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Regional Metamorphism within a Creationist Framework: What Garnet Compositions Reveal

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Abstract

The "classical" model for regional metamorphic zones presupposes elevated temperatures and pressures due to deep burial and deformation/tectonic forces over large areas over millions of years—an apparent insurmountable hurdle for the creationist framework. One diagnostic metamorphic mineral is garnet, and variations in its composition have long been studied as an indicator of metamorphic grade conditions. Such compositional variations that have been detected between and within grains in the same rock strata are usually explained in terms of cationic fractionation with changing temperature during specific continuous reactions involving elemental distribution patterns in the rock matrix around the crystallizing garnet. Garnet compositions are also said to correlate with their metamorphic grade.

However, contrary evidence has been ignored. Compositional patterns preserved in garnets have been shown to be a reflection of compositional zoning in the original precursor minerals and sediments. Compositional variations between and within garnet grains in schists that are typical metapelites at Koongarra in the Northern Territory, Australia, support this minority viewpoint. Both homogeneous and compositionally zoned garnets, even together in the same hand specimen, display a range of compositions that would normally reflect widely different metamorphic grade and temperature conditions during their supposed growth. Thus the majority viewpoint cannot explain the formation of these garnets. It has also been demonstrated that the solid-solid transformation from a sedimentary chlorite precursor to garnet needs only low to moderate temperatures, while compositional patterns only reflect original depositional features in sedimentary environments. Thus catastrophic sedimentation, deep burial and rapid deformation/tectonics with accompanying low to moderate temperatures and pressures during, for example, a global Flood and its aftermath have potential as a model for explaining the "classical" zones of progressive regional metamorphism.

Keywords

regional metamorphism, grade zones, garnets, compositional zoning, sedimentary precursors

Introduction

Of the two styles of metamorphism, contact and regional, the latter is most often used to argue against the young-earth creation-Flood model. It is usually envisaged that sedimentary strata over areas of hundreds of square kilometers were subjected to elevated temperatures and pressures due to deep burial and deformation/tectonic forces over millions of years. The resultant mineralogical and textural transformations are said to be due to mineral reactions in the original sediments under the prevailing temperature-pressure conditions.

Often, mapping of metamorphic terrains has outlined zones of strata containing mineral assemblages that are believed to be diagnostic and confined to each zone respectively. It is assumed that these mineral assemblages reflect the metamorphic transformation conditions specific to each zone, so that by traversing across these metamorphic zones higher metamorphic grades (due to former higher temperature-pressure conditions) are progressively encountered. Amongst the metamorphic mineral assemblages diagnostic of each zone are certain minerals whose presence in the rocks is indicative of each zone, and these are called index minerals. Garnet is one of these key index minerals. Across a metamorphic terrain, the line along which garnet first appears in rocks of similar composition is called the garnet isograd ("same metamorphic grade") and represents one boundary of the garnet zone. With increasing metamorphic grade and in other zones garnet continues to be an important constituent of the mineral assemblages.

Garnet Compositions

Variation in garnet compositions, particularly their MnO content, was for a long time used as an estimator of regional metamorphic grade. Goldschmidt[1] first noted an apparent systematic decrease in MnO content with increase in metamorphic grade, a relationship which he attributed to the incorporation of the major part of the rock MnO in the earliest formed garnet. Miyashiro[2] and Engel and Engel[3] also followed this line of thought, Miyashiro suggesting that the larger Mn^{2+} ions were readily incorporated in the garnet structure at the lower pressures, whereas at higher pressures smaller Fe^{2+} and Mg^{2+} were preferentially favored. Thus it was proposed that a decrease in garnet MnO indicated an increase in grade of regional metamorphism. Lambert[4] produced corresponding evidence for a decrease in garnet CaO with increasing metamorphic grade. Sturt[5] demonstrated in somewhat pragmatic fashion what appeared to be a general inverse relationship between (MnO + CaO) content of garnet and overall grade of metamorphism, a scheme which was taken up and reinforced by Nandi[6].

Not all investigators, however, agreed with this line of thinking. Kretz[7] demonstrated the possible influence of coexisting minerals on the composition of another given mineral. Variation in garnet composition was seen to depend not only on pressure-temperature variation but also to changes in the compositions of the different components within its matrix as these responded to changing metamorphic grade. Albee[8], like Kretz and Frost[9], examined elemental distribution coefficients in garnet-biotite pairs as possible grade indicators, but concluded that results were complex and equivocal, and suggested that metamorphic equilibrium was frequently not attained. Similarly, Evans[10] suggested caution in the interpretation of increasing garnet MgO as indicating increasingly higher pressures of metamorphism. He pointed out that the volume behavior of Mg-Fe exchange relations between garnet and other common silicates indicates that, for given bulk compositions, the Mg-Fe ratios in garnet will decrease with pressure.

With the advent of the electron probe microanalyzer it became possible to detect compositional variations even within mineral grains including garnet, where often it was found that traversing from cores to rims of grains the MnO and CaO contents decreased with a concomitant increase in FeO and MgO[11]. Hollister[12] concluded that this zoning arose by partitioning of MnO in accordance with the Rayleigh fractionation model between garnet and its matrix as the former grew. Perhaps more importantly he drew attention to the preservation of such zones, that remained unaffected by diffusion, and hence unequilibrated, throughout the later stages of the metamorphism that was presumed to have induced their growth. Concurrently, Atherton and Edmunds[13] suggested that the zoning patterns reflected changing garnet-matrix equilibrium conditions during growth and/or polyphase metamorphism, but that once formed garnet and its zones behaved as closed systems unaffected by changes in conditions at the periphery of the growing grain.

Through his own work, and that of Chinner[14] and Hutton[15], Atherton[16] drew attention to the presence of garnets of quite different compositions in rocks of similar grade, and sometimes in virtual juxtaposition. His conclusion was that the MnO content, and indeed the whole divalent cation component, of garnet was substantially a reflection of host rock composition and that any simple tie between garnet composition and metamorphic grade was unlikely. Subsequently Atherton[17] suggested that zoning and progressive changes in garnet compositions were due to changes in distribution coefficients of the divalent cations with increase in grade, and considered that "anomalies in the sequence (were) explicable in terms of variations in the compositions of the host rock."

Müller and Schneider[18] found that the MnO content of garnet reflected not only metamorphic grade and chemistry of the host rocks, but also their oxygen fugacity. They rejected Hollister's Rayleigh fractionation model and concluded that decrease in Mn, and concomitant increase in Fe, in garnet with increasing grade stemmed from a progressive reduction in oxygen fugacity. Hsu[19], in his investigation of phase relations in the Al-Mn-Fe-Si-O-H system, had found that the stability of the almandine end-member is strongly dependent on oxygen fugacity, and is favored by assemblages characterized by high activity of divalent Fe. In contrast, the activity of divalent Mn is less influenced by higher oxygen fugacity. Thus Müller and Schneider[20] concluded that the observed decrease in Mn in garnet with increasing metamorphic grade is due to the buffering capacity of graphite present near nucleating garnets. With increasing grade the graphite buffer increasingly stabilizes minerals dependent on low oxygen fugacity, that is, almandine is increasingly formed instead of spessartine. Müller and Schneider also noted that some of their garnets were not zoned, but exhibited inhomogeneities distributed in irregular domains throughout the garnet grains.

Miyashiro and Shido[21], in a substantially theoretical treatment, concluded that the principal factor controlling successive garnet compositions is the amount and composition of the garnet already crystallized, since the matrix will be correspondingly depleted in the oxides present in the earlier formed garnet. Also using a theoretical approach, Anderson and Buckley[22] showed that for "reasonable diffusion coefficients and boundary conditions" observed zoning profiles in garnets could be explained quite adequately by diffusion principles: that given original homogeneities in the parent rock, the interplay of diffusion phenomena could explain variation of zoning profiles in separate grains of an individual mineral species in domains as small as that of a hand specimen.

Tracy, Robinson, and Thompson[23] noted that garnets from metamorphosed pelitic assemblages show, in different metamorphic zones,

> element distribution patterns that are complex functions of rock bulk composition, specific continuous reactions in which garnet is involved, P-T history of the rock, homogeneous diffusion rates with garnet, and possibly also

the availability of metamorphic fluids at the various stages of garnet development.

They applied preliminary calibrations of garnet-biotite and garnet-cordierite Fe-Mg exchange reactions and several Fe-Mg-Mn continuous mineral reactions to the results of very detailed studies of zoned garnets in order to evaluate changing P-T conditions during prograde and retrograde metamorphism in central Massachusetts (USA).

Stanton[24–27], in his studies of Broken Hill (New South Wales, Australia) banded iron formations, suggested that the garnets represented *in situ* transformation of somewhat manganiferous chamositic septachlorite, and that any zoning reflected the original oolitic structure of the sedimentary chamosite. In a further study, Stanton and Williams[28] concluded that, because compositional differences occur on a fine (1–2 mm) scale in garnets within a simple one-component matrix (quartz), garnet compositions must faithfully reflect original compositional variations within the chemical sediments, and not represent variations in metamorphic grade.

McAteer[29] demonstrated the presence in a garnet-mica schist of two compositionally and texturally distinct garnet types, which she attributed to a sequence of mineral reactions that proceeded with changing thermal history of the rock. Of the two types, one was coarse-grained and zoned (MnO and CaO decreasing towards grain margins), while the other was fine-grained and essentially uniform in composition. Attainment of chemical equilibrium between all garnets and their rock matrix, but maintenance of disequilibrium within large garnets, appears to have been assumed.

In a review of research on compositional zoning in metamorphic minerals, Tracy[30] ignored Stanton's demonstration that the compositional zoning in garnets can only be explained in some metamorphic rocks as faithful reflections of original compositional variations within the precursor minerals and sediments, and not as a function of variations in metamorphic grade or cationic supply during crystal growth. Instead, Tracy summarized the various models already proposed—cationic fractionation particularly of Mn (resulting in variations in the supply of cations) with changing temperatures during progressive metamorphism, and reaction partitioning of cations which depends upon the exact mineralogical composition of the reservoir or matrix surrounding any one garnet grain, especially relative proportions of matrix minerals that are in direct reaction relation with a garnet grain. These models both correlate changes in garnet composition with increasing metamorphic grade, relying on mineral reactions and diffusion of cations to explain compositional zoning trends, which it is envisaged change as mineral reactions and temperatures change.

This is still the consensus viewpoint. Loomis[31], Spear[32], and Spear, Kohn, Florence, and Menard[33], for example, insist that metamorphic garnets undergo a form of fractional crystallization which involves fractionation of material into the interior of a crystallizing garnet grain with consequent change in the effective bulk composition, the zoning profile preserved in the garnet being a function of the total amount of material that has fractionated. Furthermore, Spear insists that because intracrystalline diffusion is so slow at these conditions, the interior of the garnet is effectively isolated from chemical equilibrium with the matrix. Spear then points to the work of Yardley[34] to insist that with increasing temperatures intracrystalline diffusion within garnet grains becomes more rapid until eventually all chemical zoning is erased. Indeed, Yardley claimed to have found that at the temperatures of staurolite and sillimanite grade metamorphism internal diffusion of cations within garnet grains is sufficient to eliminate the zoning that developed during earlier growth.

Yardley also rightly pointed out that the fractionation models for garnet zoning assume that that diffusion is negligible at lower metamorphic grades. That there is negligible cationic diffusion in garnet at lower grades is amply demonstrated in the garnets described by Olympic and Anderson[35], whose pattern of chemical zoning coincided with textural (optical) zones, clearly representing distinct presumed growth stages. Nevertheless, even where textural (optical) zones are not evident there may still be chemical zoning, as found by Tuccillo, Essene, and van der Pluijm[36]. Indeed, confusing the picture somewhat, Tuccillo, Essene, and van der Pluijm found that the chemical zoning in their garnets under study, though from a high grade metamorphic terrain, was not only preserved but was the reverse in terms of cations to that normally expected, and this they attributed to a diffusional retrograde effect.

However, the work of Stanton and Williams[37], who found marked compositional changes from one garnet to the next on a scale of 1–2 mm in finely bedded banded iron formations in the high grade metamorphic terrain at Broken Hill (New South Wales, Australia), has been ignored. They found that

> in view of the minuteness of the domains involved it appears evident that compositional variation cannot be attributed to variations in metamorphic pressures, temperatures or oxygen fugacities. Neither can they be attributed to variation in garnet-matrix partition functions, as most of the garnets occur in one simple matrix—quartz.

They therefore concluded

> that in spite of the high (sillimanite) grade of the relevant metamorphism, any equilibration of garnet

compositions, and hence any associated inter-grain metamorphic diffusion, has been restricted to a scale of less than 1 mm; that garnet compositions here reflect original rock compositions on an ultra-fine scale, and have no connotations concerning metamorphic grade; that, hence, the garnets must arrive from a single precursor material, earlier suggested to be a manganiferous chamositic septachlorite; and that the between-bed variation: within-bed uniformity of garnet composition reflects an original pattern of chemical sedimentation—a pattern preserved with the utmost delicacy through a period of approximately 1800×10^6 years and a metamorphic episode of sillimanite grade.[38]

These findings are clearly at odds with the claims of other investigators, yet Stanton[39, 40] has amassed more evidence to substantiate his earlier work. To test these competing claims, therefore, a suitable area of metamorphic terrain with schists containing garnet porphyblasts was chosen for study.

The Koongarra Area

The Koongarra area is 250 km east of Darwin (Northern Territory, Australia) at latitude 12°52′S and longitude 132°50′E. The regional geology has been described in detail by Needham and Stuart-Smith[41] and by Needham,[42, 43] while Snelling[44] describes the local Koongarra area geology.

The Archean basement to this metamorphic terrain consists of domes of granitoids and granitic gneisses (the Nanambu Complex), the nearest outcrop being 5 km to the north. Some of the lowermost overlying Lower Proterozoic metasediments were accreted to these domes during amphibolite grade regional metamorphism (estimated to represent conditions of 5–8 kb and 550–630 °C) at 1800–1870 Ma. Multiple isoclinal recumbent folding accompanied metamorphism. The Lower Proterozoic Cahill Formation flanking the Nanambu Complex has been divided into two members. The lower member is dominated by a thick basal dolomite and passes transitionally upwards into the psammitic upper member, which is largely feldspathic schist and quartzite. The uranium mineralization at Koongarra is associated with graphitic horizons within chloritized quartz-mica (±feldspar ±garnet) schists overlying the basal dolomite in the lower member.

Owing to the isoclinal recumbent folding of metasedimentary units of the Cahill Formation, the typical rock sequence encountered at Koongarra is probably a tectono-stratigraphy (from youngest to oldest):

—muscovite-biotite-quartz-feldspar schist (at least 180 m thick)
—garnet-muscovite-biotite-quartz schist (90–100 m thick)
—sulfide-rich graphite-mica-quartz schist (±garnet) (about 25 m thick)
—distinctive graphite-quartz-chlorite schist marker unit (5–8 m thick)
—quartz-chlorite schist (±illite, garnet, sillimanite, muscovite) (50 m thick)—contains the mineralized zone

Polyphase deformation accompanied metamorphism of the original sediments, that were probably dolomite, shales, and siltstones. Johnston[45] identified a D_2, event as responsible for the dominant S, foliation of the schist sequence, which dips at 55° to the south-east at Koongarra.

Superimposed on the primary prograde metamorphic mineral assemblages is a distinct and extensive primary alteration halo associated with the uranium mineralization at Koongarra. This alteration extends for up to 1.5 km from the ore in a direction perpendicular to the disposition of the host quartz-chlorite schist unit, because the mineralization is essentially stratabound. The outer zone of the alteration halo is most extensively developed in the semi-pelitic schists and is manifested by the pseudomorphous replacement of biotite by chlorite, rutile and quartz, and feldspar by sericite. Metamorphic muscovite, garnet, tourmaline, magnetite, pyrite, and apatite are preserved. In the inner alteration zone, less than 50 m from ore, the metamorphic rock fabric is disrupted, and quartz is replaced by pervasive chlorite and phengitic mica, and garnet by chlorite. Relict metamorphic phases, mainly muscovitic mica, preserve the S_2 foliation. Coarse chlorite after biotite may also be preserved.

Koongarra Garnets

Garnets are fairly common in the garnet-muscovite-biotite-quartz schist unit at Koongarra, being usually fresh and present in large quantities, often grouped, within various macroscopic layers. Within the inner alteration halo and the quartz-chlorite schist hosting the mineralization most of the garnets have largely been pseudomorphously replaced by chlorite. Occasionally garnet remnants remain within the pseudomorphous chlorite knots, or the common boxwork textures within these pseudomorphous chlorite knots confirm that the chlorite is pseudomorphously replacing garnets.

The garnets are always porphyroblastic, and sometimes idioblastic, indicative of pre-kinematic growth. They may be up to 2 cm in diameter, but meet are typically about 0.5 cm across. Often, the garnets also show some degree of rolling and sygmoidal traces of inclusions. These features are usually regarded as evidence for syn-kinematic growth.[46] In a few of these cases rolling is minimal and inclusion traces pass out uninterrupted into

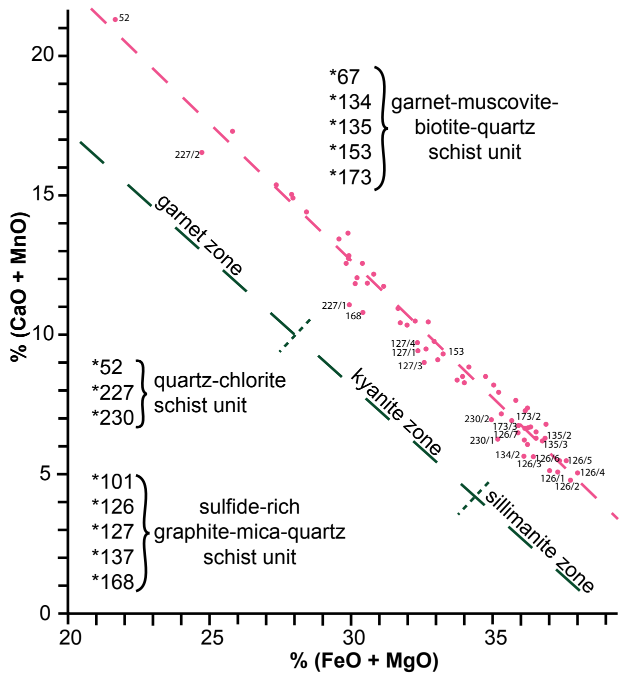

Fig. 1. Plot of (CaO + MnO) versus (FeO + MgO) variations in all analyzed Koongarra garnets, after the style of Nandi.[47] His line of best fit for his data is shown, plus his boundaries between garnet compositions of each metamorphic zone. The line of best fit through the Koongarra data is shown, as are the sample/garnet numbers of all the homogeneous garnets. The analytical data are from Snelling.[48]

the surrounding schist. The schistosity is often draped around these garnet porphyroblasts and sometimes the latter are slightly flattened. Thus the last stages of garnet growth occurred during the final stages of the D_2 deformation of the prograde metamorphic layering S_1, that is, during the development of the predominant S_2 schistosity. This, in turn, implies that garnet development and growth took place before and during the deformation of the earlier S_1 schistosity, that is, pre- and syn-kinematic to the S_2 schistosity and D_2 deformation.

Thirteen garnet-containing samples were chosen from three of the schist units—the ore-hosting quartz-chlorite schist (three samples), the sulfide-rich graphite-mica-quartz schist (five samples), and the garnet-muscovite-biotite-quartz schist (five samples). These 13 samples contained a total of 33 garnets that were all analyzed using an electron probe microanalyzer. Composite point analyses were made where garnets were of uniform composition, while traverses revealed compositional zoning when present. All results are listed in Snelling.[49]

All the garnets are essentially almandine, the Fe^{2+} end-member, with varying amounts of spessartine (Mn^{2+}), pyrope (Mg^{2+}) and grossularite (Ca^{2+}) structural units/end-members substituting in the crystal lattices. Tucker[50] reported an analysis of a Koongarra Fe-rich garnet with an Fe_2O_3 content of 6.22%, implying that the substitution of the andradite (Fe^{3+}) end-member may be quite substantial. The compositional variations in Fe, Mn, Ca, and Mg both between and within the analyzed garnets were plotted in ternary diagrams, and from these it was determined that two principal substitutions have occurred—Mn for Fe and Mg for Ca, though the latter is very minor compared to the former. Nevertheless, these Koongarra garnets revealed the general inverse relationship between (CaO+MnO) and (FeO+MgO), which can be seen clearly in Fig. 1.

Of the 33 garnets analyzed, 22 had homogeneous compositions and only 11 were compositionally zoned. In the three samples from the ore-hosting quartz-chlorite schist unit five garnets were analyzed and all were compositionally homogeneous, whereas in the overlying sulfide-rich graphite-mica-quartz schist unit the five selected samples contained 16 garnets, analyses of which revealed that 11 were compositionally homogeneous and the other five were compositionally zoned. Furthermore, four of the ten samples from the two garnet-bearing schist units overlying the ore-hosting quartz-chlorite schist contain both compositionally homogeneous and zoned garnets in a ratio of six zoned to eight homogeneous, without any textural evidence to distinguish between the two. The other samples in these schist units either had all compositionally homogeneous garnets or all compositionally zoned garnets.

Traverses of point analyses across the compositionally zoned garnets enabled the compositional zoning to be quantified. The most pronounced zoning is with respect to MnO, with cores generally having higher MnO

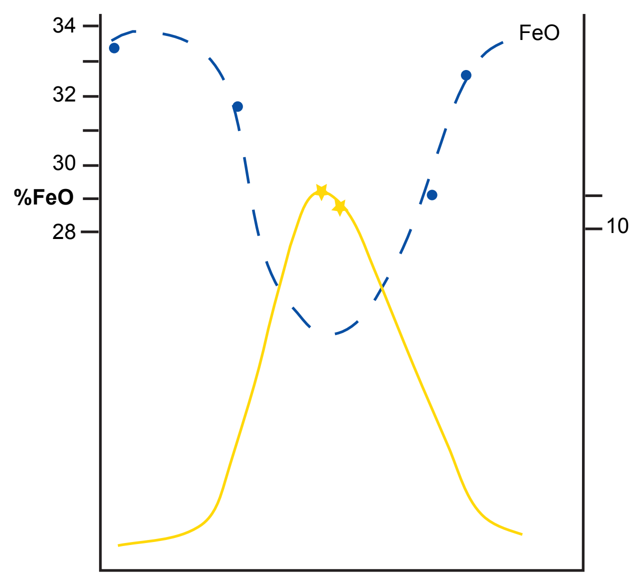

Fig. 2. A line profile across a zoned garnet grain in sample 173 from the garnet-muscovite-biotite-quartz schist unit at Koongarra, showing the variations in FeO, CaO, MgO, and MnO. Data from Snelling.[51]

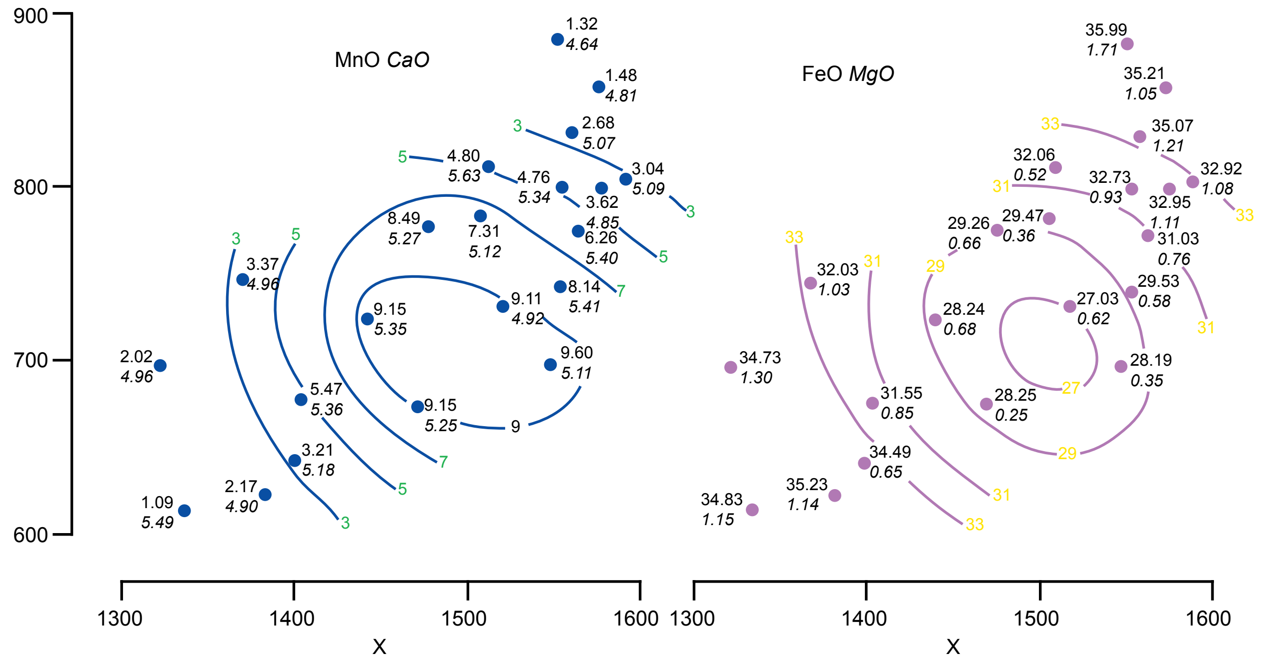

Fig. 3. Plan view of a compositionally zoned garnet grain in sample 101 from the sulfide-rich graphite-mica-quartz schist unit at Koongarra showing the FeO, MgO, MnO, and CaO contents at each analyzed point. Compositional contours have been drawn in for FeO and MnO. The data are from Snelling.[52]

relative to rims, and as FeO substitutes for MnO, FeO follows an inverse trend (figs. 2 and 3). Zonation with respect to CaO and MgO is not pronounced, but generally CaO follows the MnO trend and MgO follows FeO. This is understandable in terms of the ionic radii for the ions involved.[53] Fig. 4 shows the geochemical trends of all the analyzed zoned garnets from cores to rims, the strong compositional differences following the same inverse relationship between (CaO+MnO) and (FeO+MgO) as the compositionally homogeneous garnets.

Discussion

Garnets analyzed in the Koongarra schists are typical of garnets from metapelites, the compositional trends between and within garnet grains being almost identical to those obtained from garnets in metapelites in metamorphic terrains in other parts of the world.[54] The (CaO+MnO) versus (FeO+MgO) plot in Fig. 1 has marked on it the line of best fit and compositional subdivisions based on the typical zones of progressive regional metamorphic grade as determined by Nandi.[55] The Koongarra data are distributed along their own line of best fit and straddle the garnet, kyanite and sillimanite zones of Nandi's data.

Nandi's contention was that (CaO+MnO) content of garnets decreased with increasing metamorphic grade, as originally proposed by Sturt[56] but challenged by Bahnemann.[57] Bahnemann studied garnet compositions in granulite facies gneisses of the Messina district in the Limpopo Folded Belt of Northern Transvaal and found compositional variations which were comparable to those found by Nandi, but which scattered across the metamorphic zones of Nandi's diagram. However, Bahnemann was able to show, from earlier work on the same rocks[58, 59] and by using Currie's cordierite-garnet geothermometer,[60] that whatever the precise temperature-pressure conditions may have been during

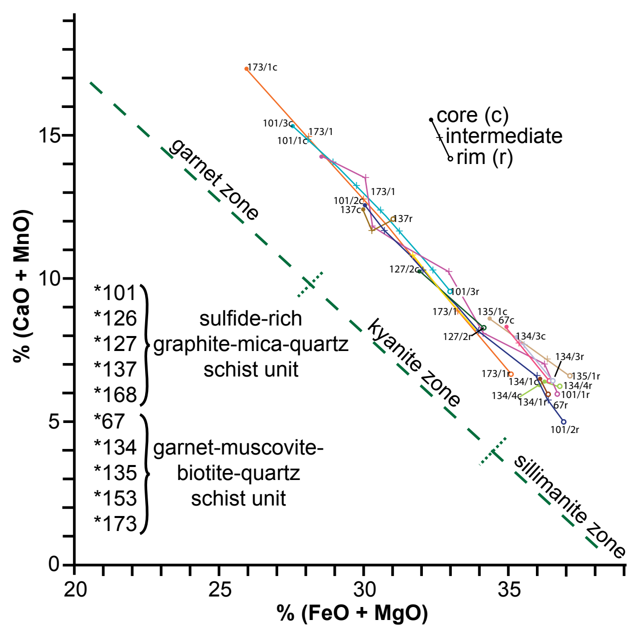

Fig. 4. Plot of (CaO+MnO) versus FeO+MgO) variations in all analyzed zoned garnets at Koongarra after the style of Nandi.[61] Again, his line of best fit for his data is shown, plus his boundaries between garnet compositions of each metamorphic zone. Core to rim compositions are plotted with lines linking them between their intermediate compositions. Sample/garnet numbers are shown. The data are from Snelling.[62]

the formation of the garnets, they were high and uniform over much of the Messina district. Thus Bahnemann concluded that the (CaO+MnO) versus (FeO+MgO) trends on the plot reflected host rock chemistry, and that metamorphic isograds cannot be inferred from the position of points on such a line. Bahnemann nevertheless noted that his line of best fit differed slightly from that of Nandi and suggested that his own line may be characteristic for the garnets from the area he had studied.

The (CaO+MnO) versus (FeO+MgO) plots of the garnets at Koongarra (Figs. 1 and 4) also define a line of best fit that differs from that of Nandi. The Koongarra schists contain some graphite, which could be an additional factor in the growth of the zoned garnets, the iron-rich rims presumably being produced by graphite buffering as the temperature of metamorphism increased. However, in four of the thirteen samples there are both homogeneous and compositionally zoned garnets side-by-side. Furthermore, in one instance (sample 173) there is a compositionally zoned garnet with a core that has almost three times the (CaO+MnO) content of its rim, yet the latter's composition is very similar to the two other adjoining homogeneous garnet grains. If the presence of graphite buffering the metamorphic reactions was needed to produce the zoned garnet, then why the adjoining homogeneous garnets? A far more logical explanation is that the zonation and compositional variations are due to chemical variations in the original precursor minerals and sedimentary rocks, as suggested by Stanton.[63, 64]

When Nandi produced his original plot, he used compositional data of 84 samples of garnets belonging to different grades of regionally metamorphosed pelitic rocks which he compiled from six papers in the then current literature. One of these, Sturt,[65] drew on some of the same data, which comes from metamorphic terrains such as the Stavanger area of Norway, the Gosaisyo-Takanuki area of Japan, the Adirondacks of the USA, and the Moine and Dalradian of Scotland. When garnet porpyroblasts of quite different compositions from the different metamorphic terrains were plotted on a (CaO+MnO) versus (FeO+MgO) diagram Nandi found that they grouped along a line of best fit in subdivisions that reflected the different metamorphic grade zones from which they came—garnet, kyanite, and sillimanite (see Figs. 1 and 4). Nandi showed virtually no overlap in the compositions of garnets from different grades at the boundaries he drew across his line of best fit, yet on Sturt's similar plot with garnet data from the same and other metamorphic terrains there was considerable overlap of compositions between garnets from the different metamorphic grades. Furthermore, those garnets that Sturt recorded as coming from garnet grade metapelites almost exclusively plotted in Nandi's kyanite grade grouping, so the picture is far from being clear-cut as Nandi originally reported it. In other words, these data do not show that garnet compositions systematically change with increasing metamorphic grade.

As Bahnemann found in the Limpopo Folded Belt, where garnets from a number of different granulite facies host-rocks showed a wide range of composition yet reflected the same general pressure-temperature conditions of metamorphism, the data here from the Koongarra schists show widely divergent garnet compositions, even within individual grains, yet the schists are typical metapelites of a classical garnet zone within an amphibolite grade metamorphic terrain. The presence of garnet in these schists without either kyanite and/or sillimanite confirms that these schists fall within the garnet zone, although kyanite has been observed with staurolite in equivalent Cahill Formation schists to the south.[66] Nevertheless, it is inconceivable that there would be any appreciable variation in metamorphic temperature-pressure conditions over the approximate 370 m of strike length and 90 m of stratigraphic range from which the studied samples came. Indeed, even in the stratigraphically lowermost ore-hosting quartz-chlorite schist unit the five compositionally homogeneous garnets in the three samples at that stratigraphic level almost spanned the complete compositional range in Fig. 1, from extremely high (CaO+MnO) content in the supposedly lower temperature end of the garnet zone to a lower (CaO+MnO) and high (FeO+MgO) content at the supposedly high temperature end of the kyanite zone.

Yet if any of these schist units at Koongarra should have been at a higher prograde metamorphic temperature it would have been this quartz-chlorite schist unit, because it is stratigraphically closer to the Nanambu Complex basement towards which the metamorphic grade increased, causing some of the metasediments closest to it to be accreted to it. Similarly, one of the samples from the sulfide-rich graphite-mica-quartz schist unit (sample 101) has in it a garnet whose core could be regarded as being of garnet zone composition, while its rim is supposedly indicative of the sillimanite zone.

These numerous "anomalies" must indicate that garnet compositions are substantially a reflection of compositional domains within the precursor sediments and/or minerals, and **not** metamorphic grade. Stanton[67, 68] has shown that diffusion during regional metamorphism has been restricted to relatively minute distances (<1 mm) and that there is no clear, direct evidence of prograde metamorphic mineral reactions, so that metamorphic equilibrium does not appear to have been attained through even very small domains. Even though the majority of researchers maintain that compositional zoning in garnets has been due to mineral reactions and cationic fractionation, and that at higher grades the compositional zoning is homogenized by diffusion, Stanton and Williams[69] have clearly shown at Broken Hill that at the highest grades of metamorphism the compositional zoning in garnets is neither homogenized nor the result of either mineral reactions or cationic fractionation, but an accurate preservation of compositional zoning in the original precursor oolites in the precursor sediment. Nevertheless, while their conclusion is not questioned, their timescale is, because it strains credulity to suppose that the original pattern of chemical sedimentation could have been preserved with the "utmost delicacy" through a presumed period of 1.8 billion years.

What is equally amazing is the discovery by Stanton[70] of distinctly hydrous "quartz" in well-bedded quartz-muscovite-biotite-almandine-spinel rocks also in the Broken Hill metamorphic terrain. He comments that it seems "remarkable" that this silica should still retain such a notably hydrous nature after 1.8 billion years that included relatively high-grade (that is, high temperature-pressure) metamorphism! Not only does this discovery confirm that metamorphic quartz has been produced by dehydration and transformation *in situ* of precursor silica gel and/or chert, but that the temperatures, pressures and timescales normally postulated are not necessarily required.

Stanton[71] maintains that it has long been recognized that particular clays and zeolites derive in many instances from specific precursors. Likewise, it is self-evident and unavoidable that many metamorphosed bedded oxides (including quartz), together with carbonates and authigenic silicates such as the feldspars, have derived from sedimentary/diagenitic precursors, and the establishment thereby of this precursor derivation for at least some regional metamorphic minerals is a principle, not an hypothesis. What Stanton then proceeds to show is how this principle applies to the broader spectrum of metamorphic silicates, including almandine garnet.

He points to his earlier evidence[72, 73] that almandine has derived directly from a chamositic chlorite containing very finely dispersed chemical SiO_2, and suggests that dehydration and incorporation of this silica into the chlorite structure induces in situ transformation to the garnet structure. Furthermore, instability induced by Mn, and perhaps small quantities of Ca, in the structure may predispose the chlorite to such transformation. Any silica in excess of the requirements of this process aggregates into small rounded particles within the garnet grain—the quartz "inclusions" that are almost a characteristic feature of the garnets of metapelites, including the garnets at Koongarra. Stanton then supports his contention with electron microprobe analyses of several hundred chlorites, from metamorphosed stratiform sulfide deposits in Canada and Australia, and of almandine garnets immediately associated with the chlorites. These analyses plot side-by-side on ternary diagrams, graphically showing the compositional similarities of the chlorites in these original chemical sediments to the garnets in the same rock that have been produced by metamorphism. This strongly suggests that the process was one of a solid-solid transformation, with excess silica producing quartz "inclusions." As Stanton insists, why should these inclusions be exclusively quartz if these garnets had grown from mineral reactions within the rock matrix, because the latter contains abundant muscovite, biotite and other minerals in addition to quartz, minerals that should also have been "included" in the growing garnet grains?

Stanton and Williams[74] have conclusively demonstrated that the compositional zones within individual garnet porphyroblasts reflect compositional zoning in precursor sedimentary mineral grains. Thus, if primary (depositional) compositional features have led to a mimicking of metamorphic grade,[75, 76] then it has been shown[77–79] that the classical zones of regional metamorphic mineral assemblages may instead reflect facies of clay and clay-chlorite mineral sedimentation, rather than variations in pressure-temperature conditions in subsequent metamorphism. Stanton[80] goes on to say that if regional metamorphic silicates do develop principally by transformation and grain growth, the problem of the elusive metamorphic reaction in the natural milieu is resolved. There is no destabilizing of large chemical domains leading to extensive diffusion, no widespread reaction tending to new equilibria among minerals. Traditionally it has been supposed that as metamorphism progressed each rock unit passed through each successive grade, but the common lack of evidence that "high-grade" zones have passed through all the mineral assemblages of the "lower-grade" zones can now be accounted for. The real metamorphic grade indicators are then not the hypothetical intermineral reactions usually postulated, but the relevant precursor transformations, which may be solid-solid or in some cases gel-solid. Stanton concludes that it would be going too far to maintain that there was no such thing as a regional metamorphic mineral reaction, or that regional metamorphic equilibrium was never attained, but the role of metamorphic reactions in generating the bulk of regional metamorphic mineral matter is "probably, quite contrary to present belief, almost vanishingly small."

The other key factor in elucidating regional metamorphic grades, zones and mineral compositions besides precursor mineral/sediment compositions would be the temperatures of precursor transformations, rather than the temperatures of presumed "classical" metamorphic mineral reactions. It is thus highly significant that dehydration and incorporation of silica into the chlorite structure induces *in situ* transformation to garnet at only low to moderate temperatures and pressures that are conceivable over short time-scales during catastrophic sedimentation, burial and tectonic activities. Indeed, the realization that the "classical" zones of progressive regional metamorphism are potentially only a reflection of variations in original sedimentation, as can be demonstrated in continental shelf depositional facies today, provides creationists with a potential scientifically satisfying explanation of regional metamorphism within their time framework, which includes catastrophic sedimentation, deep burial and rapid deformation/tectonics with accompanying low to moderate temperatures and pressures during, for example, the global Flood and its aftermath.[81]

Conclusions

Garnets in the amphibolite grade schists at Koongarra show wide compositional variations both within and between grains, even at the thin section scale, a pattern which is not consistent with the current consensus on the formation of metamorphic garnets. Rather than elevated temperatures and pressures being required, along with fractionational crystallization, elemental partitioning and garnet-matrix reaction partitioning, the evidence at Koongarra and in other metamorphic terrains is consistent with solid-solid transformation at moderate temperatures of precursor sedimentary chlorite, complete with compositional variations due to precursor oolites, into garnet such that the compositional variations in the precursor chlorite are preserved without redistribution via diffusion. These compositional variations in garnets contradict the "classical" view that particular compositions represent different metamorphic grade zones, since at Koongarra the compositional variations even in single garnets span wide ranges of presumed metamorphic temperatures and grades. Thus the "classical" explanation for progressive regional metamorphism, different grade zones being imposed on original sedimentary strata over hundreds of square kilometers due to elevated temperatures and pressures resulting from deep burial and deformation/tectonic forces over millions of years, has to be seriously questioned. A feasible alternative is that these zones represent patterns of original precursor sedimentation, such as we see on continental shelves today. Creationists may thus be able to explain regional metamorphism within their time framework on the basis of catastrophic sedimentation, deep burial and rapid deformation/tectonics, with accompanying low to moderate temperatures and pressures, during, for example, the global Flood and its aftermath.

References

1. Goldschmidt, V.M., 1920. Geologisch-petrographische studien im hochgebirge des südlichen Norwegen. V. Die injektoinmetamorphose im stavangergeblet. *Skrifter Videnskapsliq Selskap, 1* Math.-Naturw. Kl. No. 10. Oslo.
2. Miyashiro, A. (1953). Calcium-poor garnet in relation to metamorphism. *Geochimica et Cosmochimica Acta* **4**:179–208.
3. Engel, A.E.J. and C.G. Engel, 1960. Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York, Part II. *Bulletin of the Geological Society of America* **71**:1–58.
4. Lambert, R.St.J., 1959. The mineralogy and metamorphism of the Moine Schists of the Morer and Knoydart Districts of Inverness-shire. *Transactions of the Royal Society of Edinburgh* **63**:553–588.
5. Sturt, D.A., 1962. The composition of garnets from pelitic schists in relation to the grade of regional metamorphism. *Journal of Petrology* **3**:181–191.
6. Nandi, K., 1967. Garnets as indices of progressive regional metamorphism. *Mineralogical Magazine* **36**:89–93.
7. Kretz, R., 1959. Chemical study of garnet, biotite and hornblende from gneisses of Southwestern Quebec, with emphasis on the distribution of elements in co-existing minerals. *Journal of Geology* **67**:371–402.
8. Albee, A.L., 1965. Distribution of Fe, Mg and Mn between garnet and biotite in natural mineral assemblages. *Journal of Geology* **73**:155–164.
9. Frost, M.J., 1962. Metamorphic grade and iron-magnesium distribution between co-existing garnet-biotite and garnet-hornblende. *Geological Magazine* **99**:427–438.
10. Evans, B.W., 1965. Pyrope garnet—a piezometer or thermometer? *Bulletin of the Geological Society America* **76**:1295–1299.
11. Harte, B. and K.I. Henley, 1966. Zoned almanditic garnets from regionally metamorphosed rocks. *Nature* **210**:689–692.
12. Hollister, L.S., 1966. Garnet zoning: An interpretation based on the Rayleigh Fractionation Model. *Science* **154**:1647–1651.
13. Atherton, M.P. and W.M. Edmunds, 1966. An electron microprobe study of some zoned garnets from metamorphic rocks. *Earth and Planetary Science Letters* **1**:185–193.
14. Chinner, G.A., 1960. Pelitic gneisses with varying ferrous/ferric ratios from Glen Clova, Angus, Scotland. *Journal of Petrology* **1**:178–217.
15. Hutton, C.O., 1962,. Composition of some garnets in low-grade schists. *Transactions of the Royal Society of New Zealand* **1**:129–133.
16. Atherton, M.P., 1966. The composition of garnet in regionally metamorphosed rocks. In, Pitcher, W.S. and G.W. Flynn (eds.), *Controls of metamorphism.* Oliver and Boyd, London, pp. 281–290.
17. Atherton, M.P., 1968. The variation in garnet, biotite and chlorite composition in medium grade pelitic rocks from the Dalradian, Scotland, with particular reference to the zonation in garnet. *Contributions to Mineralogy and Petrology* **8**:347–371.
18, Müller, G. and A. Schneider, 1971. Chemistry and genesis of garnets in metamorphic rocks. *Contributions to Mineralogy and Petrology* **31**:178–200.

19. Hsu, L.C., 1968. Selected phase relationships in the system AI-Mn-Fe-Si-0-H: A model for garnet equilibria. *Journal of Petrology* **9**:40–83.
20. Müller and Schneider, Ref. 18.
21. Miyashiro, A. and F. Shido, 1973. Progressive compositional change of garnet in metapelite. *Lithos* **6**:13–20.
22. Anderson, D.E. and B.R. Buckley, 1973. Zoning in garnets—Diffusion models. *Contributions to Mineralogy and Petrology* **40**:87–104.
23. Tracy, R.J., P. Robinson, and A.B. Thompson, 1976. Garnet composition and zoning in the determination of temperature and pressure of metamorphism, Central Massachusetts. *American Mineralogist* **61**:762–775.
24. Stanton, R.L., 1976a. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 1—Constitution of the "Banded Iron Formations." *Transactions of the Institution of Mining and Metallurgy, London* **85**:B33–B46.
25. Stanton, R.L., 1976b. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 2—Regional metamorphism of banded iron formations and their immediate associates. *Transactions of the Institution of Mining and Metallurgy, London* **85**:B118–B131.
26. Stanton, R.L., 1976c. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 3—banded iron formations and sulfide ore bodies, Constitutional and Genetic Ties. *Transactions of The Institution of Mining and Metallurgy, London* **85**:B131–B141.
27. Stanton, R.L., 1976d. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 4—Environmental synthesis. *Transactions of the Institution of Mining and Metallurgy, London* **85**:B221–B233.
28. Stanton, R.L. and K.L. Williams, 1978. Garnet compositions at Broken Hill, New South Wales, as indicators of metamorphic processes. *Journal of Petrology* **19**:514–529.
29. McAteer, C., 1976. Formation of garnets in a rock from Mallaig. *Contributions to Mineralogy and Petrology* **55**:293–301.
30. Tracy, R.J., 1982. Compositional zoning and inclusions in metamorphic minerals. In, Ferry, J.M. (ed.), *Characterization of Metamorphism Through Mineral Equilibria. Reviews in Mineralogy.* Mineralogical Society of America, Washington DC, vol. 10, chap. 9, pp. 355–397.
31. Loomis, T.P., 1986. Metamorphism of metapelites: Calculations of equilibrium assemblages and numerical simulations of the crystallization of garnet. *Journal of Metamorphic Geology* **4**:201–229.
32. Spear, F.S., 1988. Metamorphic fractional crystallization and internal metasomatism by diffusional homogenization of zoned garnets. *Contributions to Mineralogy and Petrology* **99**:507–517.
33. Spear, F.S., M.J. Kohn, F.P. Florence, and T. Menard, 1991. A model for garnet and plagioclase growth in pelitic schists: Implications for thermobarometry and P-T path determinations. *Journal of Metamorphic Geology* **8**:683–696.
34. Yardley, B.W.D., 1977. An empirical study of diffusion in garnet. *American Mineralogist* **62**:793–800.
35. Olympio, J.C. and D.E. Anderson, 1978. The relationship between chemical and textural (optical) zoning in metamorphic garnets, South Morar, Scotland. *American Mineralogist* **63**:677–689.
36. Tuccillo, M.E., E.J. Essene, and B.A. van der Pluijm, 1990. Growth and retrograde zoning in garnets from high-grade metapelites: Implications for pressure-temperature paths. *Geology* **18**:839–842.
37. Stanton and Williams, Ref. 28.
38. Stanton and Willia,s Ref. 28, p. 514.
39. Stanton, R.L., 1982. An alternative to the Barrovian Interpretation? Evidence from stratiform ores. *Proceedings of the Australasian Institute of Mining and Metallurgy* **282**:11–32.
40. Stanton, R.L., 1989. The precursor principle and the possible significance of stratiform ores and related chemical sediments in the elucidation of processes of regional metamorphic mineral formation. *Philosophical Transactions of the Royal Society of London* **A328**:529–646.
41. Needham, R.S. and P.G. Stuart-Smith, 1980. Geology of the Alligator Rivers Uranium Field. In, Ferguson, J. and A.B. Goleby (eds.), *Uranium in the Pine Creek geosyncline.* International Atomic Energy Agency, Vienna: International Atomic Energy Agency, pp. 233–257.
42. Needham, R.S., 1984. *Alligator River, Northern Territory—1:250,000 Geological Series.* Bureau of Mineral Resources, Geology and Geophysics Australia, *Explanatory Notes, SD 53-1.*
43. Needham, R.S., 1988. Geology of the Alligator Rivers Uranium Field, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics Australia, Bulletin* **224**. Canberra, Australia.
44. Snelling, A.A., 1990. Koongarra uranium deposits. In F.E. Hughes (Ed.), *Geology of the Mineral Deposits of Australia and Papua New Guinea.* The Australasian Institute of Mining and Metallurgy, Melbourne, Australia, pp. 807–812.
45. Johnston, J.D., 1984. Structural evolution of the Pine Creek Inlier and mineralisation therein, Northern Territory, Australia. Unpublished Ph.D. thesis, Monash University, Melbourne, Australia.
46. Spry, A.H., 1969. *Metamorphic Textures.* Pergamon, Oxford.
47. Nandi, Ref. 6.
48. Snelling, A.A., 1980. A geochemical study of the Koongarra Uranium Deposit, Northern Territory, Australia. Unpublished Ph.D. thesis, The University of Sydney, Sydney, Australia.
49. Snelling, Ref. 48.
50. Tucker, D.C., 1975. Wall rock alteration at the Koongarra Uranium Deposit, Northern Territory. Unpublished M.Sc. thesis, James Cook University of North Queensland, Townsville, Australia.
51. Snelling, Ref. 48.
52. Snelling, Ref. 48.

53. Miyashiro, Ref. 2.
54. Müller and Schneider, Ref. 18.
55. Nandi, Ref. 47.
56. Sturt, Ref. 5.
57. Bahnemann, K.P., 1975. Garnets as possible indicators of metamorphic grade in the Limpopo Folded Belt near Messina in the Northern Transvaal. *Transactions of the Geological Society of South Africa* **78**:251–256.
58. Bahnemann, K.P., 1973. The origin of the Singele Granite Gneiss near Messina, Northern Transvaal. *Special Publication of the Geological Society of South Africa* **3**:235–244.
59. Chinner, G.A. and T.R. Sweatman, 1968. A former association of enstatite and kyanite. *Mineralogical Magazine 36*:1052–1060.
60. Currie, K.L., 1971. The reaction 3 Cordierite = 2 Garnet + 4 Sillimanite + 5 Quartz as a geological thermometer in the Opinicon Lake Region, Ontario. *Contributions to Mineralogy and Petrology* **33**:215–226.
61. Nandi, Ref. 47.
62. Snelling, Ref. 48.
63. Stanton, Ref. 39.
64. Stanton, Ref. 40.
65. Sturt, Ref. 5.
66. Needham and Smith, Ref. 41.
67. Stanton, Ref. 39.
68. Stanton, Ref. 40.
69. Stanton and Williams, Ref. 28.
70. Stanton, Ref. 40.
71. Stanton, Ref. 40.
72. Stanton, Ref. 25.
73. Stanton, Ref. 39.
74. Stanton and Williams, Ref. 28.
75. Stanton, Ref. 25.
76. Stanton, Ref. 39.
77. Snelling, A.A., 1994. Towards a creationist explanation of regional metamorphism. *Creation Ex Nihilo Technical Journal* **8**(1):51–77.
78. Stanton, Ref. 39.
79. Stanton, Ref.40.
80. Stanton, Ref.40.
81. Snelling, Ref. 77.