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High-grade metamorphism and partial melting in Archaean composite grey gneiss complexes

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ABSTRACT

Much of the exposed Archaean crust is composed of composite gneiss which includes a large proportion of intermediate to tonalitic material. These gneiss terrains were typically metamorphosed to amphibolite to granulite facies conditions, with evidence for substantial partial melting at higher grade. Recently published activity–composition (a – x) models for partial melting of metabasic to intermediate compositions allows calculation of the stable metamorphic minerals, melt production and melt composition in such rocks for the first time. Calculated P – T pseudosections are presented for six bulk rock compositions taken from the literature, comprising two metabasic compositions, two intermediate/dioritic compositions and two tonalitic compositions. This range of bulk compositions captures much of the diversity of rock types found in Archaean banded gneiss terrains, enabling us to present an overview of metamorphism and partial melting in such terrains. If such rocks are fluid saturated at the solidus they first begin to melt in the upper amphibolite facies. However, at such conditions very little ($< 5\%$) melt is produced and this melt is granitic in composition for all rocks. The production of greater proportions of melt requires temperatures above 800–850 °C and is associated with the first appearance of orthopyroxene at pressures below 8–9 kbar or with the appearance and growth of garnet at higher pressures. The temperature at which orthopyroxene appears varies little with composition providing a robust estimate of the amphibolite–granulite facies boundary. Across this boundary, melt production is coincident with the breakdown of hornblende and/or biotite. Melts produced at granulite facies range from tonalite–trondhjemite–granodiorite (TTG) for the metabasic protoliths, granodiorite to granite for the intermediate protoliths and granite for the tonalitic protoliths. Under fluid-absent conditions the melt fertility of the different protoliths is largely controlled by the relative proportions of hornblende and quartz at high grade, with the intermediate compositions being the most fertile. The least fertile rocks are the most leucocratic tonalites due to their relatively small proportions of hydrous mafic phases such as hornblende or biotite. In the metabasic rocks, melt production becomes limited by the complete consumption of quartz at higher temperatures. The use of phase-equilibrium forward-modelling provides a thermodynamic framework for understanding melt production, melt loss and intracrustal differentiation during the Archaean.

INTRODUCTION

The Archaean continental crust can be broadly divided into two main types, being granite-greenstone terrains and high-grade gneiss terrains (e.g. Van Kranendonk, 2010), with low grade cratonic basin sediments being a potential third group (Condie, 1981). This paper will focus on the high-grade gneiss terrains, of which the characteristic lithology is the complex unit commonly known as ‘grey gneiss’. The term grey gneiss has been used as an umbrella term for a relatively wide range of tectonically-interleaved intermediate to felsic rocks, which are compositionally dominated by TTG gneiss, and commonly includes fragments of ultramafic to mafic compositions in variable proportions (e.g. Moyen, 2011). Grey gneiss terrains are typically metamorphosed to amphibolite- to granulite-facies grade, and may exhibit a very diverse range of appearance in the field (Martin, 1994; Moyen, 2011).

The rock types comprising grey gneiss have the notable feature that, with the exception of rare granitic horizons, plagioclase is the dominant feldspar with K-feldspar being absent or a relatively minor component (e.g. Martin, 1994; Moyen, 2011; Moyen & Martin, 2012). Thus, although much emphasis is placed on such terrains being dominated by rocks of the TTG suite, they typically show a considerably greater range in composition, particularly with respect to the maficity (Moyen, 2011). This variation in maficity cannot be featured in the normative albite–anorthite–orthoclase ternary plot most commonly used for classification (Moyen, 2011). For example, the large dataset of grey gneiss compiled by Moyen (2011) ranges from diorite (with ≈ 60 wt% silica and ≈ 12 wt% FeO + MgO) through to exceptionally felsic leucotonalites (with > 75 wt% silica and ≈ 0.13 wt% FeO + MgO).

The more mafic to intermediate components of such composite gneisses are dominated by hornblende and plagioclase in the amphibolite facies or pyroxene and plagioclase ($\pm$ hornblende) at granulite facies with garnet an additional mineral present at higher P and quartz more common in the intermediate rocks (e.g. Garde, 1997; Martin, 1994; Moyen, 2011). The TTG components are dominated by plagioclase and quartz ($\pm$ K-feldspar), with biotite and/or hornblende as the main ferromagnesian minerals at amphibolite facies and orthopyroxene and/or clinopyroxene at granulite facies (Martin, 1994).

Much work relating to TTGs from grey gneisses and plutons has focussed on their initial formation, as they form a critical component in the Earth’s oldest continental crust. Thus, numerous studies have used experimental methods (e.g. Beard & Lofgren, 1991; Rapp *et al.*, 1991; Wolf & Wyllie, 1994; Laurie & Stevens, 2012), geochemistry (e.g. Martin, 1994; Martin & Moyen, 2002; Moyen, 2011), and more recently calculated phase petrology (e.g. Palin *et al.*, 2016a,b) to infer that Archaean TTGs likely formed from partial melting of garnet-bearing metabasic rocks. By contrast, considerably less work has been undertaken on the metamorphism of tonalitic rocks. This is largely due to their relatively simple mineral assemblages and relative insensitivity to changes in P – T (e.g. Nehring *et al.*, 2009; Johnson *et al.*, 2013), with metabasic and metapelitic rocks typically being more amenable to classic thermobarometric methods. However, a number of experimental studies have been undertaken on broadly intermediate to tonalitic compositions at high temperatures and pressures to investigate the partial melting of such compositions (e.g. Rutter & Wyllie, 1988; Skjerlie & Johnson, 1992; Singh & Johannes, 1996a,b; Patiño Douce, 2005; Watkins *et al.*, 2007), though some of these studies investigate conditions outside those normally encountered in the crust (e.g. Patiño Douce, 2005). Furthermore, the experimental studies are largely restricted

to upper granulite facies conditions so provide no constraints on the amphibolite-facies evolution of tonalitic gneisses

In this paper we use calculated phase diagrams for a range of compositions from metabasaltic to tonalitic to investigate the assemblage development and closed-system partial melting during high-grade metamorphism of typical Archaean layered grey gneiss complexes. The calculations use the newly-developed a - x relations of Green *et al.* (2016) to place constraints on the responses of different rock compositions to metamorphism, including their melt fertility as a function of pressure and temperature and the composition of melt produced.

FIELD OBSERVATIONS AND COMPOSITIONAL VARIATION IN GREY GNEISS COMPLEXES

Archaean high grade gneiss terrains are characteristically metamorphosed to upper-amphibolite to granulite facies, so there is the potential for them to have partially melted, with lithologies of different composition being expected to show different melt productivity. Typically, the granulite facies terrains do indeed show extensive field and microstructural evidence for partial melting (e.g. Hartel & Pattison, 1996; Nehring *et al.*, 2009; Johnson *et al.*, 2012, 2013), as do some of the upper amphibolite facies examples (e.g. Nehring *et al.*, 2009).

Figure 1a shows the Archaean composite Sand River gneiss in the Limpopo Belt with different layers ranging from near ultramafic to relatively felsic. A similar range in compositions occurs in the Lewisian Gneiss of NW Scotland between mafic layers with very little plagioclase, some more intermediate layers and felsic layers dominated by plagioclase and quartz (1b). As highlighted in Johnson *et al.* (2013) at high metamorphic grade, such rocks are expected to partially melt, but identifying melt structures in the tonalitic layers is commonly difficult. Figure 1c shows a clean washed face in a boulder of layered intermediate gneiss (lower) and leucocratic tonalitic gneiss (top). A cm-scale leucosome occurs in a small shear band in the intermediate portions and a small leucosome-filled boudin structure occurs near the boundary of the intermediate and tonalitic layers. Other gneisses show rather conspicuous evidence for melting, such as in Fig. 1d from Taishan, China, where larger leucosomes can be seen in a somewhat more homogeneous tonalitic gneiss along with dismembered ultramafic to mafic layers. In more mafic rocks, *in-situ* leucosomes are commonly associated with large pyroxene porphyroblasts forming complex vein structures (Fig. 1e).

As outlined above, the composite grey gneiss complexes contain a diverse range of rock types. This compositional variation can be shown on a series of Harker plots with SiO_2 as the x axis (Fig. 2). In these plots, the large database of grey gneiss from Moyon (2011) are shown as open squares, select amphibolite facies samples from Garde (1997) as blue filled circles and the compositions modelled below as red squares. The green lines on each plot are linear composition vectors used for subsequent T - x pseudosections. The data presented shows a relatively linear trend in total $\text{FeO} + \text{MgO}$ versus SiO_2 reflecting the primary variation in the maficity of different rocks in these terrains (Fig. 2a). A somewhat less well-defined trend in Al_2O_3 versus SiO_2 can be seen in (Fig. 2b), though with considerable variation in Al_2O_3 content for the metabasaltic rocks. The trend in $\text{FeO} + \text{MgO}$ versus SiO_2 is correlated with a somewhat more subtle trend in $\text{MgO}/(\text{FeO} + \text{MgO})$ (Fig. 2c). The trend in $\text{Na}_2\text{O}/(\text{Na}_2\text{O}$

+ K₂O) versus SiO₂ has a distinct inflection at higher SiO₂ contents with the more potassic grey gneiss components trending to lower Na₂O/(Na₂O + K₂O).

PHASE EQUILIBRIUM MODELLING

The phase equilibrium modelling was undertaken in the Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O₂ (NCKFMASHTO) chemical system using THERMOCALC version 3.45i using the Holland & Powell (2011) internally-consistent dataset version 6.62 (file created 6th February 2012). The *a*–*x* relations for melt (L), augitic clinopyroxene (aug) and hornblende (hb) are those of Green *et al.* (2016). The garnet (g), orthopyroxene (opx) and biotite (bi) models are from (White *et al.*, 2014a), ilmenite–hematite (ilm–hem) from White *et al.* (2000), C1 plagioclase (pl), K-feldspar (ksp) from (Holland & Powell, 2003), epidote (ep) from (Holland & Powell, 2011) and muscovite (mu) from White *et al.* (2014b) with a reduced ΔG^{mod} value (see notation in Green *et al.*, 2016) for the margarite end-member of 5 kJ/mol from 6.5 kJ/mol (Palin *et al.*, 2016a). Quartz (q), rutile (ru), sphene (sph), and aqueous fluid (H₂O) were treated as pure phases. In the calculated pseudosections the clinopyroxene is labelled augite to distinguish it from the omphacite–diopside *a*–*x* model from Green *et al.* (2007), and Green *et al.* (2016). In all the calculations this clinopyroxene ranged in composition from diopside to augite.

Pseudosections are presented for six rock compositions, two metabasalts, two intermediate compositions and two tonalitic compositions which cover a range of common rock types in Archaean grey gneiss terrains. The bulk rock compositions used and the molar MgO/(FeO + MgO) are given in Table 1. For the *P*–*T* pseudosections the H₂O content of the bulk-rock compositions were set such that the rock was just fluid saturated at the wet solidus at 7 kbar. Thus, the solidus is fluid-undersaturated at higher pressures.

Mineral assemblages and melt production

Basaltic compositions

Figure 3 shows *P*–*T* pseudosections for two average Archaean metabasalt compositions, a depleted Archaean tholeiite, DAT, (Fig. 3a) and an enriched Archaean tholeiite, EAT, Fig. 3b) from Condie (1981). Both pseudosections have a similar topology in terms of the modally-dominant minerals, though the enriched composition additionally contains some biotite- and/or K-feldspar-bearing fields at amphibolite facies conditions. For both compositions the solidus occurs at upper amphibolite-facies conditions.

For conditions below about 8.5 kbar the suprasolidus assemblages are garnet absent and dominated by hornblende, clinopyroxene, plagioclase, orthopyroxene and melt. In both compositions orthopyroxene first appears at temperatures between 800 °C and 850 °C, with the loss of quartz from the assemblage within 25 °C of this. At higher temperatures, both compositions contain the assemblage opx–aug–hb–pl–ilm–L until temperatures of at least 970 °C, above which hornblende becomes absent. The garnet-in boundary reaches a minimum pressure of ~8.5 kbar at ~850 °C. Within 1–2 kbar above the garnet-in line, the orthopyroxene-in line is close to isobaric, with the assemblage g–aug–hb–pl–ilm–L or g–aug–hb–pl–ru–L stable to higher pressures.

The relative proportions of the stable phases are shown on a series of T -mode plots for isobaric sections at 7 kbar and 10 kbar (Fig. 3c–f). Modes, or modal proportions, of phases are presented as mole proportions, and are calculated with each phase expressed on a 1-cation basis, approximating volume proportions. For both metabasalt compositions amphibolite facies assemblages are dominated by hornblende, plagioclase and quartz with epidote, sphene, biotite and clinopyroxene variably present. In the DAT composition, augite is stable across the P – T window considered (Fig. 3c,d) whereas it is restricted to upper amphibolite to granulite facies in the EAT composition (Fig. 3e,f). In both compositions, little melt (< 8 mol %) is produced below 800 °C, with the onset of significant melt production coinciding with the appearance of orthopyroxene at 7 kbar (Fig. 3d,f) and garnet at 10 kbar (Fig. 3c,e).

Intermediate compositions

The predicted stable mineral assemblages for intermediate compositions are shown in the pseudosections in Fig. 4 for a leucoamphibolite (Fig. 4a) and a metadiorite (Fig. 4b), both taken from Garde (1997). The two pseudosections for intermediate compositions are topologically similar, though the metadiorite has a smaller garnet stability field and an extended quartz stability field compared to the leucoamphibolite. The pseudosections for the intermediate compositions show some key differences from those for the metabasalt. The most notable difference lies in the relative stability range of hornblende, which breaks down at temperatures of 850 to 900 °C in the intermediate compositions compared to $T > 950$ °C in the metabasalts. As shown also in Palin *et al.* (2016a), this restricted hornblende stability reflects the higher SiO₂ content and hence greater quartz content of these compositions. Thus, for the intermediate compositions the complete consumption of hornblende occurs within 60 °C of the first appearance of orthopyroxene, corresponding to a narrow field of enhanced melt production across the amphibolite–granulite facies transition. Another feature of the pseudosections for intermediate compositions is that K-feldspar is predicted at higher- P upper amphibolite-facies conditions and biotite at lower- P upper amphibolite-facies conditions, in contrast to these phases being absent or having a very restricted stability range in the metabasalts (Fig. 3). As with the metabasalts, garnet-bearing assemblages reach a minimum P extent close to the intersection of the orthopyroxene-in and garnet-in lines at $T \approx 850$ °C and P of 8.5–9.5 kbar.

The metabasalts and the intermediate rocks differ significantly in the overall proportions of phases, as can be seen in comparing Figs 3c–f and Figs 4c–f, with the intermediate rocks having a lower hornblende content and higher plagioclase and quartz content. The sharp increase in melt proportion across the amphibolite–granulite facies transition is also evident in the the modebox diagrams (Figs 4c–f).

Tonalitic compositions

Figure 5 shows P – T pseudosections for two tonalitic compositions. Figure 5a is an average of the grey gneiss compositions from the dataset presented in Moyen (2011) and Fig. 5b is an average tonalitic grey gneiss composition from Garde (1997). Both compositions are dominated by plagioclase and quartz which, excluding melt, comprise over 80% of the

solid mineral assemblage with the ferromagnesian minerals and oxides occurring in minor proportions (Fig. 5c–f).

For both compositions garnet-bearing assemblages are restricted to higher pressure, being restricted to $P > 9$ kbar for the composition in Fig. 5a, but as low as 7 kbar in Fig. 5b. At lower T biotite is predicted to be the dominant ferromagnesian phase, where it may co-exist with augite, hornblende or both. Following the appearance of orthopyroxene, biotite and hornblende are rapidly consumed and the assemblage opx-pl-ksp-q-ilm-L persists until the eventual up-temperature consumption of K-feldspar. A key feature of both pseudosections for tonalitic bulk compositions is the highly variable stability of hornblende- and/or clinopyroxene-bearing assemblages between the upper amphibolite facies and temperatures just above the appearance of orthopyroxene in the granulite facies. This variability is a reflection of the relatively low total FeO + MgO contents of these rocks (2.4–4.1 mol%) and hence the very low total ferromagnesian mineral content expected in rocks of this composition. At higher grade, both compositions develop orthopyroxene, or orthopyroxene + garnet at high P , as the major ferromagnesian minerals.

T–x pseudosections from basaltic to tonalitic compositions

The variation in mineral assemblages and melt production between a metabasalt composition and a metatonalite composition is shown in a pair of T – x diagrams, calculated for pressures of 7 kbar (Fig. 6a) and 10 kbar (Fig. 6b). In both T – x diagrams, the x axis ranges from the composition of the EAT used in Fig. 3b at $x = 0$ and that of the average tonalitic grey gneiss used in Fig. 5a at $x = 1$. This composition range is shown in Fig. 2 as a green line. The two intermediate compositions cannot be directly plotted on Fig. 6 but the leucoamphibolite experiences an up- T mineral assemblage evolution similar to that for $x = 0.3$ – 0.4 and the metadiorite similar to that for $x = 0.5$. The approximate range of grey gneiss analyses, in terms of FeO + MgO and SiO₂ content from the dataset of Moyen (2011) is shown, and ranges from approximately $x = 0.55$ to $x = 1$, noting that the least mafic/most silica-rich compositions reported in Moyen (2011) would plot above $x = 1$.

For most temperatures, the T – x pseudosections show relatively minor changes in the overall assemblages across most of the composition range. The most significant changes seen are at values of $x = 0.9$ – 1 where the presence/absence of hornblende and augite may change significantly as a function of T and x . This range would encompass much of the data presented in Moyen (2011), thus allowing for a notable variation in the stable ferromagnesian minerals in TTG–grey gneiss with a relatively modest variation in bulk rock composition. For values of $x < 0.9$, there are a few significant changes. At $T < 700$ °C augite is restricted to $x > 0.6$ at 7 kbar and is absent across the diagram at 10 kbar. K-feldspar is stable across the diagram at upper amphibolite to granulite conditions at 10 kbar but has a much more restricted stability at 7 kbar, a feature also seen in most of the P – T pseudosections. In both T – x pseudosections the intersection of the hornblende-out and quartz-out lines at $x = 0.2$ – 0.3 separates the diagram into a region at lower x where hornblende persists to very high temperature and a region to higher x where quartz persists and hornblende becomes absent. This separates the assemblages into hornblende granulite and hornblende-absent two-pyroxene granulite, suggesting both can coexist over a substantial T range in different bulk compositions.

The relative proportions of the stable phases are shown on a series of x -mode plots (modeboxes) for sections at 850, 900, 950 and 1000 °C (Fig. 7), showing the assemblages and proportions as a function of x at different granulite-facies temperatures. The T -mode plots highlight the significant modal differences that may occur over the composition range considered, especially with regard to the total modal content of ferromagnesian phases. The greatest change across the modebox diagrams is in the hornblende mode, especially at 850–900 °C, where hornblende goes from being a major constituent in the metabasic compositions to a minor one or absent from the tonalitic composition. With increasing T the hornblende mode decreases, as does the maximum value of x at which hornblende is part of the stable assemblage. The maximum extent of garnet also shifts to lower values of x with increasing T . The mode of plagioclase is typically higher at higher values of x and shows a modest decrease with increasing T .

As also shown in the melt mode contours in Fig. 6, the modebox diagrams show that at any given T the most fertile compositions are the intermediate ones lying at $x = 0.25$ – 0.6 , with the tonalitic composition being the least fertile, reflecting the overall lower bulk H_2O content required to saturate the solidus. The metabasalt compositions are also less fertile than the intermediate ones for most crustal temperatures despite their high H_2O content, as much of the H_2O remains bound in hornblende to very high T .

Composition of melt produced

The composition of melt produced from 700 °C to 1050 °C in the six modelled compositions at 7 kbar and 10 kbar is shown in Fig. 8a,b, expressed as normative (Barth-Niggli norms) proportions of anorthite, albite and orthoclase. The melt compositions are shown as trend lines from low T (filled squares) to high T (filled circles) with tick marks marking each 50 °C increment. For these calculations no progressive melt loss from the source rocks was assumed. This simplification results in only minor differences in melt composition compared to that calculated for a process of sequential melt extraction below temperatures of about 950 °C (Palin *et al.*, 2016b), but does have moderate effects at higher temperatures with the melts having lower normative orthoclase contents than those presented here. Furthermore, progressive melt loss along the prograde path will lower the overall melt production compared to the calculations here, especially at higher temperatures (e.g. White & Powell, 2002; Yakymchuk & Brown, 2014; Palin *et al.*, 2016a). For all bulk compositions considered, the low T melts are granite, with the exception of the DAT bulk composition at 10 kbar for which the melt composition extends just into the trondhjemite field. The two metabasalt compositions show substantially different trends in melt composition. Melt from the DAT composition quickly becomes granodioritic with increasing T , then tonalitic above 800 °C. By contrast, the EAT composition produces granite melt until just below 850 °C, granodioritic melt from 850 to just above 900 °C and tonalitic above that.

The intermediate bulk compositions primarily produce granitic to granodioritic melt, particularly below about 950 °C, but with the leucoamphibolite producing tonalite at 1050 °C and 10 kbar and trondhjemite at 1050 °C and 7 kbar. The melt produced from the tonalitic bulk compositions lies entirely within the granite field for the P – T conditions considered, with the exception of the 7 kbar/1050 °C point for the average TTG bulk composition of Moyen (2011), which plots just in the trondhjemite field.

The range in melt composition as a function of bulk rock composition at constant P – T can be seen in Figure 8c,d, which shows the range of calculated melt compositions for several temperatures across the T – x pseudosections in Fig. 6. For each temperature, the melt compositions range from that produced via melting of the enriched Archaean tholeiite (filled square) to that produced via melting of the average tonalitic grey gneiss (filled circle) of Moyen (2011) with the ticks along each line representing steps in x of 0.1. Over the pressure, temperature and composition range considered, the melts produced range from tonalite to granite, largely scattered along the tonalite–trondhjemite–granodiorite–granite boundary. At the lowest T considered (850 °C) the melts show a relatively limited range in compositions, being granitic for all compositions except for the 7 kbar $x = 0$ point which is in the granodiorite field. With increasing T the overall range of melt composition increases and the range additionally shows an overall shift away from the Or apex. Thus, as T increases the melt produced from the metabasalt composition becomes tonalitic whilst that for the metatonalite remains granitic. Melt produced from the intermediate compositions remains granodioritic to granitic. These melt composition relationships are broadly consistent with those discussed in Moyen & Stevens (2006).

DISCUSSION AND CONCLUSIONS

Archaean grey gneiss terrains are composed of composite gneisses that show a considerable range of rock compositions from ultramafic to leucotonalitic, with subordinate granitic and metasedimentary rocks present. However, the intermediate to felsic TTG rocks are commonly the dominant rock type in such terrains. Calculated pseudosections, using the Holland & Powell (2011) thermodynamic dataset and new a – x relations of Green *et al.* (2016), have been presented for six bulk rock compositions that range from metabasic to tonalitic. The calculations allow investigation of the main mineral assemblage changes and melt productivity during high grade metamorphism and partial melting of each of the main meta-igneous components of Archaean grey gneisses.

For the compositions investigated, the phase-equilibrium modelling predicts the predominance of plagioclase over K-feldspar, the presence of biotite as the main ferromagnesian mineral in felsic compositions, the presence of hornblende in more intermediate compositions, and the rarity or absence of biotite and/or K-feldspar from more mafic compositions. This is consistent with the observations of Martin (1994), reported for an undifferentiated selection of low-K grey gneisses. The models additionally predict the presence of clinopyroxene in all but one of the bulk compositions, though where it appears in one of the two tonalitic compositions it is present only in tiny proportions, and over a limited temperature and pressure range. It should be noted that in leucocratic tonalites the high plagioclase modes and very low bulk content of FeO + MgO make it difficult to predict the most stable ferromagnesian mineral assemblage appropriately. Small errors in the predicted partitioning of Ca and Na between plagioclase and hornblende or clinopyroxene have significant consequences for mass balance, affecting which combinations of ferromagnesian phases will be predicted in a given bulk composition. Thus, in calculations such as Fig. 5, in which assemblages involving hornblende and/or clinopyroxene show complex distributions, the relevant phase boundaries should be considered to have a high uncertainty.

The calculations presented in this study show that a wide array of mafic to intermediate rock types will experience similar assemblage evolutions across the amphibolite–granulite boundary, which occurs at 800–850 °C at 7 kbar, before diverging into four main groups. For the most mafic to the most felsic bulk compositions, these groups are 1) quartz-absent hornblende granulite, 2) quartz- and hornblende-absent two pyroxene granulite, 3) intermediate to felsic quartz-bearing two-pyroxene granulite, and 4) quartzofeldspathic orthopyroxene granulite. The assemblage changes that take place during the onset of granulite-facies conditions are dominated by the growth of orthopyroxene, concomitant with the consumption of hornblende, quartz and biotite, and a increase in the rate of melt production.

Under closed system conditions composite grey gneiss terrains are predicted to produce significant quantities of melt only upon reaching the granulite facies. Under such conditions, closed-system melt fractions increase rapidly as orthopyroxene grows at the expense of hornblende and/or biotite, exceeding 30 mol% at ≥ 900 °C. Such temperatures have been invoked for several Archaean gneiss terrains such as the Lewisian Gneisses in Scotland (e.g. Johnson & White, 2011), with the rocks showing convincing evidence for significant melt production (e.g. Fig. 1c). Furthermore, orthopyroxene-bearing assemblages or garnet–clinopyroxene–plagioclase-bearing high pressure granulites have been reported from a moderate number of Archaean terrains such as the Fiskefjord area, SW Greenland (Garde, 1997), the Kapuskasing Structural Zone, Superior Province (Percival, 1983), the Iisalmi block, Finland (Nehring *et al.*, 2010), the Hebei Province, China (?) and the Ashuanipi Complex, Superior Province (?), for example. While, in older studies, reported temperatures in such terrains are typically 750–850 °C (?), such estimates are typically based on conventional thermobarometry which is susceptible to resetting during cooling (e.g. Pattison *et al.*, 2003; Powell & Holland, 2008). The phase equilibrium approach here is consistent with orthopyroxene-bearing assemblages at mid crustal levels (6–8 kbar) typically requiring temperature in excess of 850 °C but temperatures in such terrains may potentially be much higher. Higher pressure garnet–orthopyroxene–clinopyroxene-bearing assemblages will typically require temperatures in excess of 900 °C, consistent with substantial melt production in the Archaean mid to lower crust.

By contrast, if metamorphism only reaches temperatures below the appearance of orthopyroxene, only 5–12 mol % melt generation is predicted, though this may be sufficient to develop melt segregation structures in such rocks. The main controls on melt fertility are the relative proportions of quartz and hornblende, and the volumetrically-dominant TTGs are particularly infertile with less than 5 mol.% melt produced at 800 °C at 7 kbar. Under such conditions, convincing evidence for melt presence might be cryptic.

Amphibolite facies grey gneisses with markedly larger volumes of preserved leucosome than predicted here are therefore inconsistent with simple closed system *in-situ* melting and would require either an external source of H₂O to increase melt contents or contain a proportion of melt injected from elsewhere (e.g. Brown 13, Brown 16). Given that the currently exposed levels of amphibolite-facies grey gneisses are likely to be underlain by higher-grade grey gneiss, such rocks provide a likely external source for melt. Such a source is consistent with the melt depleted nature of the higher pressure and higher temperature rocks found in Archaean terrains (e.g. Johnson *et al.*, 2012).

Partial melting of the wide spectrum of source rocks in these composite gneisses would result in melts ranging from tonalite to granite. However, given the volumetric dominance

of intermediate to felsic compositions, the vast majority of melt produced would be granitic to granodioritic in composition in terms of the An–Ab–Or triangular plot (Fig. 8), with the intermediate to felsic rocks exclusively producing melts of this composition. The production and loss of large quantities of melt in high grade Archaean grey gneiss terrains has been inferred from geochemical and field studies (e.g. Johnson *et al.*, 2012, 2013) and would result in the internal differentiation of the crust (e.g. Brown, 1994, 2004; Johnson *et al.*, 2012). The overall paucity of such granitic rocks in these high-grade terrains is consistent with such melt having left the source and ascended to higher crustal levels.

As high-grade metamorphism and melting of most rocks in grey gneiss terrains produces granite, it is likely that the Earth’s earliest primary granites (excluding any formed by fractional crystallisation of intermediate to tonalitic magmas) date back to the time of high-grade metamorphism of the oldest grey gneiss terrains and could potentially have been emplaced into the, now eroded, upper crustal part of such terrains. Granite is a somewhat underemphasised component of many Archaean terrains, with granite plutons estimated to make up close to 20% of the exposed rock of Archaean shields (Condie, 1993). Where such granites were emplaced during cycles of active tectonism and metamorphism it is possible that they are genetically linked to high grade metamorphism and melting at depth, with the melt extracted from high-grade gneisses similar to those exposed in granulite facies Archaean gneiss terrains.

The phase diagram approach has the potential to offer new thermobarometric constraints on the metamorphism of Archaean terrains, a problem which has proved challenging for conventional barometry where garnet is scarce or absent. Whilst some Archaean terrains contain substantial proportions of garnet-bearing mafic to tonalitic rocks (e.g. the central region of the Lewisian Gneiss, Johnson *et al.* (2012)), many others do not (e.g. Ancient Gneiss Complex, Swaziland, ?). Phase diagram calculations can provide an estimate of maximum pressure given the absence of garnet, if the observed assemblage places a reasonable constraint on the temperature of metamorphism. For intermediate bulk compositions and temperatures below the appearance of orthopyroxene, the presence or absence of K-feldspar is a further constraint on pressure. The pseudosection calculations do however confirm that assemblage fields tend to be large, with boundaries that are mainly dependent on temperature, especially above 800 °C. This observation is consistent with historical difficulties in developing conventional barometers for garnet-absent rocks (e.g. Spear, 1993; Powell & Holland, 2008).

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Figure captions

Fig. 1. Field photographs of Archaean gneisses. (a) Layered mafic, intermediate and felsic gneiss from the Sand River Gneiss in the Limpopo belt, South Africa. (b) Granulite facies layered gneiss from Scourie in the Lewisian Complex. The gneiss is composed of alternating cm-scale mafic/intermediate and felsic layers. (c) Partially melted intermediate/dioritic gneiss and small leucotonalitic layer in a boulder at Scourie in the Lewisian Complex. (d) Partially melted tonalitic gneiss with dismembered mafic/ultramafic layers from Taishan, China. (e) Small *in-situ* leucosomes with coarse-grained clinopyroxene porphyroblasts, and larger in-source tonalitic leucosomes in a mafic gneiss from Taishan, China.

Fig. 2. Harker plots of whole rock compositions from composite grey gneiss samples from the literature. The open squares are data from Moyen (2011), the blue filled circles are select data from Garde (1997) and the red filled squares are the compositions modelled here, as labelled on Fig. 2b. The green line is the composition range used in the T - X pseudosections.

Fig. 3. P - T pseudosections and modebox plots for two basalt compositions. (a) P - T pseudosection for a depleted Archaean tholeiite (DAT) composition from Condie (1981). (b) P - T pseudosection for an enriched Archaean tholeiite (EAT) composition from Condie (1981). (c) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 3a. (d) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 3a. (e) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 3b. (f) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 3b.

Fig. 4. P - T pseudosections and modebox plots for two intermediate/dioritic compositions. (a) P - T pseudosection for a leucoamphibolite composition from Garde (1997). (b) P - T pseudosection for an average dioritic TTG composition from Garde (1997). (c) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 4a. (d) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 4a. (e) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 4b. (f) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 4b.

Fig. 5. P - T pseudosections and modebox plots for two tonalitic compositions. (a) P - T pseudosection for an average tonalitic grey gneiss composition from Moyen (2011). (b) P - T pseudosection for an average amphibolite facies TTG composition from Garde (1997). (c) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 5a. (d) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 5a. (e) Modebox plot showing the predicted mineral proportions along an isobaric 10 kbar section through Fig. 5b. (f) Modebox plot showing the predicted mineral proportions along an isobaric 7 kbar section through Fig. 5b.

Fig. 6. T - x pseudosections showing the main mineral assemblage changes from the EAT composition in Fig. 3b to the average grey gneiss in Fig. 5a. (a) T - x pseudosection for 7 kbar, contoured for melt mode. (b) T - x pseudosection for 10 kbar, contoured for melt mode.

Fig. 7. Modebox plots for isothermal sections across the T - x pseudosections in Fig. 6. (a-d) Modebox plots for isothermal sections at 7 kbar and 850 °C (a), 900 °C (b), 950 °C (c), 1000 °C (d). (e-h) Modebox plots for isothermal sections at 10 kbar and 850 °C (e), 900 °C (f), 950 °C (g), 1000 °C (h).

Fig.8. Normative anorthite–albite–orthoclase ternary plots showing the compositions of melt produced from the different rocks modelled. (a) Melt composition trend lines at 7kbar for the P – T pseudosections along isobaric paths from 700 to 1050 °C. (c) Melt composition trend lines at 10 kbar for the P – T pseudosections along isobaric paths from 700 to 1050 °C. (c) Melt composition trend lines at 7 kbar across the T – x pseudosection in Fig 6a at 850, 900, 950 and 1000 °C. (d) Melt composition trend lines at 10 kbar across the T – x pseudosection in Fig 6a at 850, 900, 950 and 1000 °C.

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Table 1: Bulk rock compositions used in the construction of pseudosections

mol. %	H ₂ O	SiO ₂	Al ₂ O ₃	CaO	MgO	FeO	K ₂ O	Na ₂ O	TiO ₂	O	x_{Mg}
Fig. 3a	4.781	50.052	9.106	12.391	11.192	8.943	0.139	2.078	0.705	0.612	0.592
Fig. 3b	5.286	50.516	9.141	9.367	10.374	9.977	0.449	2.672	1.144	1.076	0.570
Fig. 4a	2.737	63.684	10.224	6.601	5.351	4.981	1.011	4.304	0.497	0.608	0.587
Fig. 4b	3.591	58.463	10.337	8.087	6.064	7.171	0.754	4.074	0.684	0.774	0.519
Fig. 5a	1.712	74.476	9.644	3.474	1.731	2.386	1.308	4.869	0.281	0.119	0.446
Fig. 5b	1.062	76.64	9.841	2.912	0.917	1.528	1.823	4.926	0.203	0.146	0.426

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Figure 1:

Figure 2:

Figure 4:

Figure 5:

Figure 6:

Figure 7:

Figure 8:



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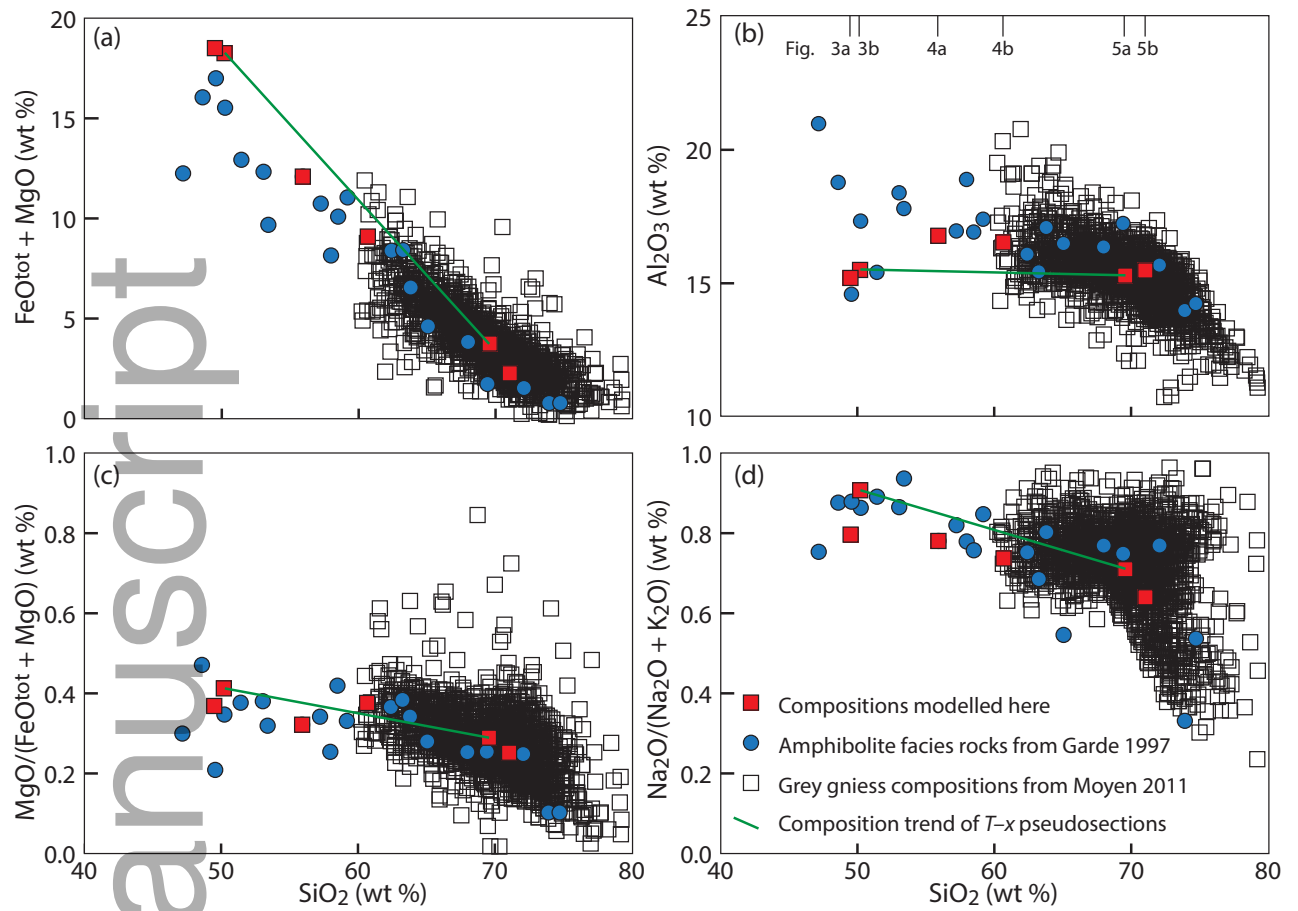


Fig. 2

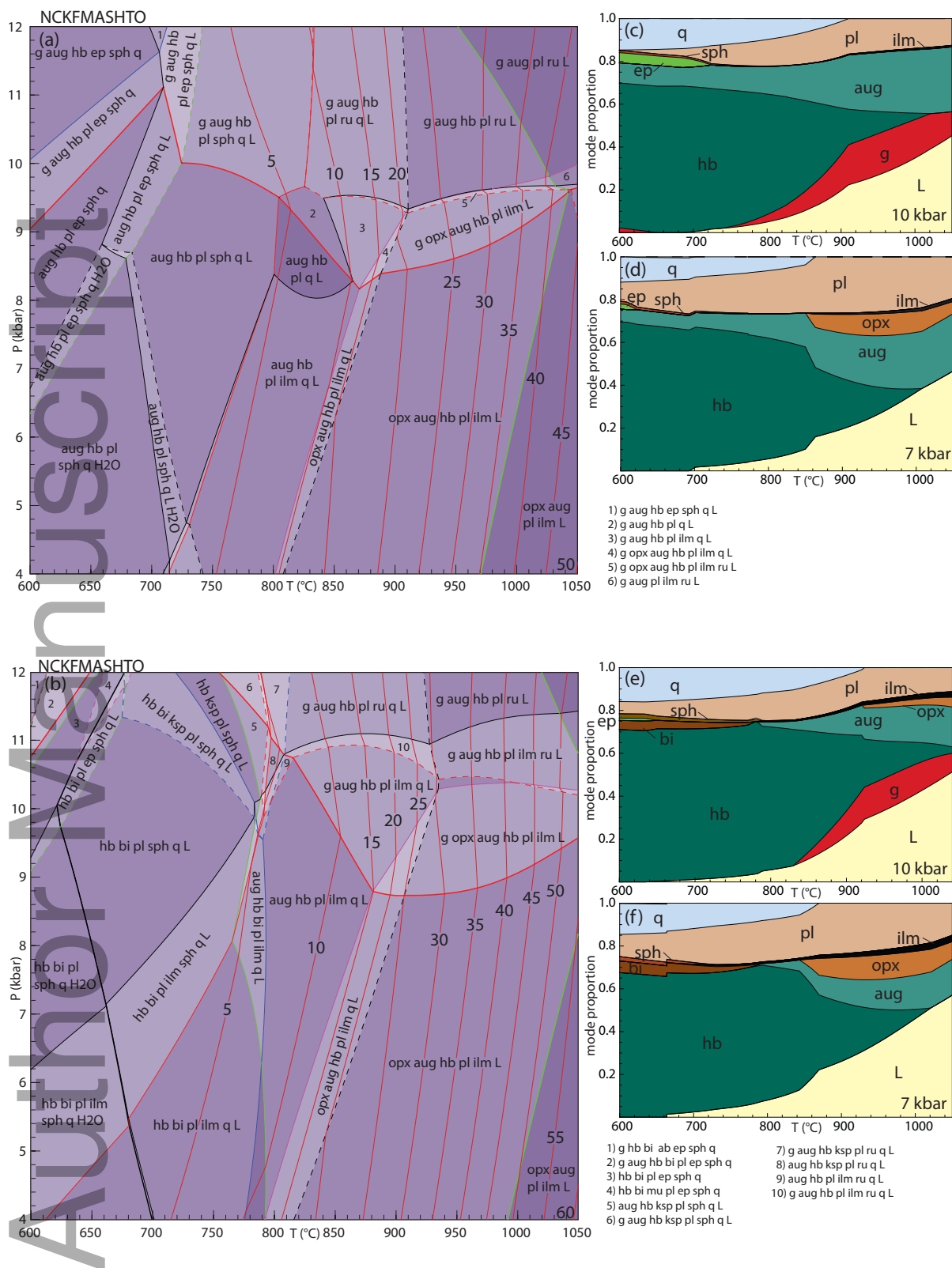


Fig. 3

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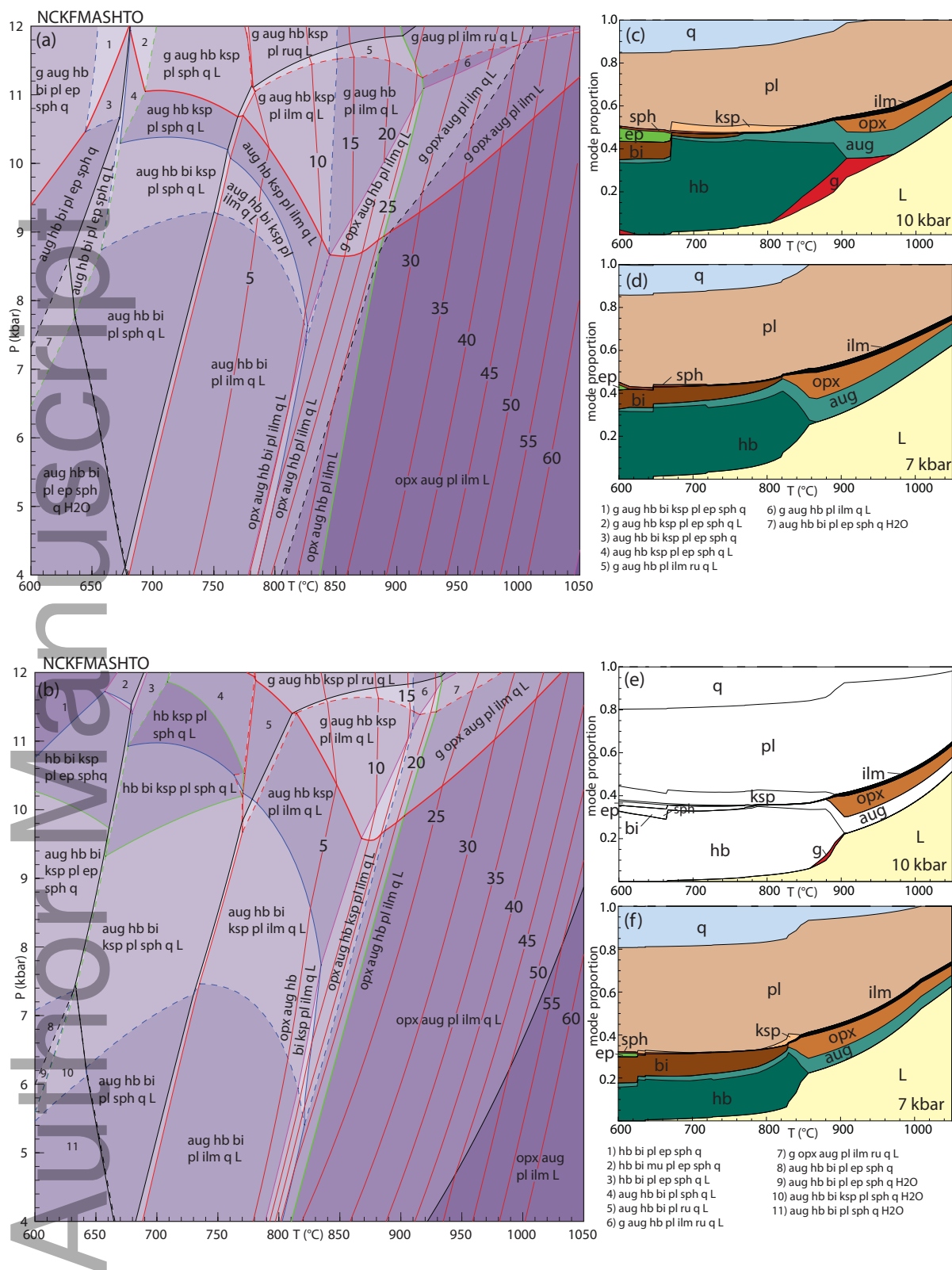


Fig. 4

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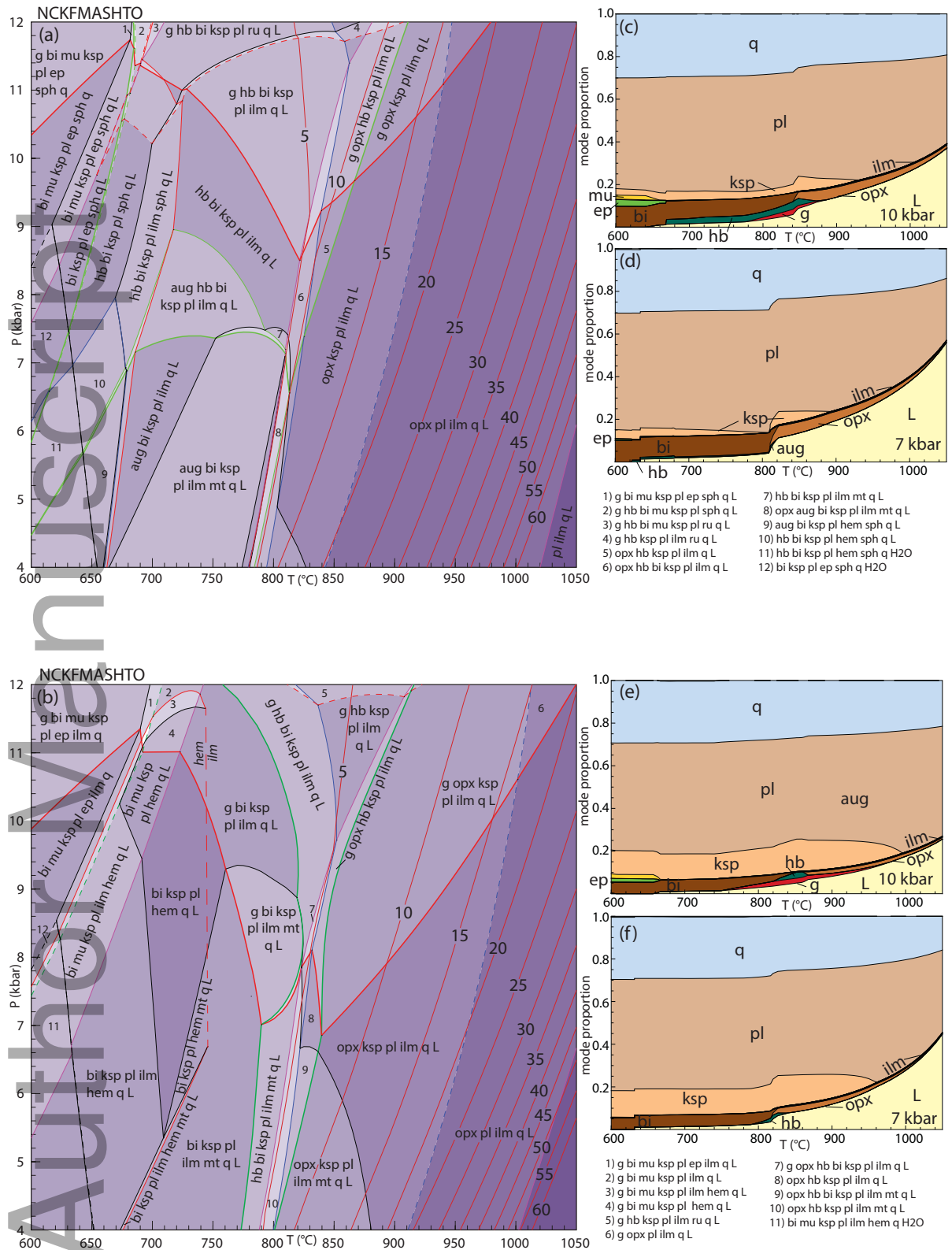


Fig. 5

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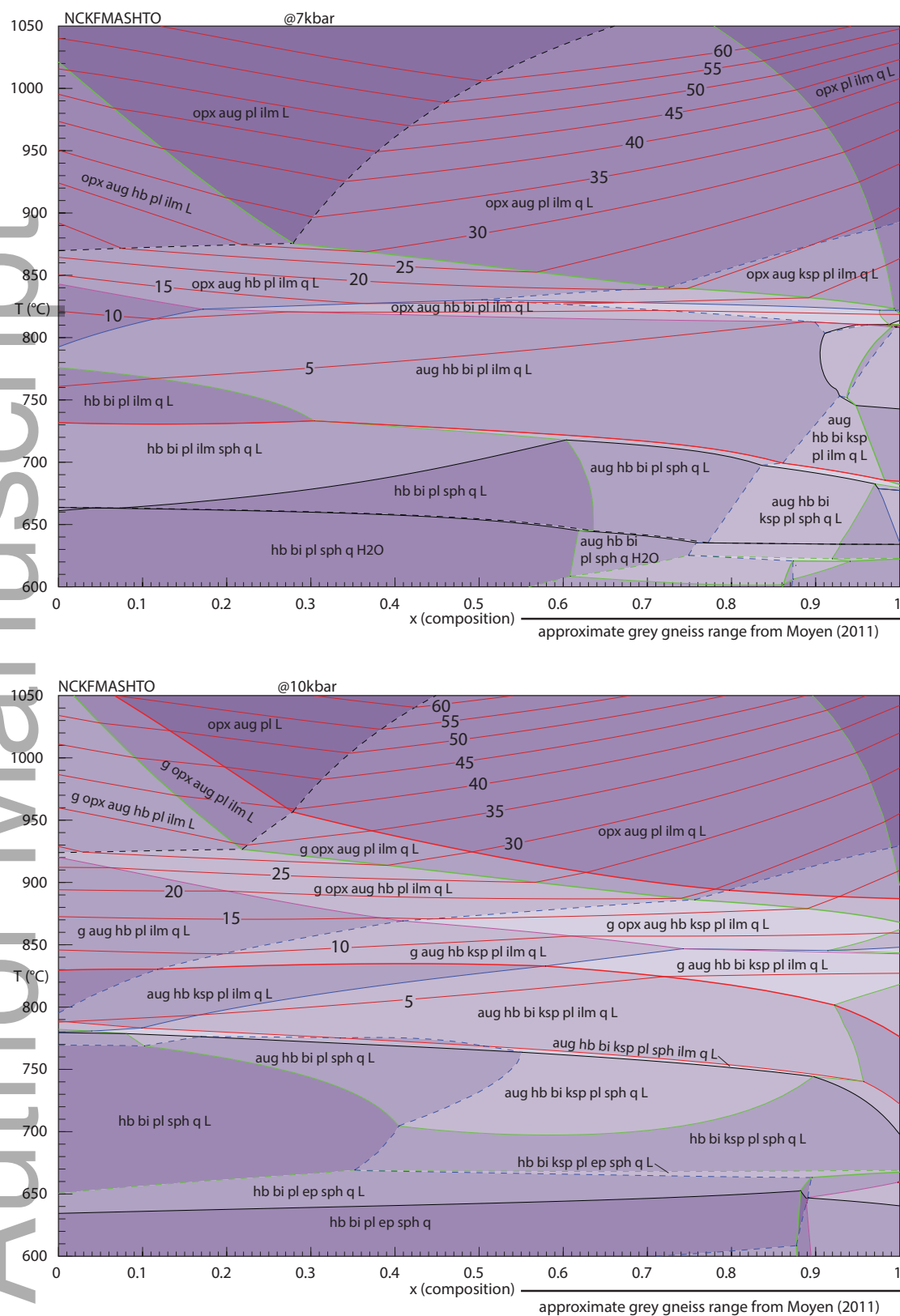


Fig. 6

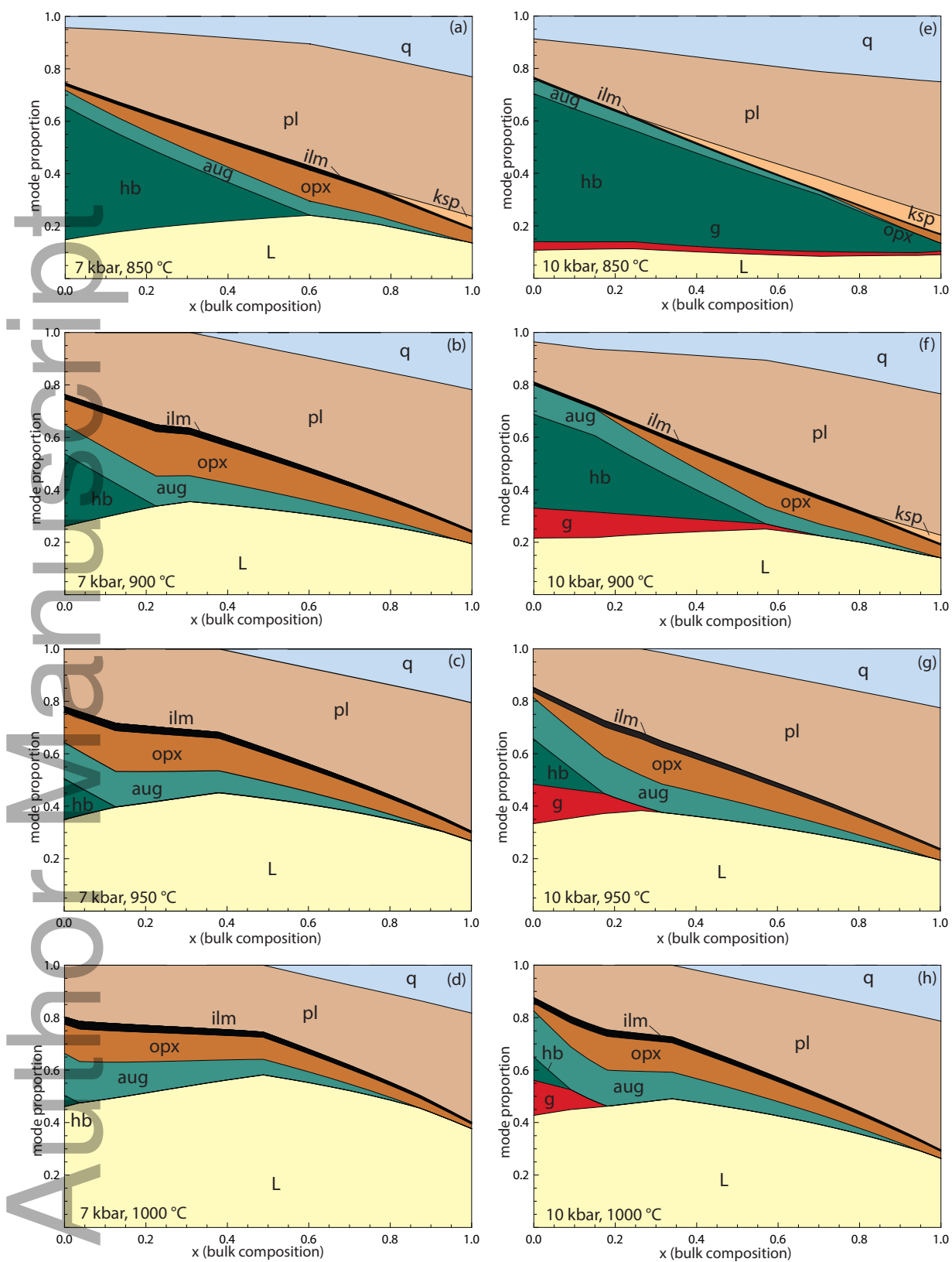


Fig. 7

