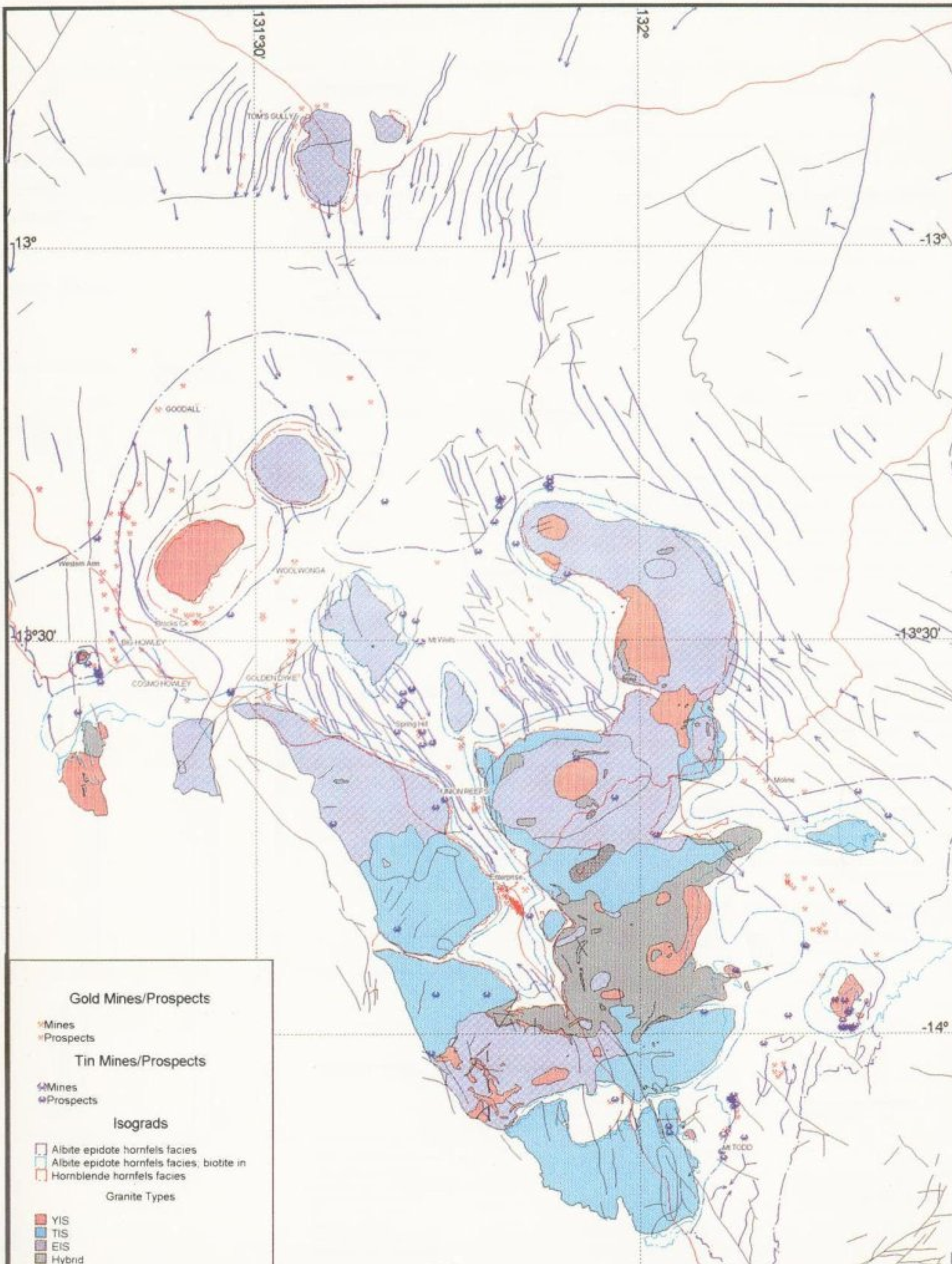

Figure 2. The Cullen Batholith mineral field.

Table 1. Central Pine Creek Geosyncline stratigraphy (Nicholson et al., 1994)

AGE	Walpole et al. (1968)	Needham, Crick and Stuart-Smith 1980	STRATIGRAPHIC UNIT (Nicholson et al., 1994)		ESTIMATED THICKNESS (metres)			LITHOLOGIES
JURASSIC - CRETACEOUS				Petrel/Bathurst Island Formation	15-1350			sandstone, siltstone
CAMBRIAN - ORDOVICIAN			DALY RIVER GROUP		260-550			conglomerate, basalt, sandstone, limestone, dolomite
ADELAIDEAN			TOLMER GROUP		1430			sandstone, conglomerate, dolomite
CARPENTARIAN			KATHERINE RIVER GROUP		2750			sandstone, basalt, andesite
CARPENTARIAN			EDITH RIVER GROUP		1200			rhyolite, sandstone, conglomerate basalt
CARPENTARIAN			EL SHERANA GROUP					rhyolite, sandstone, basalt
EARLY PROTEROZOIC	FINNISS RIVER GROUP	FINNISS RIVER GROUP	CENTRAL PINE CREEK GEOSYNCLINE: FINNISS RIVER GROUP	Burrell Creek Formation (marine)	> 4000	>2900	UPPER	greywacke, grit, mudstone
						> 2000	LOWER	greywacke, mudstone, conglomerate
	GOODPARLA GROUP: Golden Dyke Formation	SOUTH ALLIGATOR GROUP	FRANCES CREEK GROUP	Mt Bonnie Formation (marine)	150–400	5–30	UPPER	iron formation, mudstone
						50–300	MIDDLE	tuffaceous albitic chert mudstone
						50–200	LOWER	greywacke, mudstone, carbonaceou mudstone, tuffaceous albitic chert
				Gerowie Tuff (volcanic, marine)	200–400			tuff, mudstone, chert, siltstone, tuffaceous albitic chert
				Koolpin Formation (shallow marine, marine)	300–1000	50–100	UPPER	carbonaceous mudstone
						10–100	MIDDLE	iron formation, mudstone
						200–700	LOWER	carbonaceous mudstone, limestone, siltstone, greywacke
	GOODPARLA GROUP: Acacia Gap Tongue	MT PARTRIDGE GROUP		Acacia Gap Quartzite/Mundogie Sandstone (marine)	0–1000			quartzite, greywacke, conglomerate, carbonaceous mudstone
	GOODPARLA GROUP: Golden Dyke Formation			Whites Formation (shallow marine - marine)	500–1400	200–400	Ppl 5	carbonaceous slate, quartzite, sericitic tuffaceous mudstone
						150–300	Ppl 4	slotted carbonaceous slate, carbonaceous slate, sericitic tuffaceous mudstone
						50–100	Ppl 3	carbonaceous dolomitic slate, sericitic tuffaceous mudstone
						200–500	Ppl 2	dololutite, carbonaceous dolomitic slate, sericitic tuffaceous mudstone
						100–300	Ppl 1	carbonaceous dolomitic mudstone, sericitic slate
	BATCHELOR GROUP		BATCHELOR GROUP	Coomalie Dolomites (shallow marine, evaporitic)	200–800			dolomite, magnesite
				Crater Formation (fluviatile)	200–900			conglomerate, sandstone, shale, hematitic siltstone
		NAMOONA GROUP		Celia Dolomite (shallow marine, evaporitic)	0–1000			dolomite, magnesite
				Beestone Formation (fluviatile)	0–1200			conglomerate, sandstone, pebbly arkose
ARCHAEAN / EARLY PROTEROZOIC			DIRTY WATER METAMORPHICS LITCHFIELD COMPLEX MYRA FALLS METAMORPHICS NOURLANGIE SCHIST CAHILL FORMATION KAKADU GROUP RUM JUNGLE COMPLEX WATERHOUSE COMPLEX					schists, gneiss, iron formation, amphibolite, quartzite, marble, meta arkose
ARCHAEAN			MYRA FALLS METAMORPHIC LITCHFIELD COMPLEX RUM JUNGLE COMPLEX WATERHOUSE COMPLEX WOOLNER GRANITE					granite, gneiss

exposed in the Frances Creek area, along the eastern margin of the Burnside Granite and in the cores of the Burrundie Dome, to the south of the Howley Anticline and in the Mt. Bundey area. The formation is predominantly a pelitic sequence containing up to 10 % psammitic rocks, it has been divided into two members on the basis of dominant lithology (Stuart-Smith, 1985). The Wildman siltstone conformably overlies the Mundogie Sandstone and is overlain by the Koolpin Formation. The pelitic rocks in the formation are comprised of carbonaceous mudstone, siltstone and shale. Ironstone lenses similar to those found in the lower Koolpin Formation occur near the base of the unit. Sandstone and siltstone with rare dolomite beds are more common towards the top of the sequence.

The rocks which have been assigned to the South Alligator Group occur in the north and south of the Pine Creek Geosyncline and form the core of the Howley Anticline, the flanks of the Batchelor Dome, the Burnside Granite, Mt Bundey Granite and the Burrundie Dome areas. The South Alligator Group consists of the Koolpin Formation, which is comprised of a series of alternating mudstones, shales, carbonaceous pyritic shales, ironstones and yellow claystones. The upper contact of the Koolpin with the Gerowie Tuff has generally been the focus for the intrusion of sills of Zamu Dolerite. The lithologies belonging to the Gerowie Tuff, which lie stratigraphically above the rocks of the Koolpin Formation, comprise a sequence of bedded chert, tuff, mudstone and yellow and grey/blue siltstone, tuffaceous greywacke and nodular mudstone. Many of the cherts are finely laminated and contain cross-bedding. The upper part of the South Alligator Group is comprised of the Mt. Bonnie Formation, which occurs stratigraphically above the cherts which form the Gerowie Tuff. The first occurrence of the Mt. Bonnie Formation is taken to be a coarse-grained greywacke, which forms a distinctive marker horizon along the eastern limb of the anticline. The main rock types consist of alternating mudstones, greywackes and thin ironstone horizons.

The Burrell Creek Formation conformably overlies or is faulted against the Mt. Bonnie Formation and is the only member of the Finniss River Group. The formation crops out extensively throughout the area of the Cullen Batholith, forming more than 50 % of the outcrop. This formation generally consists of tombstone-like outcrops of massive dark grey greywacke, interbedded with red-brown phyllite, locally a pebble conglomerate with dacitic clasts and rare lenses of altered felsic to intermediate felsic volcanics. A red to olive green siltstone comprises up to 70 % of the formation. This lithology can contain sulphide-rich horizons and cross bedding. The siltstone is interbedded with 2 to 10 metre thick greywacke units. The beds are lithic often grading into conglomerate with volcanilithic clasts. Rare bodies of medium grained altered intermediate to felsic volcanics occur near the Margaret Granite and south of the Union Extended Mine.

Two groups of Early to Middle Proterozoic volcanic sequences overlie the Lower Proterozoic sediments. These include sandstone, rhyolite, amygdaloidal mafic volcanics and turbidites of the El Sherana Group, which appear to have formed between 1870 and 1860 Ma, and sandstone, conglomerate rhyodacite, rhyolite, ignimbrite and tuffs of the Edith River Group which appears to be co-magmatic with the Cullen Batholith in 1830 Ma.

The sediments of the Koolpin, Gerowie Tuff and Mt. Bonnie Formations are intruded at various levels by thin sills of dolerite. The dolerites also occur as pods and sheets which cross-cut bedding, but have been metamorphosed and deformed along with the sediments. The sills, regionally termed the Zamu Dolerite, are dominantly a massive greenish, fine to medium grained quartz dolerite (Stuart-Smith, 1985). Descriptions of the dolerite with detailed petrology and geochemical analysis can be found in Ferguson and Needham (1978).

2.2. Geochemistry

Ferguson (1980) collected 350 samples of the various lithologies that comprise the sedimentary sequences in the Pine Creek Geosyncline. These samples were analysed for 41 elements. Ewers et al. (1985) followed this study with a more detailed study on whole-rock and trace element trends for various parts of the stratigraphy. The means and standard deviations for the various elements for the four main stratigraphic groups, and the average compositions for the three major rock types that comprise these groups are given in Table 2. There appears to be a metal enrichment at the base of the Noonamah Group, which is interpreted to be related to felsic and mafic volcanism. Values up to 30 ppb Au, 60 ppm Cu, 40 ppm Pb and 100 ppm Zn occur in these lower groups. Higher in the sequence, especially within the South Alligator Group, base metal values and As are anomalously high. These can reach up to 10 ppb Au, 80 ppm Cu, 60 ppm Pb and 140 ppm Zn. The higher base metal content of these rocks is interpreted to relate the black shale/felsic volcanic component to this group.

One interesting feature of the study by Ewers et al. (1985) is the lack of enrichment in metals in carbonaceous pelites in comparison to ordinary pelitic sediments. This also includes gold. It is clear from Table 2 that contrary to recent suggestions by such authors as Nicholson and Eupene (1990), Goulevitch (1980) and Nicholson et al. (1994) the best source rocks for gold mineralisation are not the carbonaceous shales of the South Alligator Group, but rather the rocks of the lower stratigraphy, mainly within the Noonamah Group. This enrichment may be related to mafic volcanism which occurred as the Pine Creek Geosyncline opened, although the upper stratigraphic units do not appear to be the best candidates for sourcing gold mineralisation, their carbonaceous content iron content and chemical variability, often related to felsic volcanism, makes the lithologies of both the Finniss River and South Alligator Groups the ideal chemical reactants for depositing gold mineralisation.

Table 2. Average composition of Early Proterozoic clastic sedimentary rocks from the Pine Creek Geosyncline (Ewers et al. 1985)

	FRG		SAG		MPG		NG	
(%)	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
SiO_2	69.55	6.91	66.61	10.33	67.42	15.75	58.43	10.73
TiO_2	0.51	0.10	0.44	0.28	0.47	0.35	0.84	0.79
Al_2O_3	14.39	2.99	14.79	4.18	13.95	6.85	12.92	4.37
Fe_2O_3	1.83	1.24	1.48	1.20	1.61	1.59	1.93	1.56
FeO	3.08	1.91	3.03	2.30	3.04	3.29	4.16	4.09
MnO	0.06	0.08	0.11	0.22	0.04	0.06	0.07	0.06
MgO	1.66	0.78	2.26	1.51	3.26	4.46	7.19	5.79
CaO	0.63	0.61	0.81	1.64	0.87	1.73	3.13	3.97
Na_2O	1.28	0.78	1.18	1.30	0.67	0.91	0.89	1.31
K_2O	3.61	1.21	4.80	1.92	3.41	2.08	2.74	2.32
P_2O_5	0.15	0.19	0.09	0.05	0.08	0.04	0.20	0.17
$H_2O_{(tot)}$	2.63	1.01	2.48	1.18	3.22	2.28	3.99	2.23
CO_2	0.35	0.71	3.12	4.14	1.91	3.07	2.75	2.83
Total	99.73		101.20		99.95		99.24	
ppm								
As	11	18	11	14	4	6	< 1	-
Au	0.005	-	0.006	0.004	0.005	-	0.011	0.017
B	64	33	74	57	83	99	50	59
Ba	671	262	642	390	551	308	518	411
Be	2	1	3	1	2	2	2	1
Ce	86	19	86	39	47	34	52	29
Co	15	7	16	12	16	12	26	18
Cu	21	41	41	42	20	20	32	30
F	655	349	1023	510	574	574	878	657
Ga	18	5	20	9	16	9	17	6
La	43	10	45	21	25	21	28	16
Li	18	8	26	24	33	26	34	23
Mo	3	5	1	-	3	-	7	10
Nb	9	2	11	3	8	6	10	9
Ni	20	8	32	34	41	54	48	27
Pb	21	28	29	34	11	10	16	23
Rb	151	61	193	80	115	81	83	70
Sn	3	2	3	4	2	-	2	-
Sr	78	82	71	53	63	66	77	105
Th	19	3	24	14	16	21	13	14
U	4	1	6	3	4	4	3	5
V	94	40	97	84	96	81	159	121
W	3	-	3	-	3	-	3	-
Y	28	17	27	10	15	9	20	8
Zn	116	183	75	68	53	41	61	48
Zr	176	52	156	58	144	102	138	64
No. of samples	26		39		60		14	

FRG, Finniss River Group; SAG, South Alligator Group; MPG, Mouth Partridge Group; NG, Namoona Group. Only six samples from the FRG, 15 samples from the SAG, 13 samples from the MPG, and six samples from the NG were analysed for Au. CO_2 values are for total carbon expressed as CO_2.

	Pelitic rocks		Arenaceous rocks		Carbonates	
(%)	mean	s.d.	mean	s.d.	mean	s.d.
SiO_2	60.27	11.62	78.03	11.40	11.80	10.36
TiO_2	0.52	0.26	0.36	0.38	0.09	0.10
Al_2O_3	15.77	4.90	9.82	4.57	1.84	1.96
Fe_2O_3	2.00	1.63	0.86	0.69	0.37	0.53
FeO	3.45	2.58	2.06	2.92	1.20	0.91
MnO	0.08	0.16	0.04	0.06	0.11	0.09
MgO	4.05	4.53	1.52	2.25	27.98	15.00
CaO	1.59	3.39	0.74	1.60	15.12	12.79
Na_2O	0.79	1.04	1.15	1.13	0.05	0.09
K_2O	4.23	2.02	2.68	1.46	0.48	0.77
P_2O_5	0.11	0.12	0.09	0.06	0.07	0.05
$H_2O_{(tot)}$	3.47	1.83	1.76	1.44	0.82	1.13
CO_2	4.36	7.46	0.72	1.53	39.70	9.04
Total	100.69		99.83		99.63	
ppm						
As	10	18	5	14	1	-
Au	0.005	-	0.008	0.015	-	-
B	79	50	65	117	59	74
Ba	601	376	556	265	102	290
Be	3	1	2	2	1	-
Ce	67	36	53	39	8	10
Co	19	13	9	7	4	4
Cu	33	38	11	10	6	12
F	961	532	328	365	380	482
Ga	20	8	11	6	2	3
La	35	20	27	20	4	5
Li	33	22	17	22	8	19
Mo	3	5	1	-	3	3
Nb	10	5	6	5	2	-
Ni	44	46	13	8	7	7
Pb	22	28	14	17	2	-
Rb	164	85	85	52	11	18
Sn	2	3	2	-	2	-
Sr	70	69	67	70	42	50
Th	19	11	14	12	3	4
U	6	3	3	3	1	-
V	116	75	61	68	18	23
W	3	-	3	-	3	-
Y	22	12	16	12	7	5
Zn	84	89	48	111	14	11
Zr	137	54	159	87	29	43
No. of samples	91		38		25	

Only 28 pelitic rocks and eight arenaceous rocks were analysed for Au. CO_2 values are for total carbon expressed as CO_2.