PRELIMINARY REPORT ON THE GEOCHEMISTRY OF SOME UNWEATHERED ROCKS FROM THE GROUNDRUSH DEPOSIT, TANAMI REGION

Summary

- Ti/Zr classification has confirmed the presence of two mafic/intermediate igneous suites – dolerite and primitive diorite
- Most mineralisation appears to be hosted in the diorite
- Two chemically and spatially distinct but probably cogenetic dolerites were identified
- Chemical variation in dolerite is consistent with fractionation/sorting of plagioclase and clinopyroxene
- The diorite appears to be a relatively chemically homogenous body with little evidence for crystallisation-controlled chemical variation
- It is strongly and pervasively mineralised and probably metasomatised, but this has not yet been quantified.
- Sampling of least-altered diorite is required to establish baseline chemistry
- Diorite-hosted mineralisation is associated with quartz and pyrite. No significant association with base metals or arsenic was found.
- The next stage of research will comprise petrological and SEM-Probe investigation

Sampling and Analysis

A suite of 108 samples was collected and analysed for the purpose of constraining the lithogeochemistry of the primary ore-hosting and surrounding rocks at Groundrush. Samples comprised diamond drillcore from holes GHD 8, 60 and 62, grab samples from the southern end of Groundrush Pit 4 and two whole-rock standards, a basalt and a quartz arenite, supplied by CRS. The breakdown of sample types is given in Table 1, where 9+5 refers to nine samples with five submitted in duplicate, for a total of 14 analyses. Sample numbers were allocated in a random sequence

Samples comprised fine to medium grained grey igneous rock of (meta-) doleritic (amphibole-phyric) to dioritic (sparsely quartz-phyric) appearance, sedimentary rocks, ranging from coarse grained arenite to grey siltstone, tonalitic and basaltic dyke material and breccia. This report discusses the dolerite and diorites only.

Table 1. Sample lithologies and source

	GHD 8	**GHD 60**	**GHD 62**	**Pit 4 grab**	**Standard**	
Dolerite	**12**	**9+5**	**16**			42
Diorite	**13**	**1**	**26+3**			43
Sedimentary		**10**	**1+1**		**3**	15
Basalt				**2**	**3**	5
Tonalite				**2**		2
Other			**1**			1
	25	25	48	4	6	108

GHD 8 intersected sedimentary rocks to 139m downhole, followed by mafic igneous rocks to end-of hole at 215m , chemically divided into dolerite to 163m and diorite from there until at least the end of the sampled interval at 189m. Hole 60 similarly intersected sedimentary rocks to 205m, dolerite to 270m, sedimentary rocks to 308m, then a dolerite/diorite unit to 363m, before terminating in sedimentary rocks at 379m. Hole 62 also commenced in sedimentary rock, then passed through a dolerite (170-237m), then diorite (237-301m), brecciated from 291m, before ending in a fault breccia and sandstone at 315m. High grade gold mineralisation in present in holes 8 and 62, hosted dominantly, although not exclusively, within diorite. GHD 60 and 62 are on Section 25250N and GHD 60 passes approximately 100m vertically beneath GHD 62. GHD 8 is collared 350m further south on 24900N.

Core samples comprised approximately 20 cm lengths of either ¼ or ½ HQ diameter core selected from within an interval of either one or one-half metre, depending on the original company sampling interval. Downhole sample locations were selected (a) to represent the lithologies present, principally the mafic/intermediate rocks, (b) to obtain samples ranging from apparently unmineralised to strongly mineralised, and, (c) to focus on the zones peripheral to high-grade mineralisation by collecting close spaced samples while adopting a broader sample spacing through unmineralised or uniformly mineralised zones. Within the selected interval, the actual sample was selected to represent as best possible the host rock and minimise exotic vein material. In some veined and brecciated zones such material could not be avoided.

Analyses were completed by Ultratrace, Perth. Major and some minor elements were determined by fusion/XRF. A suite of minor, mainly chalcophile, elements, gold and majors Ca, Fe, Mg and Mn, which may be present in carbonate or sulphide minerals, was determined by mass spectrometry following an aqua regia digest. Th, Ta, Y and Nb were assayed by mass spectrometry after a fusion digest, and CO2 was determined by LECO. Loss on ignition was recorded at four temperatures up to 1000ºC.

Lithological Discrimination

The small amount of geochemical data previously collected by Groundrush staff suggested that the host rock comprised two lithological associations, a dolerite *sensu stricto* and a more evolved rock with the composition of a primitive diorite. Major element oxides such as SiO2 and MgO differentiated these units, as did Ti/P ratios. It was considered that the dioritic unit represented a more fractionated variant of the dolerite, a conclusion supported by consultant petrographers' reports.

The ratio of high field strength elements titanium to zirconium has been widely used to classify and discriminate felsic to mafic igneous rocks, following Halberg. Zirconium analyses were not available from the previous dataset. However, clues to the nature of the Groundrush dolerite were uncovered during the initial exploration stages at Groundrush, when samples from two RAB drillholes were assayed for Ti and Zr, along with may other elements. These gave a ratio of around 42, based on acid digests. Previous comparisons of acid-soluble to total Ti and Zr, eg Boddington data, suggest that most Ti and between one half and one third of the Zr reports to the acid digest. Therefore the values of around 42 are likely to represent maxima, with the real ratio lower. Basalts and dolerites have Ti/Zr ratios of over 60, hence these data point towards a more evolved composition.

Returning to the present dataset, Figure 1 shows Ti/Zr ratios plotted against raw SiO2 values. The division between dolerite and diorite is apparent. The dolerite samples have, as a result of Pearce Element Ratio ("PER") analysis discussed later, been further divided into high and lower Mg/P groups, denoted high-Mg and low-Mg in the following text and figures. Some samples show anomalously high SiO2, a result of incorporation of quartz vein material, however Ti and Zr are equally diluted and their ratio unaffected.

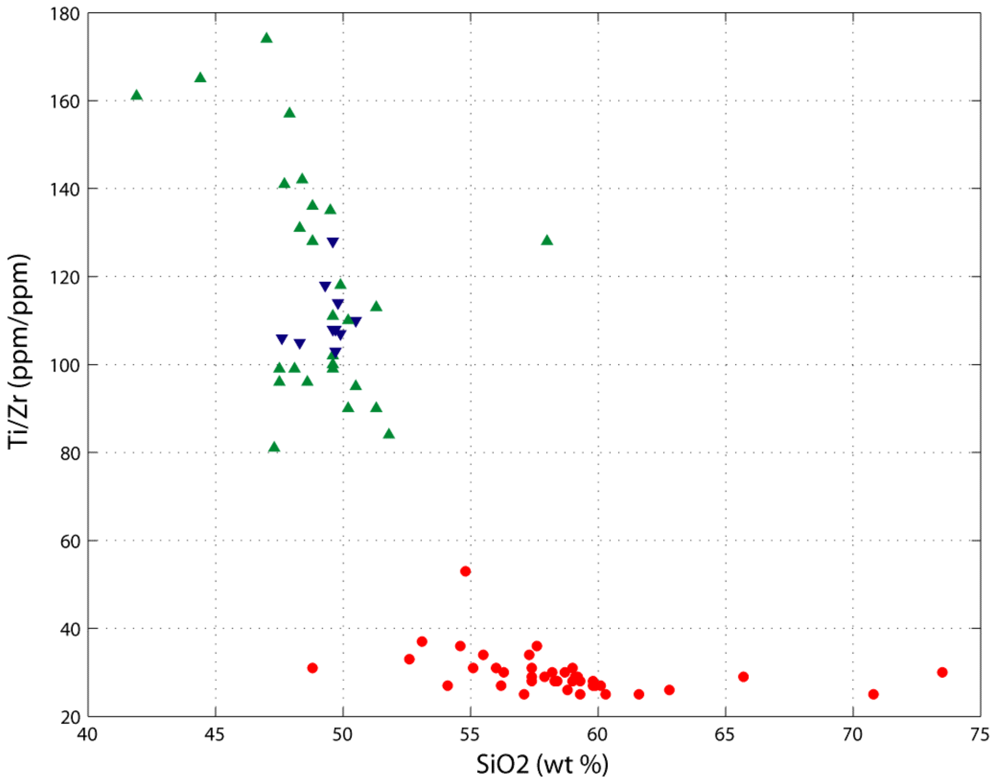

Fig. 1. Ti/Zr ratio against SiO2 wt %. Symbols: red circles – diorite, green triangles – low-Mg dolerite, blue triangles – high-Mg dolerite.

Conserved Constituent Analysis

Titanium and zirconium are incompatible elements, not commonly partitioned to any significant extent into major rock-forming or alteration/weathering minerals. Ratios, therefore, tend to survive the main material transfer processes. Other potentially incompatible elements in the dataset are phosphorous, yttrium, thorium, tantalum and niobium.

Conserved elements for a given geological process are those which do not participate in the process. Incompatible elements are commonly conserved. Whether an element behaves compatibly or otherwise depends on the nature of the process; for example potassium may be incompatible in picrite but compatible in granite.

Conserved elements may be used to test the cogenetic hypothesis – whether two suites of rocks are (strictly, are *not*) related by a material transfer process in which the given element or elements, were conserved. A suite of rocks related by a material transfer process in which two or more elements were conserved, retain a consistent ratio of these elements. This is equivalent to them plotting on a straight line though the origin on a scatteplot. Conversely, if ratios of conserved elements differ between groups, the groups cannot be cogenetic if the conserved elements are indeed conserved. Therefore incompatible elements can be used to determine whether the diorite represents a fractionated product of the dolerite or is genetically distinct.

The identification of a conserved element is essential for PER analysis, as it is the variation in abundance of the conserved element that recovers the system size change information and enables the PERs to model extensive processes.

Of the potentially conserved elements in the dataset, thorium, tantalum and niobium have very low abundances, which would lead to very high propagated ratio errors. Similarly, yttrium, while more abundant than these, barely reaches 100 ppm. Zirconium is more abundant, particularly in the diorites, but dolerites commonly report less than 100 ppm. Phosphorous and titanium are present in the thousands of ppm to low percentage values.

Figures 2 to 4 show the dolerite and diorite samples plotted against titanium, phosphorous and zirconium. Diorite and dolerite samples show different slopes on Figure 1, indicative of different P/Ti ratios. This suggests that diorite does not represent a more fractionated variant of the dolerite. It is a genetically distinct intrusion.

Four veined and brecciated diorite samples show lower abundances of titanium and zirconium but the same ratio. The inclusion of quartz (dominantly) has diluted the conserved elements equally. These samples represent a system size increase (addition of material) over the less-veined diorites.

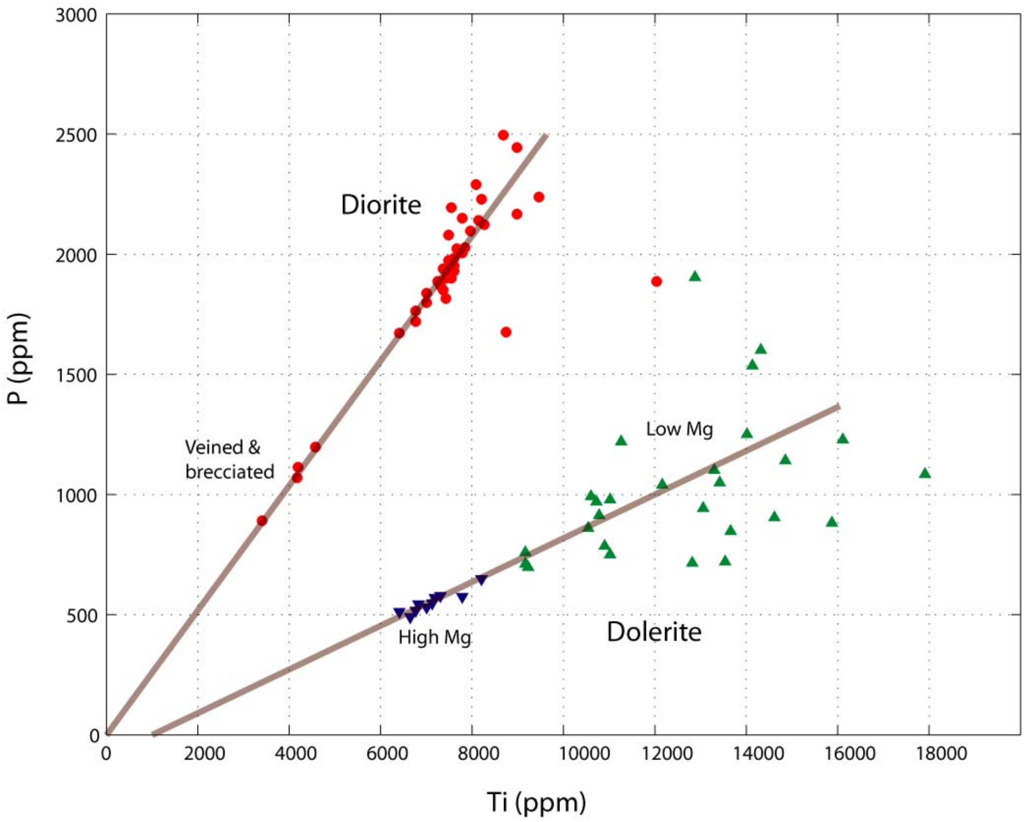

Fig. 2. Conserved constituent scatterplot, P vs Ti. Symbols as per Fig. 1.

The two dolerites occupy the same trend and this diagram does not suggest that they are not cogenetic. However, there is a marked difference in the spread and ratio variation – scatter – between the high and low-Mg dolerites.

The zero-intercept for the diorite trend indicates that both elements are equally conserved, while for the dolerites, given that the line position is more subjective, phosphorous may be more conserved than titanium.

The plot of zirconium against titanium is very similar to that of phosphorous against titanium. The dolerites and diorites have different ratios and again, both elements appear equally conserved for the diorite, and titanium perhaps less conserved than zirconium for the dolerites.

The diagram of zirconium plotted against phosphorous (Figure 4) shows similar ratios for the diorite and dolerite samples, and much less scatter in the latter. The cogenetic hypothesis would be harder to reject on the basis of this diagram alone, as the ratios are similar.

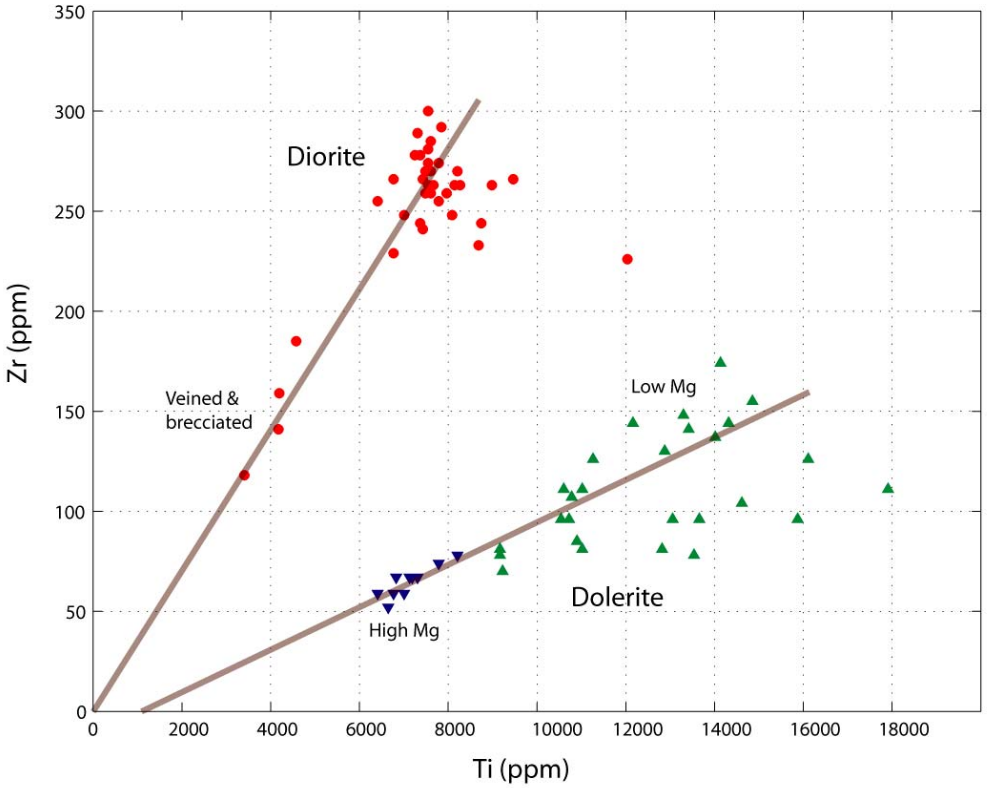

Fig. 3. Conserved constituent scatterplot, Zr vs Ti. Symbols as per Fig. 1.

In conclusion, titanium, phosphorous and zirconium appear to be conserved, with some indication that titanium may be less conserved than the others in the low-Mg dolerites. There is evidence for the lack of cogeneity between the dolerite and diorite – the latter represents a separate intrusion rather than a fractionated variant on the former.

On the basis of its higher abundance, phosphorus has been adopted over zirconium as the conserved element in the PER diagrams following, although the implications of the diagrams are unchanged with either of the other elements as denominator.

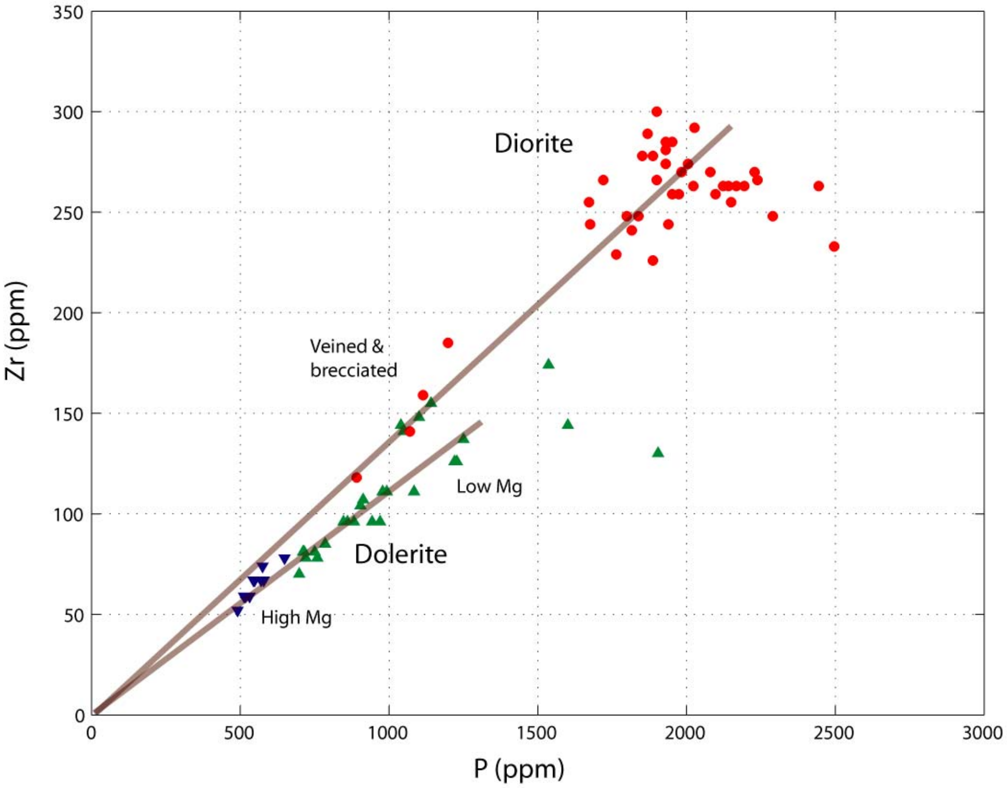

Fig. 4. Conserved constituent scatterplot, Zr vs P. Symbols as per Fig. 1.

Pearce Element Ratio Analysis

PER Assemblage Test ("AT") diagrams are plots of linear combinations of PERs designed to test a hypothesis that the variation in a suite of rocks is attributable to a given geological process. The axes of the diagrams are such that the addition or removal of a given phase or phases causes displacement along a line of unit slope. Within crystalline igneous rocks, much of the chemical variation is due to crystal fractionation and sorting, which modifies both the rock size, as material is added or removed, and its chemistry according to the stochiometry of the added or removed phases. The identification of this source of chemical variation allows the establishment of a baseline against which other geological processes, such as alteration, may be evaluated.

In rocks of doleritic and dioritic composition, the common silicate minerals potentially being added to or removed from the melt include olivine, ortho- and clinopyroxene, plagioclase, amphibole and quartz. AT diagrams can be constructed to test for the involvement of these minerals (except quartz, which with only one analysed element, manifests itself as excess Si).

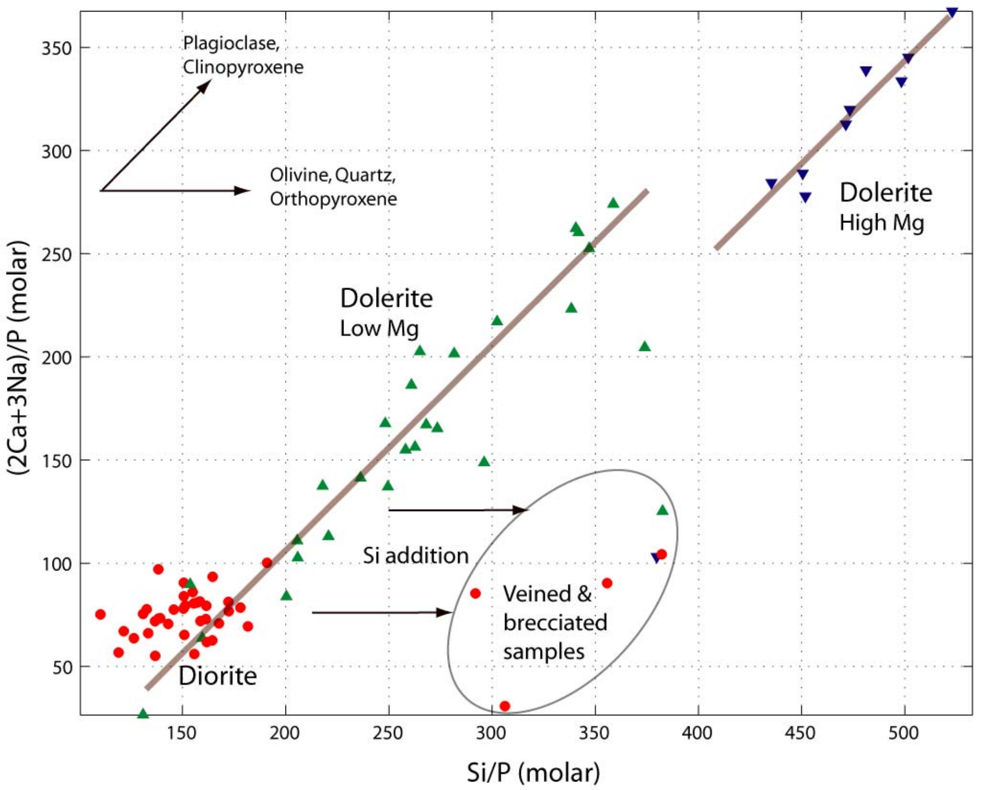

Fig. 5. PER AT diagram to test the application of a Plagioclase – Clinopyroxene fractionation model. Symbols as per Fig. 1.

Figure 5 shows the data plotted on a diagram which will generate unit slope from variation in plagioclase (albite-anorthite solid solution) and clinopyroxene. This is the simplest diagram on which good approximations to unit slopes are generated, the interpretations from which are not voided by another diagram. For example, the dolerites seem to fit better to a unit slope on a plagioclase-olivine diagram, however if the rocks were troctolites, they would also have unit slope a plagioclase diagram with aluminium on the horizontal axis, olivine having no effect on the diagram. However, the trend on such a diagram is considerably greater than one, indicating excess calcium for aluminium in feldspar, probably in clinopyroxene.

The dolerite samples divide into two groups, both of which have very close to unit slope, and so are compatible with the variation model, but are offset from each other. The diorites show much less spread and plot as a cluster. Four diorite and one low-Mg dolerite sample plot well to the left of the line – these are the four veined and brecciated diorites and one veined dolerite sample, and the displacement is due to quartz addition. One high-Mg dolerite with a primitive composition also plots in this region.

Dolerite

It is hypothesised that the high-Mg dolerites represent a more primitive variant in the cogenetic dolerite suite. Both dolerites have excess silica for the amount of Ca and Na needed to form plagioclase and clinopyroxene, and the amount of this excess is higher in the high-Mg dolerite. This excess is likely to be due to the presence of more silica in non-calcic ferromagnesian minerals, such as olivine or orthopyroxene. Figure 6 shows that the high-Mg dolerites also generally contain higher Ni/P than the low-Mg dolerites. The trend for both dolerites on Figure 5 is one, so the variation in the samples is not due to olivine fractionation, however the difference between the high and low-Mg dolerites is consistent with there having been an olivine fractionation event.

Spatially, the upper dolerite in GHD 60 and the upper part of the dolerite portion of GHD 62 comprise high-Mg dolerite. GHD 8, in which the dolerite is apparently thinner, intersected low-Mg dolerite only.

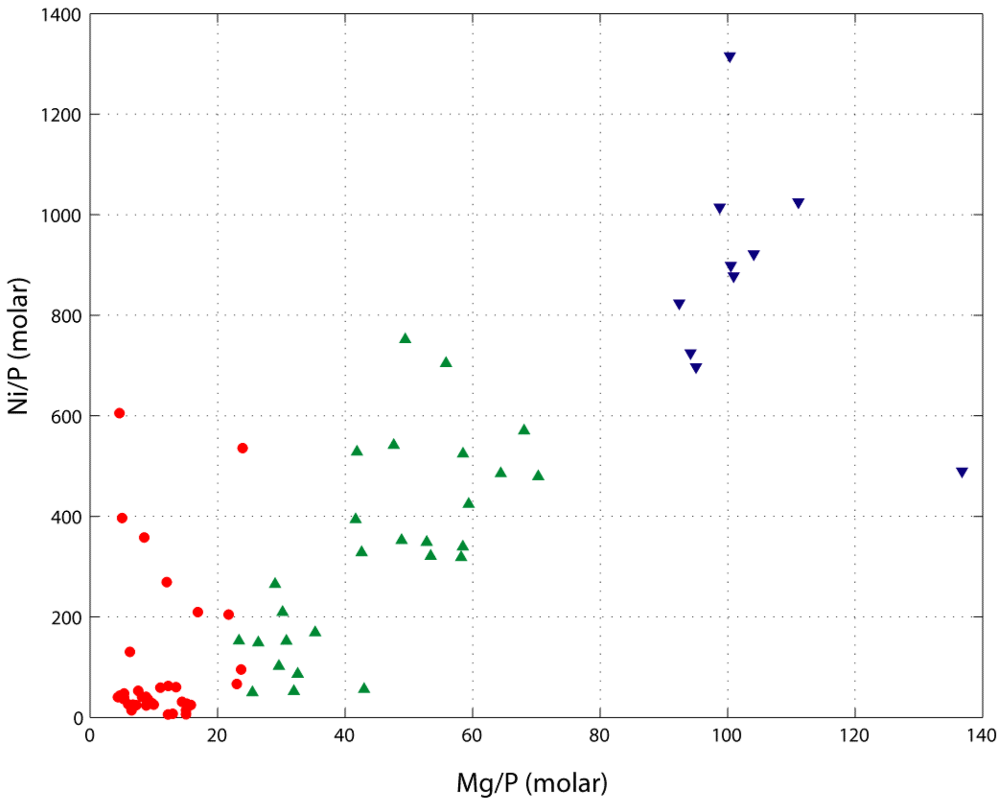

Fig. 6. PER diagram to discriminate dolerite high- and low-Mg dolerite. Symbols as per Fig. 1.

Diorite

Rock of intermediate composition pose a more difficult AT modelling problem than dolerites as the range of minerals which may exercise control over their geochemistry is larger. More siliceous dioritic rocks than these (at Boddington) have been successfully modelled with a combination of plagioclase and hornblende, represented by a tremolite/ferroactinolite – pargasite solid solution. Here, clinopyroxene would also be likely, and quartz phenocrysts have been observed.

The diorite in the three holes is chemically similar and apparently cogenetic, therefore it would be reasonable to hypothesise that diorite samples represent a single intrusion. However there are some differences between samples from holes 8 and 62, with samples from the latter exhibiting higher Mg/P, lower Ca/P and higher acid soluble to total magnesium ratios than those in GHD 8. These holes were collared 350m apart. The single diorite sample from GHD 60 is similar to the samples from GHD 62.

The difficulty of establishing an igneous trend from which to examine alteration-controlled deviations is compounded by the lack of evidence of for significant precursor variation in the rocks. System size change, as modelled by conserved elements, is small, other than in those samples obviously containing veining and other exotic material. Phosphorous contents range from around 0.4 to 0.55 wt % P2O5, a 25-30% size variation. In both GHD 8 and 62, the P content increases systematically up-hole, suggesting a progressive removal of silicate minerals. The same pattern and magnitude of variation is seen in the ZrO2 data. The variation in titanium is perhaps even less; although no clear trend is apparent.

PER-AT diagrams to model combinations of plagioclase, olivine, clinopyroxene and hornblende were constructed. Figures 7 and 8 show the diorite data on olivine-plagioclase-clinopyroxene (“three phase”) and plagioclase-hornblende diagrams, respectively, with points scaled by $Au^{½}$.

Neither diagram shows a convincing fractionation trend, although the eye of faith might argue a unit-slope trend on the three phase diagram. However, no systematic distribution of mineralised samples is evident.

The diorite samples range in grade from 4 ppb to 51.5 ppm gold, with a median value of 707 ppb. Only 13 samples of 44 (including duplicates) report less than 100 ppb and almost half (20 samples) have over 1 ppm gold. Although the samples do not provide an unbiased statistical representation, being preferentially collected around mineralised zones, the data do suggest that the diorite is pervasively mineralised.

Petrological and SEM studies are required. If diorite samples can be sourced from elsewhere in the deposit, more distal to mineralisation, the hypothesis that these rocks have all been metasomatised during mineralisation (and that we are not seeing variation because we too far into the system), may be tested. Thirdly, literature research into the chemistry and mineralogy of similar rocks will be undertaken.

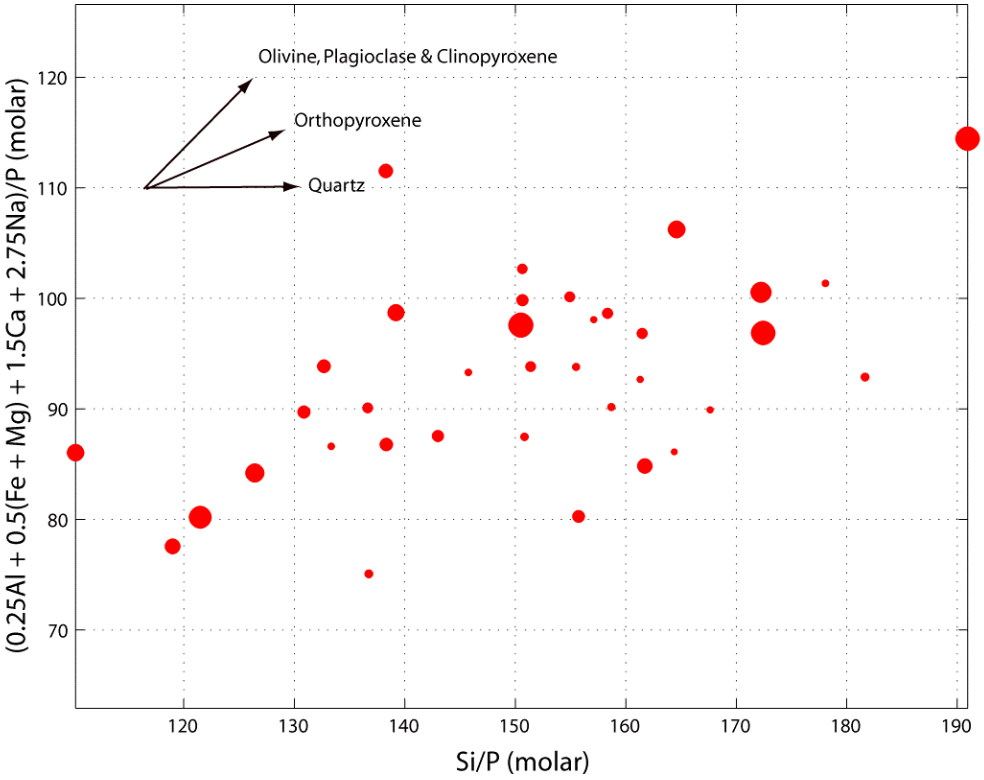

Fig. 7. PER AT diagram for olivine, plagioclase and clinopyroxene, with diorite data plotted. Symbols are scaled by Au (square-rooted). Four veined and brecciated samples plot off the diagram to the right.

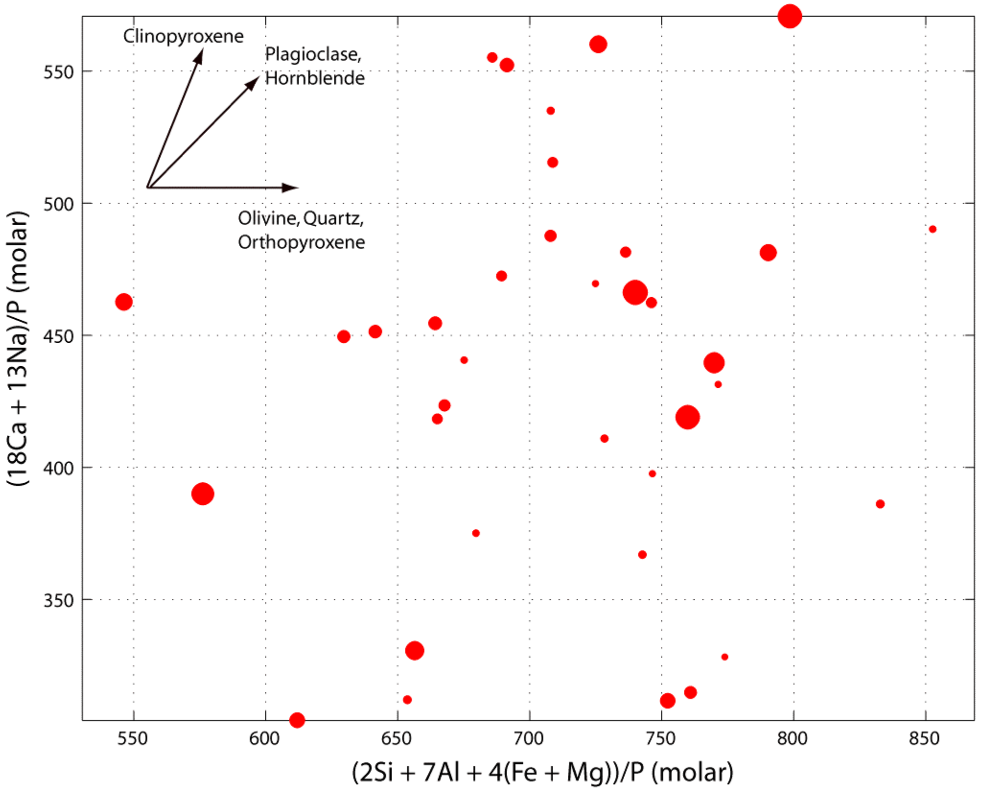

Fig. 8. PER AT diagram for plagioclase and hornblende (tremolite/ferroactinolite-pargasite), with diorite data plotted. Symbols are scaled by Au (square-rooted). Four veined and brecciated samples plot off the diagram to the right.

Mineralisation and Sulphidation

As an alternative to modelling deviation from an igneous trend, could the gold grade be used to indicate which samples are altered? Most gold mineralisation is associated with sulphur, in that all but one high sulphur samples collected (>2% $SO3$) contain over 1 ppm gold and only four of the greater than1 ppm gold samples report less than 1% $SO3$. The major diorite-hosted gold mineralised zones in holes GHD 8 and 62 are associated with high sulphur. Sulphur may provide a better indicator of more significant mineralisation-related alteration than gold alone, as it may be more indicative of bulk rock changes as opposed to brittle veining with minimal alteration.

There is no base metal or arsenic association with gold mineralisation. The only base metal displaying a clear chalcophile association is copper, which reaches a maximum value of 354 ppm. Some high copper samples contain high gold, but these are high in sulphur also.

There is no apparent correlation between the conserved elements and sulphur. The only high sulphur sample in which the conserved elements can be seen to be diluted is high in quartz vein material, which would have a major effect on the conserved element abundance. Either the sulphide was already present in the rocks, or the data has not (yet) resolved the competing material transfer effects – igneous, veining and sulphidation.

If mineralisation were related to a sulphidation event, was iron introduced at the same time? Total iron levels are unrelated to sulphur abundance, suggesting that iron sulphide was formed from iron already in the rock, such as derived from the decomposition of ferromagnesian silicates. The dominant sulphide mineral is pyrite, as indicated by a trend with slope of two on a molar S/P to Fe/P PER diagram within sulphidised samples (molar S/P ratios greater than two, corresponding to SO3 greater than about 1%).

Conclusions and Further Work

The presence of the two rock suites at Groundrush has been confirmed by Ti/Zr ratios. Variation in dolerite chemistry is consistent with crystal fractionation/sorting effects. The diorite, which, on the basis of the samples collected, hosts the bulk of the mineralisation, seems to be a relatively homogenous and undifferentiated body. Mineralisation is associated with quartz veining and sulphidation, which forms pyrite with iron probably liberated from ferromagnesian minerals.

The next stage of investigation involves petrological and SEM studies. Unaltered and unmineralised diorite samples are needed to test the hypothesis that the samples collected to date are pervasively altered. Literature research on similar rocks will be undertaken.