Towards an Understanding of the Effects of Alteration on the Physical Properties of Mafic and Ultramafic Rocks

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SUMMARY

New physical rock property data from the Plutonic Well Greenstone Belt are presented. P-wave velocity (Vp), magnetic susceptibility and density measurements have been taken from rare stratigraphically complete drill core. Preliminary results show that variations of physical rock property data are successful in resolving most lithologies. However, questions remain regarding the interpretation of physical property data involving ultramafic and mafic rock, and, in particular, the effect of alteration.

Variable alteration is suggested to be the cause of the wide ranges within physical property data populations. This problem is not exclusive to the Plutonic Well Greenstone Belt, and is a common feature within many greenstone terranes. Geochemical and mineralogical data are also available from the study area and may allow a better understanding of the effects of common types of alteration (serpentinisation, talc-carbonate alteration) on the physical properties of mafic and ultramafic rocks from granitoid-greenstone terrains.

Key words: Petrophysics; ultramafic; mafic; Plutonic Well Greenstone Belt; Plutonic Gold Mine; serpentinisation; alteration

INTRODUCTION

Petrophysics is the link between geology and geophysics, and is commonly required for reliable 'geological' interpretations of geophysical data-sets. Petrophysical data compilations are becoming more common and accessible, but are often defined in accordance with associated lithology. Lithologically categorised data often possess a wide range and are commonly multi-modal. This may be due to the effects of alteration, which may have at least as much influence as lithology of petrophysical properties (Lapointe et al., 1986; Clark et al., 1992; Bourne et al., 1993; Chopping, 2008; Dentith & Mudge, 2014), but there have been few systematic studies.

Alteration of Ultramafic and Mafic Rocks:
The relationship between metamorphic grade of mafic and ultramafic rocks, subsequent alteration mineralogy, and physical rock properties is not completely understood. It has been suggested that serpentinisation is the most important and widespread alteration process in terms of influencing geophysical responses (Toft et.al, 1990; Dentith & Mudge, 2014). Retrograde serpentinisation is most common, and involves low temperature (≤500°C) hydrothermal alteration of olivine and orthopyroxene to serpentine group minerals (i.e. lizardite, chrysotile and antigorite), brucite and magnetite. Evans et al. (2013) suggest that the precipitation of magnetite is due to the nature of a low temperature environment, reducing oxidisation fluids, and subsequent slow prevailing rates of MgFe diffusion. The hydration of olivine, and accompanying oxidisation of Fe^{2+} and Fe^{3+} is summarised in equation (1). Beard & Hopkinson (2000) note that once all olivine is consumed the oxygen fugacity of infiltrating fluids typically rebounds, and permits a reaction involving methane or CO_2 (equation 2). Consequently, once brucite is replaced (equations 3-6), silica activity is no longer buffered at extremely low values, allowing the formation of talc and other relatively silica-rich phases (equations 7-8), thus potentially allowing for the complete alteration of olivine.

Prograde alteration of serpentinisation involves dehydration and the growth of olivine and talc. However, as noted in Evans (2008), a reintroduction of water would be required in order to sequester ferric iron and hence reverse magnetite-forming serpentinisation, and would be petrologically unlikely. As such, metaperidotites that formed by deserpentinisation usually have an abundance of magnetite, and more magnesium-rich olivine and serpentinites (Evans, 2008). Increasing temperature will lead to imbalances and consumption of H_2O and the subsequent release of H_2. Evans (2008) provides a summary of prograde serpententisation reactionary equations.

Alteration of Ultramafic and Mafic Rocks – A Brief Summary of Petrophysical Consequences:
Metamorphic rocks will generally have higher densities than the rocks they are derived on account of metamorphic reformation into more compact forms. As summarised in Dentith & Mudge (2014), experiments by Miller & Christensen (1997) and Komor et al. (1985) show that bulk density is inversely proportional to the degree of serpentinisation – this is also true for velocity (Christensen, 2004). The reduction in density, despite the creation of magnetite ($5.2 g/cm^3$, Deer et al., 1992) is significant. Toft el al. (1990)

suggests that the creation of brucite (2.39g/cm^3, Deer et al., 1992), and talc (2.58-2.83g/cm^3, Deer et al., 1992), combined with increases in porosity, may attribute to an aggregate decrease in bulk density of up to 0.9g/cm^3.

Contrasting with bulk density and velocity, magnetisation increases with the degree of serpentinisation. Experiments by Toft et al. (1990) show that the logarithmic relationship between degree of serpentinisation and magnetic properties indicates that the rate of production of magnetite increases as the rock becomes more serpentinised. Furthermore, Malvoisin et al. (2012) and Malvoisin et al. (2015) note, that the the effect of serpentinisation is noticeable before the reaction process exceeds 10%, with an increase in recorded magnetisation by two orders of magnitude on account of the development of ferromagnetic magnetite at the expense of paramagnetic olivine and orthopyroxene.

Case Study: Plutonic Gold Mine Area:
The Plutonic Gold Mine area is located approximately 800km north-east of Perth, Western Australia. The Plutonic Gold Mine is situated within the south-eastern end of the Archaean Plutonic Well Greenstone Belt of the Marymia Inlier, located between the Yilgarn and Pilbara Cratons. The early work of Bagas (1999) interprets the north-east trending Plutonic Well Greenstone Belt as a south-east facing complex synclinorium. A northern mafic-ultramafic sequence is separated from the southern sedimentary-mafic sequence by a central, greenschist-facies conglomerate-dominated sedimentary unit – all units within the Plutonic Well Greenstone Belt are encapsulated by granite or gneissic rocks (Fallon et al., 2010). The north-western and south-eastern sequences of the Plutonic Well Greenstone Belt comprise metamorphosed ultramafic and mafic rocks, including komatiites, tholetittic basalt, banded iron formation, chert, arkose and pelites. Contrasting with the central conglomerate sequence, the northern and southern sequences have been metamorphosed to amphibolite facies (Vickery, 2004; Gazley et al., 2014). Proterozoic dolerite dykes transect all greenstone-sequences and contiguous granites (Rowe et al., 2002).

Gold mineralisation at Plutonic Mine is hosted principally in the 'Mine Mafic Unit' as replacement lodes (Rowe et al., 2002; Fallon et al., 2010). The Mine Mafic Unit is sandwiched between ultramafic units: a magnesium-rich talc chlorite schist hanging wall; and variably serpentinised komatiitic footwall. The aggregation of the Mine Mafic Unit and ultramafic sequences is known as the Mine Mafic Package (Nielsen et al., 2015). The Mine Mafic Package is a succession of cm-to-dm-scale thin mafic subaqueous lava flow units interbedded with thin, typically <1m metasediments (Gazley et al., 2015a; Gazley et al., 2015b). The overall thickness of the Mine Mafic Package varies from 30 to 300m.

Limited petrophysical data from the Plutonic Well Greenstone Belt suggest that there is potential for the geophysical identification of the Mine Mafic Package (Birchall, 2012), whilst comparisons between different ultramafic and mafic lithologies and analysis of the sub-populations within specific lithotypes may allow the petrophysical consequences of alteration to be better understood.

METHOD AND RESULTS

Physical property measurements were made on a ~1400m section of diamond drill-core at the Plutonic Gold Mine. Due to a requirement of commercial confidentiality, drill-hole ID and relative depths have been omitted. Selected drill-core was chosen predominantly due to interpreted stratigraphic continuity (Duclaux et al., 2013) of the Plutonic Well Greenstone Belt succession. Recent Hylogger (Duclaux et al., 2013) and portable X-ray fluorescence (pXRF) (Gazley et al., 2011) studies mean the mineralogical and chemical context of the physical property data are well established. Consequently this provides a useful platform from which to study physical property variations associated with different types of alteration.

Methodology
Portable instruments were utilised during the collection of P-wave velocity and susceptibility data. A handheld Acoustic Control Systems UK1401 ultrasonic tester and Terraplus Kappameter KT-10 Plus v2 magnetic susceptibility meter were employed at approximately 5m intervals for the first ~900m of drill-hole length and intermittently thereafter across remaining ~500m of barren basal sediments. Five readings were recorded from each sample using each instrument. An appropriate statistical mean was calculated (Tarling & Hrouda, 1993), compared with geological logs and lithological interpretation, and plotted against an apparent depth scalar (Figures 1 & 2). Density data were calculated using Archimede's principle as per procedures summarised in Emerson (1990). Measurements were made using an A&N HF-3000G precision mass balance using core samples from the aforementioned intervals. The density data were also compared with lithological logs (Figure 3).

Results
The comparison of individual physical rock property measurements with lithological logs is of limited benefit. Large contrasts at unit boundaries as well as general trends may be recognised. In the case of the Plutonic Well Greenstone Belt, magnetic susceptibility appears to be most useful when identifying granitoids, some sedimentary units, and ultramafics– However, susceptibility does not clearly discern between ultramafic units. The sole application of density data is to resolve granitoid and some garnetiferous-amphibolite units – other units are ambiguous on account of sharing similar density variance. Individual P-wave velocity data are only able to confidently resolve talc-chlorite ultramafic schist units that are proximal to shear zones.

The use of multi-petrophysical investigation is more effective in the identification of subpopulations within lithologies. Acoustic impedance data show that two dolerite populations and two talc-chlorite schist populations may be confidently resolved (Figure 4). A composite plot of susceptibility and velocity data (Figure 5) can be used to clearly distinguish ultramafic rocks from all other stratigraphic units – furthermore, hanging-wall ultramafic talc-chlorite schists can be confidently distinguished from footwall komatiites. It would therefore be expected that magnetic geophysical-survey data, when constrained with with seismic data, are capable of resolving individual hanging-wall (talc chlorite schist) and footwall (komatiite) units. The identification of hanging-wall and foot-wall units provide an excellent vector towards the Mine Mafic Package, but are still unable to be directly resolve the Mine Mafic Unit. The use of Cr concentrations from pXRF data have shown to be effective at discriminating most Mine Mafic Package metabasic basalt flow sequences (Gazley et al., 2011). However, provision remains for the investigation of more recent pXRF technologies, and the subsequent investigation of Mg and Al concentrations – this may improve the understanding of previously unrecognised metabasic basalt flows and physical rock property variations caused by serpentinisation.

DISCUSSION AND CONCLUSIONS

A preliminary petrophysical investigation of the Archaean Plutonic Well Greenstone Belt has been undertaken. Populations of P-wave velocity, magnetic susceptibility and density data from a stratigraphically complete drill-core have been compared. Alone, P-wave velocity, magnetic susceptibility and density data are unable to directly distinguish stratigraphic/lithologic units. However, magnetic susceptibility and P-wave velocity data, when used in conjunction, are able to resolve and effectively separate metabasic units in the hanging wall and footwall. Preliminary interpretation suggests this is due to different types of alteration; a hypothesis that will be tested using mineralogical and geochemical data. Further studies involving data from other drill-holes, as well as the use of alternate physical property measurements (i.e. natural remanent magnetism, conductivity, radioelement content) are on going and may prove useful in the development of a workflow for the direct detection of the Mine Mafic Package as well as understanding the local alteration.

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Reactionary Equations for the Retrograde Serpentinisation/Alteration of Olivine (by fluids):

$6(Mg,Fe)_2SiO_4 + 7H_2O = 3(Mg,Fe)_3Si_2O_5(OH)_4 + Fe_3O_4 + H_2$ Eq.1
(Olivine + Water → Serpentinite + Brucite + Magnetite + H_2)

$Mg_2SiO_4 + 4Mg(OH)_2 + 3SiO_2 = 2Mg_3Si_2O_5(OH)_4$ Eq.3
(Olivine + Brucite + Silica → Serpentinite)

$3Mg_2SiO_2 + 2SiO_2 + 4H_2O = 2Mg_3Si_2O_5(OH)_4$ Eq. 4
(Olivine + Silica → Serpentinite)

$Mg_3Si_2O_5(OH)_4 + H_2O = 3Mg(OH)_2 + SiO_2$ Eq.5
(Serpentinite + Water → Brucite + Silica)

$Mg_3SiO_5(OH)_4 + 2SiO_2 = Mg_3Si_4O_{10}(OH)_2 + H_2O$ Eq.7
(Serpentinite + Silica → Talc + Water)

Reactionary Equations for the Retrograde Serpentinisation/Alteration of Olivine (by CO_2)

$CH_4 + 2O_2 = CO_2 + 2H_2O$ Eq.2
(Methane + Oxygen = Carbon Dioxide + Water)

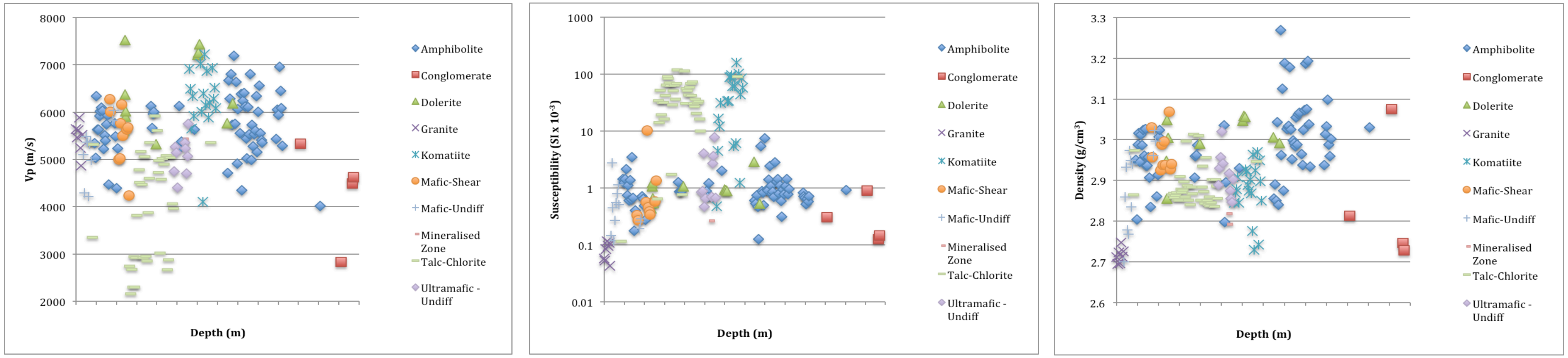
$2Mg_3Si_2O_5(OH)_4 + 3CO_2 = Mg_3Si_4O_{10}(OH)_2 + 3MgCO_3 + H_2O$ Eq.8
(Serpentinite + Carbon Dioxide = Talc + Magnesite + Water)

$4Mg(OH)_2 + CO_2 = 3MgCO_3 + H_2O$ Eq.6
(Brucite + Carbon Dioxide = Magnesite + Water)

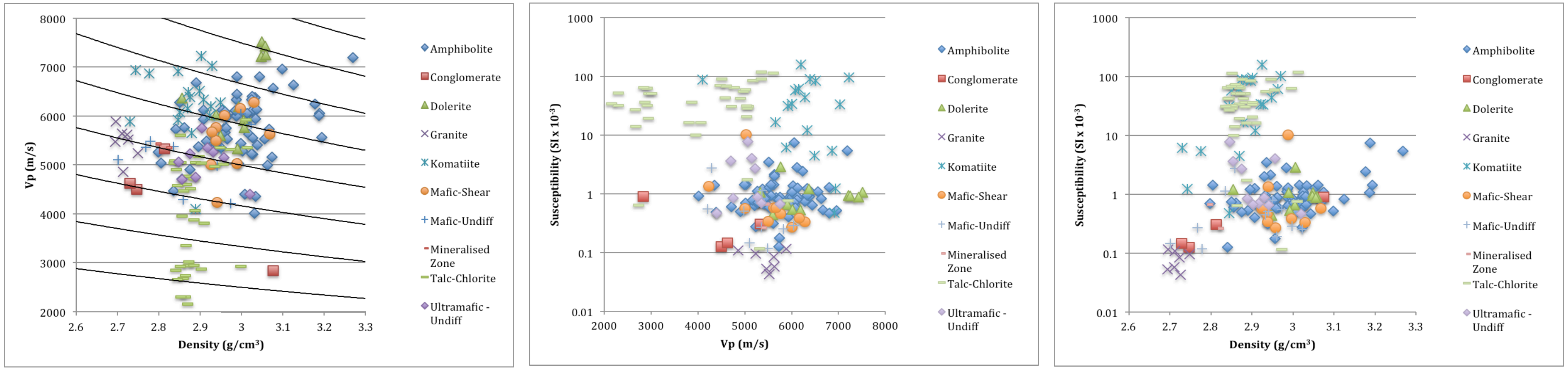
Reactionary Equations for the Retrograde Serpentinisation/Alteration of Orthopyroxene:

$6MgSiO_3 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg_3Si_4O_{10}(OH)_2$ Eq.9
(Orthopyroxene + Water = Serpentine + Talc)

$3MgSiO_3 + SiO_2 + H_2O = Mg_3Si_4O_{10}(OH)_2$ Eq.10
(Orthopyroxene + Silica + Water = Talc)



Figures 1-3 (above - left to right): P-wave velocity, density and magnetic susceptibility plotted against apparent depth, respectively: Depth axes are to scale, and span a length of approximately ~1400m, scalar ticks represent 100m increments. Susceptibility axis within Figure 2 is logarithmic. Figure 2 provides an example of how susceptibility is useful in discriminating ultramafic units from other lithologies, but is unable to resolve sub-classification or type of ultramafics.



Figures 4-6 (above – left to right): P-wave velocity plotted against density, susceptibility plotted against p-wave velocity, and susceptibility plotted against density, respectively: Tracer lines of acoustic impedance, spaced at intervals of R≈6%, are shown in Figure 4. As noted in Salisbury et al. (1996), planar surfaces with a reflection coefficient of 6% (i.e. R≈0.06) or greater will be detectable by the seismic reflection method. Susceptibility axis within Figure 5 is logarithmic. Figure 5 shows how susceptibility and P-wave velocity are able to resolve ultramafic units as either hanging wall (intercalated talc-chlorite schists) or footwall (komatiites). A sub-population of shear-zone-proximal intercalated talc-chlorite schists may also be confidently identified (Figures 1 & 4). Amphibolite (sans garnetiferous) and mafic-shear lithlogically classified units remain the most ambiguous to discern using currently employed methodologies – this may be in part due to mineralogical or protolith similarity.