
Towards a Creationist Explanation of Regional Metamorphism

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Abstract

The "classical" model for regional metamorphism presupposes elevated temperatures and pressures due to deep burial and deformation/tectonic forces over large areas over millions of years—an apparently insurmountable problem for the creationist framework. Furthermore, zones of index minerals are said to represent differences in temperatures and pressures, and therefore mineral reactions, across the regionally metamorphosed terrain. However, evidence is now mounting that such mineral reactions do not occur and diffusion is severely limited. Furthermore, rather than temperatures and pressures being the key factors, compositional variations within and between metamorphic minerals are shown to reflect patterns of original sedimentation.

The metasedimentary sheaths surrounding stratiform sulfide orebodies have facilitated the study of regional metamorphic processes on a much smaller scale. Such orebodies were produced by hydrothermal waters discharging both sulfides and a variety of other minerals and chemicals onto the sea-floor, where they have been superimposed on "normal" marine sedimentation. Rapid fluctuations have resulted in zones of different clay and related minerals of varying compositions being found at scales of centimeters and meters. When subsequently metamorphosed, these patterns of sedimentation are reflected in zones identical to the "classical" zones of regional metamorphism, and yet minerals are together in the same assemblage that would normally be regarded as having formed under vastly different temperature and pressure conditions. Thus it is shown that these metamorphic minerals have been primarily formed from precursor minerals and materials by in situ transformation, and at only moderate temperatures and pressures or less. Indeed, several "remarkable" examples of pre-cursor minerals/materials having survived the supposed highest grades of metamorphism over presumed millions of years are adequate testimony against the "classical" model of regional metamorphism.

This leads to a proposal for a creationist explanation of regional metamorphism. Two major events within the creationist framework of earth history are capable of producing regionally metamorphosed terrains—the tectonism, catastrophic erosion, and sedimentation during the formation of dry land on day three of creation week, and the catastrophic erosion and sedimentation, deep burial and rapid deformation/tectonics during the Flood. Catastrophic sedimentation linked to increased volcanic activity and release of hydrothermal waters during the Flood particularly would have aided the production of zones of sediments of differing clay and related minerals, while catastrophic burial and higher heat flow from that volcanism and hydrothermal activity would have aided the transformation of these precursor materials to produce the resultant index mineral ("grade") zones across these metamorphic terrains.

Keywords

Regional Metamorphism, Metamorphic Zones, Metamorphic Facies, Stratiform Ore Deposits, Metamorphic Diffusion, Mineral Reactions, Metamorphic Equilibrium, Mineral Zoning, Precursor, Mineral Assemblages, Clay Minerals, Creationist Explanation, Zones of Precursor Materials, Moderate Temperatures, Hydrothermal Waters

Introduction

One of the seemingly most potent, oft-repeated objections to the young-earth creation-Flood model of earth history is the supposed processes of metamorphism and the formation of metamorphic rocks. There are two major types of metamorphism—contact and regional. Contact metamorphism is basically the baking of rocks around an intruding and cooling magma and thus only involves elevated temperatures. Creationists must here not only explain how the surrounding sediments could have been metamorphosed rapidly, but how the magma

cooled quickly enough within their young-earth time framework.

However, it is not in the formation of contact metamorphic rocks that the most common metamorphism objections to the creation-Flood model occur. Regional metamorphic rocks are believed to have been subjected to high pressures as well as high temperatures. This, in addition to the fact that they are always found over areas of hundreds of square kilometers, has led geologists to believe that regional metamorphism occurs when the parent rocks are buried to great depths. Consequently, at current rates

of sedimentation the burial process itself would take many millions of years, but creationists can counter that problem by pointing to the increased rate of sedimentation to catastrophic levels during the Flood, when deep burial is envisaged to have been accomplished in only a matter of days or months. However, as pointed out by Wise (1986) the biggest problem lies again in the heat presumed to have been involved. Rapid burial beneath many kilometers of sediments would have produced virtually instantaneous pressure increases, but once again the evolutionist would argue that it takes too much time to heat the sediment. He would argue that it takes many millions of years to heat up sediments buried twenty kilometers beneath the earth's surface.

These problems and objections are not minor, nor can they simply be ignored. As Young (1977) has stated:

Much of the earth's surface is immediately underlain by vast tracts of crystalline metamorphic rock. Much of the exposed rock of the eastern two-thirds of Canada consists of metamorphic rocks. The Blue Ridge Mountains of the southern Appalachians, the southern Piedmont virtually all of New England, New York's Manhattan Island, and nearly the entire area between Philadelphia and Washington DC, consist of metamorphic rock. So do large areas of the mountainous western parts of the United States and Canada. Metamorphic rocks also are widely exposed in other parts of the world such as Australia, Scandinavia, Siberia, and India.

Young goes on to say that a great many of these crystalline metamorphic rocks are believed to be Precambrian in age, and so suggests that creationists might be tempted then to relegate such rocks to the activity of creation week. However, even if some metamorphic activity could be relegated to the creation week (for example, during day three), there is still evidence that many regionally metamorphosed rocks had to have been, according to the creation-Flood model, formed during the Flood year and subsequently.

Young points to the metamorphic terrain of the New England, USA, and quite rightly states that despite many of these rocks having been very severely heated and deformed, it is evident that they were chiefly of sedimentary and volcanic character prior to their metamorphism. Furthermore, the original sedimentary character of many of these rocks is, apart from differences from various compositional, textural and structural characteristics, firmly established by the discovery in places of several fossils (even if somewhat deformed) within these metamorphic rocks (Boucot, MacDonald, Milton, & Thompson, 1958; Boucot & Thompson, 1963). Thus, on the basis of these contained fossils, creationists would argue that

the sediments from which these metamorphic rocks developed were deposited during the Flood year. Young also points out that in southern New England the metamorphic rocks are unconformably overlain by unmetamorphosed fossiliferous sedimentary rocks, and so therefore Flood geologists are faced with the necessity of concluding that the metamorphic rocks of New England metamorphosed during the time-span of less than one year.

Furthermore, quantification of what is involved seemingly adds to the problem. Since it has been possible to experimentally determine the range of stability of almost all important metamorphic minerals in terms of pressure and temperature, and the pressure and temperature at which many important metamorphic mineral reactions may occur, it can be concluded that the mineral assemblages of these New England rocks indicate that many of the precursor sedimentary and volcanic rocks must have been subjected to temperatures approaching 600°C and pressures of 5 kilobars (Thompson & Norton, 1968). Such conditions are interpreted as implying that the sediments were buried under a load of rock 16–19 km thick. Thus Young insists that Flood geologists are obliged to explain in terms of their model for earth history how it would have been possible in less than one year for the precursor sediments of these New England metamorphic rocks to have been deposited, then progressively buried to a depth of between 16 and 19 kilometers as they were first converted to sedimentary rocks. They subsequently, according to Young, had to be progressively metamorphosed as the temperatures rose to around 600°C, and then uplifted and eroded to eventually be exposed as metamorphic rocks at the earth's surface today!

Metamorphic Zones and Facies

Like other terrains of regionally metamorphosed rocks in other parts of the world, the New England (USA) area has been carefully mapped and the rocks divided into metamorphic zones and facies according to their contents (Figure 1 and Table 1) (Thompson & Norton, 1968). As already indicated, conventional uniformitarian thinking like that of Young envisages that in regions such as the New England sedimentary strata must have been subjected to elevated temperatures and pressures due to deep burial and deformation/tectonic forces over millions of years, and that the resultant mineralogical and textural formations are due to mineral reactions in the original sediments during those prevailing temperature-pressure conditions. Thus the mapped zones of strata, as in Figure 1, contain mineral assemblages that are believed to be diagnostic and confined to each zone respectively. It is assumed that these mineral assemblages reflect the metamorphic

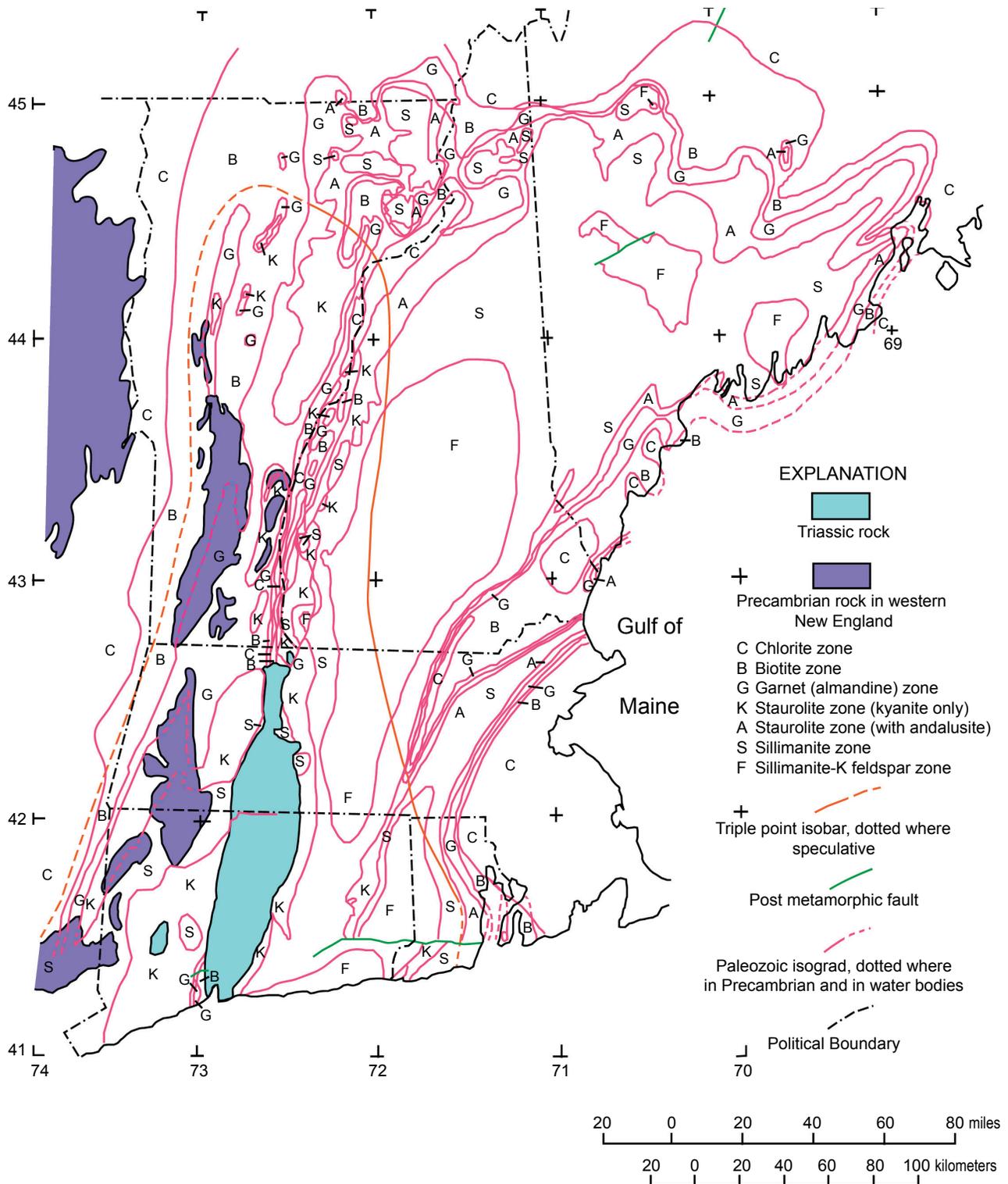


Figure 1. Paleozoic regional metamorphism in New England and adjacent areas. Precambrian rocks in eastern New England and of the New York City area are not shown.

transformation conditions specific to each zone, so that by traversing across these metamorphic zones, from the chlorite zone to the sillimanite-K feldspar zone, higher metamorphic grades are progressively encountered, from low to high grade respectively. In the case of the New England area the original

sedimentary strata were not just pelitic rocks, but included mafic igneous rocks, and carbonate units that had been metamorphosed into calc-silicates. Thus while the metamorphic zones are often more easily mapped in the field within the pelitic rocks, there is believed to be an approximate correlation

with characteristic mineral facies developed in the associated mafic rocks and with index minerals found in the calc-silicates, as shown in Table 1.

Table 1. Approximate correlation of mineral zones in pelitic rocks, as shown in Figure 1, with characteristic mineral facies developed in associated mafic rocks and with index minerals found in calc-silicate rocks.

Pelitic Rocks	Mafic Rocks	Calc-Silicate Rocks
Biotite zone	Greenschist facies	Talc, phlogopite
Garnet zone	Epidote amphibolite facies	Tremolite, actinolite, epidote, zoisite
Staurolite zone	Amphibolite facies	Diopside
Sillimanite zone		Grossularite, scapolite
Sillimanite-K feldspar zone	Hornblende-pyroxene granulite facies	Forsterite

The lines that separate the different metamorphic zones, as depicted in Figure 1, are called isograds, and are defined as the line along which the index mineral or mineral pair characteristic of the next metamorphic zone first appears in rocks of similar composition. Such first appearances are believed to be dependent not only on externally imposed conditions of temperature, pressure, and the activities of components that have comparatively free mobility, such as water, but also on the original bulk compositions of the rocks. These isograds, of course, are ideally drawn on maps so as to minimise the effects of variations in initial bulk compositions which invariably occur due to the fact that these metamorphic zones and facies cross the boundaries between different original strata—for example, pelitic sedimentary rocks, with interbedded mafic igneous rocks and carbonates. It is envisaged that the mineral assemblages in these zones and facies are the result of mineral reactions, whereby the temperature and pressure conditions, along with active components like water, have induced the minerals in the original rocks to react and form new minerals. Thus, for example, it is envisaged that at the boundary between the biotite and garnet zones in typical pelitic rocks is the first appearance of the completed reaction:

chlorite + muscovite + quartz \rightarrow garnet + biotite + water.

Of course, such reactions will vary according to which minerals are available to react with one another in the original rocks, so for example, if the rock contained more aluminum the resultant reaction might be:

chloritoid + chlorite + quartz \rightarrow garnet + water.

Considerable effort has therefore been expended to elucidate all possible reactions between minerals in the almost limitless potential variations in original bulk compositions.

Historically, the concept of metamorphic zones and facies was developed by Barrow as a result of his geological mapping of the metamorphic rocks and the mineral zones in them in the Scottish Highlands (Figure 2) (Barrow, 1893, 1912; Kennedy, 1949). Barrow's mineralogical zones, which he ascribed to the effect of systematically increasing temperature on the sedimentary rocks of the area he described, laid the foundation for, and formed the basis of, the concept of progressive regional metamorphism as we know it today. The terrain with which Barrow happened to be involved was restricted almost entirely to commonly-occurring silicate rocks—primarily greywackes and subordinate pelites. Barrow was not concerned with metamorphic assemblages associated with metal ores of any kind, for he appears quite simply not to have encountered them. Had he encountered them he may have come to rather different conclusions with respect to the processes of regional metamorphism. It is now known that many ores are metamorphosed, and such ores and their environments yield clues to a better understanding of metamorphism in general, an understanding that may help to resolve some of the perceived conflicts between the current uniformitarian view of regional metamorphism and the young-earth creation-Flood model.

Although there have been some doubts expressed, it appears to be widely accepted amongst geologists that the achievement of chemical equilibrium in regional metamorphism is the rule rather than the exception. Metamorphic petrology today is based on

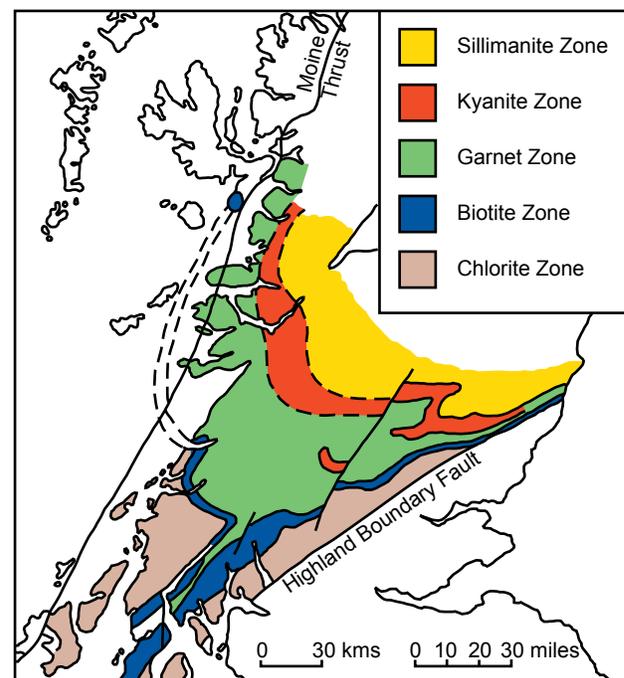


Figure 2. Simplified regional representation of the metamorphic zones of the Grampian Caledonides, Scotland.

the assumption that chemical equilibrium is virtually always attained and hence that mineral assemblages can be evaluated in the context of the Phase Rule. It appears to be generally accepted that diffusion occurs over distances large enough to permit mineral reactions to occur through large volumes of rock, and that with rise in temperature and pressure, such reactions occur in progressive fashion so that any particular set of pressure-temperature conditions comes to manifest itself through the development, in rocks of like chemical composition, of a particular set of metamorphic minerals. In this way grades of metamorphism and metamorphic gradients and zones are identified, and metamorphic rocks of different compositions are linked through the facies principle.

Current Inherent Difficulties

This view of metamorphism is now so well established that it constitutes an essentially unquestioned basis for some very highly refined studies of relationships between mineral chemistry and metamorphic grade. These include studies of trace element abundances in individual minerals, trace element partitioning between mineral species, fractionation of stable isotopes, and related fields of investigation.

However, there are some reasons to doubt whether the basic assumptions are as sound as they have been thought to be. More precise studies, on the scale of the microscope and particularly of the electron microprobe, are beginning to place severe limits on the distances involved in metamorphic diffusion. This is critical, because limits on diffusion set limits to the extent to which minerals may react, and this in turn limits the extent to which the metamorphic system can approach equilibrium.

Writing in the same year as Barrow's epic work, Harker (1893) set severe limits to the scale on which metamorphic diffusion might take place. From his observations of the delicate preservation of bedding in some metamorphosed strata, Harker (1893, p.557) concluded:—

... that within the mass of rock undergoing thermal metamorphism any transfer of material (other than volatile substances) is confined to extremely narrow limits, and consequently ... the mineral formed at any point depends on the chemical composition of the rock mass within a certain very small distance around that point.

In the same year Harker & Marr (1893) through their very careful consideration of metamorphic phenomena associated with the contact of the Shap Granite, concluded that in that case diffusion distances were probably of the order of "1/20 or 1/25 inch" (around 1 mm) Harker & Marr (1893, p.369).

More recently, Turner & Verhoogen (1960) observed

that what little evidence there is seems to indicate that metamorphic diffusion is probably effective at most over distances measured in centimeters, over times of the order of millions of years. However, in the same year Chinner (1960) noted:—

The confinement of rocks of varying oxidation ratio to well-defined sedimentary bands suggests that the differences in oxygen content are of premetamorphic, diagenetic origin ... Chinner (1960, p.178)

In contrast, Carmichael (1969) has estimated diffusion limits of the order of 0.2 mm–4.0 mm.

Thus in the century since Barrow's and Harker's early work, opinion on diffusion distances, concomitant material transfer, and resulting modification of rock compositions, has varied widely. Many investigators have assumed extensive diffusion and substantial material transfer, though careful mass-balance calculations by others have repeatedly indicated that in at least many cases diffusion distances have been very small. Opinion probably remains diverse, though Winkler has encapsulated the view of many modern investigators:—

There are many indications that rocks constitute a "closed" thermodynamic system during the short time required for metamorphic crystallization. Transport of material is generally limited to distances similar to the size of newly formed crystals. It has been observed frequently that minute chemical differences of former sediments are preserved during metamorphism.

Metamorphism is essentially an *isochemical* process... (emphasis his) (Winkler, 1979).

Whether diffusion is in fact restricted to very small distances, and what, precisely, these distances are, is a critical matter for regional metamorphic petrogenesis. If, as indicated by Harker in 1893 and reiterated by Winkler in 1979, the chemical components of a metamorphic grain now occupying a given small domain are derived directly from those chemical components occupying that domain immediately prior to the onset of metamorphism, that metamorphic mineral must represent the in situ growth and/or transformation of a pre-metamorphic material of similar overall composition, or it must be one of two or more products of the in situ breakdown of pre-metamorphic material of appropriate composition.

If this is the case, and it follows not only from the considerations of Harker and Winkler, but also from all those whose findings have indicated metamorphic mineral growth to be isochemical on a fine scale, the implications for metamorphic petrogenesis are profound. The development of metamorphic minerals would stem from simple grain growth, ordering of randomly-disposed structures, and solid-solid transformations, not from "mineral reactions" as these are currently visualized. Such metamorphic mineral development would be attained on no more,

and perhaps often less, than a single grain scale, and the proposition that groups of minerals, on a thin-section scale, commonly represent "equilibrium assemblages" developed in accordance with the Phase Rule, would be seriously open to question.

For the geologist studying ore deposits this question of diffusion distances, and the likelihood that metamorphic diffusion might induce short-range modification of rock compositions, is vital in the detailed consideration of metamorphic processes. There are some ore deposits that form as a primary part of the pelitic rocks in which they occur and which, hence, suffer any metamorphism that the latter may undergo. One approach to the elucidation of the physical and chemical conditions of formation of these ores is the consideration of their present chemical compositions. However, such an approach is soundly based only if present constitutional features are a close reflection of the original ones. This will not be the case if metamorphism has induced differential movement of components. Thus the ore petrologist is obliged to have a vital concern with the nature, and particularly the scale, of metamorphic diffusion.

Such limitations on the distance of migration of the elements in metamorphism impose severe constraints on the extent of reaction and the opportunity for equilibration of mineral assemblages. Indeed, clear microscopical evidence of mineral reaction, as distinct from solid-solid transformations, such as the transformation of andalusite to kyanite, is usually very hard to find, even where minerals that might be expected to react lie in contact. Where good microscopical evidence for a fact or process exists, in whatever field of science, it is usual for this to be presented photographically (for example, Vernon, 1978). It therefore seems significant that of the three great metamorphic texts in English of recent years (Miyashiro, 1973; Turner, 1968; Winkler, 1979) none shows a single photograph illustrating the destruction of one mineral and the concomitant development of another. Two other texts of a specialist nature on metamorphic textures (Spry, 1969) and metamorphic processes (Vernon, 1976) also do not have any photographs of any mineral transformations, although the former text has photographs of textures and some "reaction rims and coronas." Mineral aggregates said to indicate particular reactions commonly present an equivocal picture, and in most cases, the postulated product-reactant grouping does not, within that group, yield a balanced chemical equation with respect to all elements (Kwak, 1974). What seems the best evidence, that is, two or more "products" habitually replacing what could be seen to be formerly juxtaposed "reactants," the whole yielding a balanced equation, seems very difficult to find.

Quite frequently some minerals present in a rock,

for example, quartz and muscovite, might have been expected to have reacted prior to the achievement of the metamorphic grade indicated by the presence of an associated mineral, in this case sillimanite, but there is no unambiguous microscopical evidence indicating that they have done so. Such difficulties led Carmichael (1969) to propose the operation of "metasomatic cation-exchange," though it is difficult to see how such a mechanism can be reconciled better than any other mechanism with limits set by diffusion. Certainly, evidence of reaction should be preserved along isograds, but even here it seems to elude us. This almost general absence of direct evidence of reaction has led some observers (Atherton, 1965; Yoder, 1952, 1955) to suggest that metamorphic rocks may attain their mineral assemblages directly, rather than by a series of mineral reactions, and hence without passing through each successive grade. When viewed in a detached way it may be seen that any evidence for mineral reactions is really largely circumstantial. On traversing a metamorphic terrain we find that as one mineral diminishes and disappears another appears to take its place, and so it has been assumed that there must have been a reaction leading to the demise of the first mineral and the generation of the second. There are, however, other reasons why one mineral might give way to another in a spatial sense.

Coupled with doubts concerning the reality of many postulated reactions are doubts on equilibrium. The preservation of zoning in garnets, for example, revealed so spectacularly in the past twenty years by the electron microprobe, has been an indication that, even at high grades of metamorphism, equilibrium may remain unattained even in a single crystal. The significance of this has often been minimized on the grounds that diffusion in garnet is probably sluggish due to the complex close-packed structure and strong bonding of the garnet crystal. However, evidence of the preservation of compositional inhomogeneities in other minerals, including sulfides (Scott, Both, & Kissin, 1977) is now mounting, indicating that compositional equilibrium may not have been attained even in the most sensitive crystal structures, and even where these are subjected to the highest grades of metamorphism.

Ore Deposits in Metasedimentary Rocks

There are two principle categories of ore deposits in sedimentary and metasedimentary rocks: those that, prior to any post-depositional deformation, are concordant and those that are discordant with respect to the bedding of the containing rocks.

The discordant group are those referred to as veins that occupy openings, frequently faults, that cut across bedding. The materials in the veins have been introduced from elsewhere in liquid

and gaseous solutions, and they have built up by accretion on the walls of the openings concerned. Frequently the solutions and gases have not only yielded the minerals of the ores, they have also caused alteration of the walls of the opening. Such alteration may extend some meters into the enclosing rocks and is commonly referred to as wall-rock alteration, an almost ubiquitous accompaniment of vein formation. Common products of this alteration are sericite, chlorite, quartz, kaolinite, and pyrite. In all cases both ore and alteration are the products of materials manifestly introduced from elsewhere and superimposed on the geological environment of the original opening.

The concordant group of deposits are those now usually referred to as “conformable” or “stratiform” ores. The ore minerals, usually sulfides, have the appearance of being an integral, and hence normal, component of the sedimentary or metasedimentary rocks in which they occur, being simply grains within a granular rock. The orebodies are usually lens-shaped and grossly elongated, with their long dimensions parallel to the stratification of the enclosing rocks, and they themselves commonly display good internal bedding which may usually be demonstrated to be continuous with that of the enclosing pelitic sediment.

In a manner that appears somewhat analogous to the wall-rock alteration zones around discordant or vein ores, many stratiform deposits contain, and are immediately ensheathed by, metapelitic rocks displaying distinctive metamorphic mineral assemblages. These assemblages are sometimes quite complex and exotic and include all of sericite, chlorite, garnet; metamorphic pyroxenes, amphiboles, and olivines; staurolite, sillimanite, and most of the other well-known metamorphic minerals.

Because the materials of discordant/vein ores are so demonstrably introduced, and that at some discrete time after the formation of the host rocks, it was for a long time thought that the materials of the concordant/stratiform ores must, simply because they were ores, have likewise been introduced. Because they were clearly not formed by the filling of openings it was concluded that they formed by a process of metasomatic replacement. At the same time the rather unusual metamorphic mineral assemblages that often occurred within and surrounding concordant/stratiform orebodies were identified also as “metasomatic” and equated with the zones of wall-rock alteration so commonly associated with the discordant/vein ores.

However, it is now generally accepted that most of these concordant/stratiform ores have not developed by replacement of pre-existing, lithified sedimentary or metasedimentary rocks, the sulfides of these ores having been laid down as fine chemical precipitates

as part of the original sediments themselves. Indeed, such modern-day analogs have been found and observed forming on the sea-floor associated with hydrothermal springs (Alt & Jiang, 1991; Durga Prasada Rao, Behairy, & Al-Imam, 1984; Hackett & Bischoff, 1973; Lonsdale et al., 1980; Rona, 1986; Scholten, Stoffers, Walter, & Plüger, 1991). These ores are, as of course they have the appearance of being, intrinsic parts of the rocks in which they occur, and they have shared the whole of the latter’s history.

This being the case, the somewhat unusual metamorphic mineral assemblages within and surrounding the ores can no longer be ascribed to late-stage metasomatic activity associated with ore deposition by hydrothermal replacement. They must result from the metamorphism of the sedimentary materials laid down with, and adjacent to, the sulfide precipitates. Thus they are genuine metamorphic rocks, even if unusual, and are likely to be just as significant in the study of metamorphic phenomena as the metamorphosed pelitic rocks observed by Barrow, Harker and their many modern counterparts (Stanton, 1982a, 1989a, 1989b).

These stratiform orebodies and their enclosing metapelites often provide very sharp chemical and mineralogical contrasts down to a very small scale, such contrasts being commonly preserved in the very ordered form of the earlier fine bedding of the sediment concerned. Such ores represent high, and usually highly fluctuating, concentrations of particular elements and minerals set in a medium of very much lower concentrations of these elements and minerals. For example, a stratiform orebody may contain 15% Pb, whereas the enclosing rocks a few centimeters away normally only contain parts per million Pb. In the ore Fe may be in excess of 40%, whereas immediately outside the orebody the Fe concentration usually decreases to less than 10%. Expressed mineralogically, the orebody contains abundant galena whereas the surrounding strata contain none. Similarly, the ore-beds and their sheath may contain abundant chlorite, garnet, and other metamorphic minerals that are absent from, or very much less abundant in, the enclosing rocks. In addition to this highly localized nature of the metamorphic minerals these also occur in a bedded arrangement; that is, metamorphism of the rock and the development of the metamorphic minerals in many cases has not led to the disruption of the original bedding or other sedimentary structures. Thus these orebodies provide unusually good opportunities for studying the incidence of individual metamorphic mineral species and of compositional variations in them, and the relation of this to the original features of sedimentation. As a result they also provide good opportunities for studying distances over which

concentration equilibria are attained, and hence instances over which metamorphic diffusion has occurred.

Evidence of Regional Metamorphic Processes from Stratiform Ore Environments

The Extent of Metamorphic Diffusion

It seems reasonable to expect that the maximum distances of the diffusion would be indicated by the distance over which compositional homogeneity is achieved on a small scale between, and within, individual crystalline grains of an individual mineral species. Stratiform ores and their envelopes provide some striking examples of the preservation of compositional inhomogeneities over very small distances. The following examples occur in assemblages that include garnet, staurolite, and sillimanite, that is, "high-grade metamorphic" assemblages in which diffusion would be expected to have operated to the maximum extent.

Beginning with the relatively gross scale of centimeters, Stanton & Vaughan (1979) and Vaughan & Stanton (1986) have studied variations in garnet compositions associated with the Pegmont orebody in north-west Queensland. Close examination of Figure 3 shows that over a distance of 23 cm, between 357.03 m and 357.26 m in drill core PD31, substantial variations exist in the compositions of garnet grains. Furthermore, at each of the three sample points concerned there was also substantial variation in garnet grain compositions within each single electron microprobe section concerned. Yet garnet is not the only mineral to exhibit such short range variations of this general kind in this particular orebody. For example, FeO/MnO weight percent in manganiferous fayalitic olivine was found to vary from 10 to 24 weight percent then back to 10 weight percent again over a distance of less than a meter.

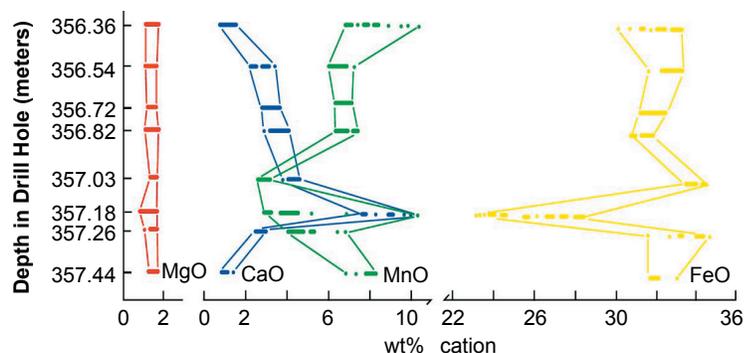


Figure 3. Variation in divalent cation composition of almandine garnets at eight points over a total down-core distance of 1.08 m in diamond drill-hole PD31 through the fringe of the ore horizon at Pegmont, Queensland. Note the gross variation in garnet composition over the 23 cm interval from 35557.03 m to 357.26 m. Rows of filled circles at each depth position indicate variation in composition observed in each individual probe section.

On a somewhat finer scale Stanton & Williams (1978) investigated the preservation of garnet compositions as related to bedding in a finely laminated garnet-quartzite (a variant of a banded iron formation) from Broken Hill, New South Wales. They found significant differences in garnet compositions developed and preserved from one thin bed to the next on a scale of 1 mm or less. However, systematic microanalyses showed that whereas garnet compositions varied grossly across bedding they were, within the high order of accuracy of the analyses, completely uniform along beds, indicating that the observed finely layered compositional arrangement was a direct reflection of original bedding. That is, a chemical sedimentary feature of the finest scale had been preserved through a proposed period claimed to be at least 1.8 billion years, and through a metamorphic episode generally regarded as of very high grade (Binns, 1963).

On an even finer scale, there is clear evidence of within-grain inhomogeneities in some of the minerals associated with stratiform ores, the presence of these inhomogeneities indicating limits to diffusion within a single crystal grain during high grade metamorphism. For example, metamorphism of the Mount Misery stratiform orebody near Einasleigh, North Queensland, has produced an assemblage which includes andradite, hornblende and epidote (Stanton, 1982b, 1982c). Pairs of analyses from single grains of andradite (0.05 mm apart) and epidote (0.20 mm apart) reveal compositional differences that are substantial. In neither of these or other examples does it appear that these differences are due to segregation or exsolution resulting from a tendency for the achievement of a lower energy state by the gathering of elements into structural domains within the crystals. Neither do they represent visible zoning. Instead, they appear to be patchy inhomogeneities that probably represent earlier individual grains of

slightly different composition that have amalgamated to become one larger grain as a result of grain boundary movement during metamorphism.

The maintenance of such clear compositional disequilibrium between and within grains of single mineral species, and the preservation of this disequilibrium on such a fine scale through the highest supposed grades of metamorphism, seems to indicate that, at least in some cases, metamorphic diffusion is limited not only to distances of a fraction of a millimeter but also to distances less than the grain sizes of the minerals concerned.

Mineral Reactions

With the development of very extensive

assemblages of metamorphic minerals within what are relatively very small volumes it might be expected that metamorphosed stratiform ores and their envelopes would provide, better perhaps than almost any other metapelitic environment, good textural evidence of mineral reactions. This, however, they do not seem to do.

In the ore environs at Broken Hill, New South Wales, quartz and muscovite occur together in rocks also containing sillimanite, but the muscovite exhibits its characteristic sub-idiomorphic, sharply defined, platy form and shows no sign of reacting with the adjacent quartz to form sillimanite and K-feldspar (Stanton, 1976), as would normally be expected according to the frequently quoted reaction quartz + muscovite → K-feldspar + sillimanite + water

Similarly, muscovite-biotite and muscovite-biotite-quartz aggregates are common, but show no sign of reaction in situ to form garnet (or cordierite) and K-feldspar, although they might have been expected to have done so at the grade of metamorphism that appears to have been achieved. Similarly, in the Mount Misery orebody chlorite, muscovite, and quartz occur in contact in samples whose apparent high-grade nature is indicated by the presence of abundant staurolite and sillimanite or kyanite, but in spite of the high iron content of the chlorites (Stanton, 1982a, p. 17, Table 2) there is no textural evidence of the three reacting to produce biotite, or cordierite-biotite, which they might be expected to have done given the overall apparently high-grade assemblages of the rocks concerned.

Stanton reported that his examination of many thin sections of rocks from these, and similar metamorphosed stratiform ore environments, has failed to yield clear micro-structural evidence of mineral reactions. Indeed, there appears to be no unequivocal indication, in the development of corrosion features, reaction rims or pseudomorphs, that minerals that might have been expected to react with each other have done so, nor does there seem to be any clear micro-structural indication of reactions through which the higher grade minerals have formed. Given that some stratiform ore zones possess a very wide range of metamorphic minerals within volumes of a few cubic centimeters, it might have been expected that evidence of such reactions would be found here even if they could be found nowhere else. The inference is that metamorphic mineral reactions, as these are currently visualized, are unlikely to have been a significant factor in the development of these particular extensive metamorphic mineral assemblages.

Attainment of Metamorphic Equilibrium

Probably the most basic of all the assumptions in the current consensus about metamorphic rocks and

metamorphism is that prograde mineral assemblages as those now observed reflect the attainment of chemical equilibrium. It seems widely accepted that, because of the supposed long periods of presumed millions of years available, lag effects were not significant and thus the various mineral phases present developed and were preserved in accordance with the Phase Rule. On the other hand, because of the lack of these presumed long periods of time in the young-earth Creation-Flood model we would expect chemical/metamorphic equilibrium not to have been attained. Thus it is highly significant that from time to time evidence of doubt about the attainment of metamorphic equilibrium has appeared in the literature.

Tilley (1925, p.314), referring to chloritoid-andalusite schists of the Broken Hill area, noted:

One rock ... is described as containing in thin slice, quartz, muscovite, biotite, andalusite, sillimanite, chloritoid, chlorite, garnet, magnetite and tourmaline. Such a mineral association is clearly one in which equilibrium is far from being completely attained, and the associations bear witness to this great departure from equilibrium conditions.

Atherton (1968, p.367), in examining variations in garnet, biotite, and chlorite compositions in medium-grade pelitic rocks from the Dalradian, noted:

Biotites 1 and 2 from rocks of higher grade have very similar Mg/Mg+Fe values; so do the rocks, but the chlorite values are different. The reason for this is not clear. However, the host rock chlorite 2 is thinly banded and chlorite tends to be confined to the quartzose portions, in which case the analyzed chlorite may include material from a sub-system of a different composition to the whole.

Blackburn (1968), working on high-grade gneisses from the Grenville Province of Ontario (Canada), concluded that the volumes over which metamorphic equilibrium was established in rocks of this kind were limited to a few cubic centimeters at most, and might be directionally related to foliation. Similar estimates, based on the mineral chemistry of co-existing phases, as well as on the simple co-existence of such phases, have been expressed by many other investigators (Albee, Chodes, & Hollister, 1966; Ashworth, 1975; Atherton, 1965, 1968; Hagner, Leung, & Dennison, 1965; Kretz, 1960, 1966; Phinney, 1963).

An ideal opportunity to further investigate whether metamorphic equilibrium has been attained is afforded by some of the assemblages that occur within, and immediately adjacent to, some metamorphosed stratiform ores. In most cases the ores and their enclosing metasedimentary sheaths have been extensively drilled, and continuous, spatially well-controlled, samples are thus available for study in a highly systematic way.

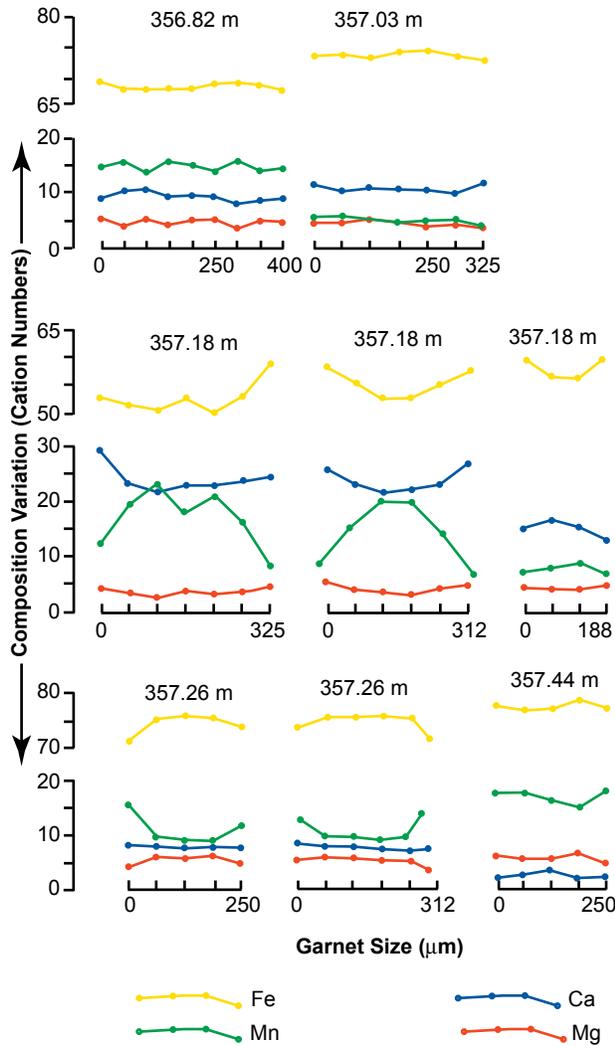


Figure 4. Zoning patterns in eight garnets in diamond drill hole PD31 through the fringe of the ore horizon at Pegmont, Queensland. These garnets are in the lower iron formation unit and the variations observed are over the small interval 356.82 m to 357.44 m (Figure 3). Compositional variation (*y*-axis) is expressed in terms of Fe, Ca, Mn, and Mg cation numbers; the *x*-axis indicates the size of the garnet (9 mm) and the relative positions of the probe analyses.

A lack of short-range equilibrium between grains of a single mineral species during growth is quite spectacularly illustrated by the differences in zoning patterns developed in garnets, for example, in drill-hole PD31 from the Pegmont ore deposit, Queensland (Figure 3). Vaughan & Stanton (1986, pp. B103–B106) have examined, using the electron microprobe, the patterns of zoning developed in garnets of the several beds of garnet quartzite within an iron formation encountered in this hole. Figure 4 shows the results obtained on eight garnets within three beds 15 cm and 8 cm apart respectively. The zoning patterns present a complex picture and are widely divergent. There is both “normal” Mn-Fe

zoning (Mn-enriched, Fe-depleted core relative to the rim) and “reverse” zoning (Mn-depleted, Fe-enriched core relative to the rim), although Ca also contributes to zoning. These zoning patterns vary sharply over short distances, and therefore if these zones developed during metamorphic growth they were apparently not in equilibrium when they did so.

The most striking evidence of the apparent lack of metamorphic equilibrium is, however, provided by the total assemblages of the ore zones of deposits in metasedimentary rocks. Table 2 gives those associated with six such occurrences—the Gorob orebody in Namibia, the Gamsberg deposit in Namaqualand (South Africa), the Broken Hill deposit (A-lode) in New South Wales, the Pegmont and Einasleigh (Mount Misery deposits) in Queensland, and the Geco deposit in Ontario (Canada) (Stanton, 1989b, p. A543, Table 1).

Each of the metamorphic mineral assemblages in these ore zones is extensive, and in most cases they cover the whole spectrum of metamorphic index minerals of all the presumed zones of progressive regional metamorphism. Yet each assemblage is contained within what is, compared to the regional scale of the classical metamorphic zones, almost an infinitesimally small volume of rock. For example, the whole of the Mount Misery assemblage occurs in a single diamond drill-hole within a core length of 20 m, and a major portion of the whole assemblage can be found within a single thin section (Stanton, 1982a, p. 19). The assemblage at Gorob is contained within a core length of 3 m, and again a major part of it can be observed in almost any individual thin section. Obviously, not all of the minerals listed in Table 2 as occurring in a given ore zone are found in mutual contact, though the majority are so found in each case. Exhaustive examination of the Gorob metapelites shows, for example, that quartz, chlorite, muscovite, biotite, almandine, staurolite, and kyanite all occur within a single homogeneous thin section and in mutual contact. While there is certainly a tendency for the various minerals to occur as different groupings, that is, different “assemblages”, from one small metasedimentary unit to the next, the propensity for extensive groupings of minerals to occur together is very clear.

Significance of the Metapelites Associated with Stratiform Ores

All of the ores that have just been considered in connection with diffusion, reaction and equilibrium have been metamorphosed to high grade; all contain abundant garnet, staurolite, and sillimanite or kyanite. They thus show that even at what are currently regarded as high grades of metamorphism of pelitic rocks

1. metamorphic diffusion is, at least in some cases, confined to distances of a small fraction of a millimeter,
2. microscopic evidence of metamorphic reactions is usually poor and ambiguous, or absent, and
3. the whole spectrum of metamorphic index minerals may occur within centimeters of each other, indicating either that metamorphic mineral equilibrium is not established even over very small distances, or that some factor other than, or additional to, temperature and pressure is responsible for the development of these minerals.

The confinement of metamorphic diffusion to minuscule distances indicates that the metamorphic minerals now occupying a given domain in space must have grown from materials that previously occupied that domain, so that what is now present in any small segment of a metamorphic rock must be a close constitutional (that is, compositional and crystal-structural) reflection of what previously occupied the space concerned. Furthermore, the coexistence of the whole spectrum of metamorphic index minerals in such confined spaces indicates that, given a temperature and pressure sufficient to induce mineralogical change, there is some other factor that is of dominating importance in determining what minerals will develop. There seems no doubt that this is composition, the constitutions of the minute volumes of material from which each metamorphic mineral grain develops.

It has of course long been recognized that compositional variation is an important factor in the development of a given metamorphic mineral assemblage. Indeed, the development of a particular set of metamorphic minerals has always been considered as being dependent on pressure (*P*), temperature (*T*) and composition (*X*). However, it has been thought that by taking a particular group of rocks of essentially uniform composition, such as the “argillaceous” rocks (Barrow, 1893, 1912; Tilley, 1924), the composition *X* could be made essentially a constant; that is, observation could be restricted to what was regarded, to a first approximation, as an isochemical system, so that variations in mineralogy became independent of rock composition and could be regarded substantially as indicators of variations in temperature and pressure.

A careful study of the literature shows, however, that this assumption of constancy of composition in argillaceous rocks has been an uneasy one. Repeatedly, different investigators have suggested

Table 2. Silicate mineral assemblages of some exhalative stratiform orebodies and their metasedimentary sheaths.

Gorob (Namibia)	Gamsberg (south Africa)	Broken Hill (A-lode) (Australia)	Pegmont (Australia)	Einasleigh (Australia)	Geco (Canada)
sillimanite K-feldspar kyanite staurolite cordierite anthophyllite almandine biotite muscovite chlorite prehnite quartz	sillimanite K-feldspar olivine clinopyroxene orthopyroxene pyroxenoids grunerite cordierite almandine andradite biotite zoisite clinozoisite muscovite chlorite quartz	sillimanite K-feldspar olivine staurolite hornblende hedenbergite and related pyroxenoids grunerite almandine biotite muscovite chlorite quartz	sillimanite andalusite K-feldspar staurolite clinopyroxene hornblende grunerite biotite muscovite chlorite greenalite quartz	sillimanite staurolite andesine scapolite clinopyroxene hornblende andradite almandine actinolite epidote biotite muscovite chlorite stilpnomelane prehnite laumontite chamosite quartz	sillimanite K-feldspar staurolite hornblende cordierite gedrite biotite muscovite chlorite kaolinite sudotic chlorite quartz

that “anomalous” occurrences of index minerals and resulting “reversals” of zones might be due to minor vagaries of parent rock composition; that the composition of the original argillaceous rocks might not have been so constant that the subsequent assemblages of metamorphic minerals reflected only variations in temperature and pressure. However, these doubts and hesitations have generally been stated relatively unobtrusively, and so have had no significant effect on mainstream thought.

Now, however, the evidence of the metapelites associated with stratiform ores confirms these doubts, pulling them instead into a position of primary importance. Whole-rock analyses of the different lithological units and bands at Gorob, Mount Misery, Broken Hill, and Pegmont show these to vary in composition from one to another very substantially over very short distances, even though the original rocks in all cases appear to have been pelitic (Stanton, 1982a, p.19). The total volumes of rock concerned have been far too small to have sustained differences in temperature, pressure, or partial pressures of volatiles, over any significant period of time. The huge array of metamorphic minerals displayed in each case must, therefore, reflect variations in the compositions of the parent shales. It appears that the sedimentary environments of formation of the stratiform ores have been such as to induce marked and sudden changes in sediment constitution from one bed to the next, and it is this that led to the development of such extensive metamorphic mineral assemblages in such very small volumes of rock.

What significance has this to our understanding of metamorphic grade and progressive regional metamorphism? It indicates, as was pointed out by Yoder in 1952, that differences between metamorphic mineral assemblages may be, in at least some cases,

entirely a result of variations in the bulk compositions of the parent rocks, and need not represent variations in temperature and pressure at all. It also thus indicates that the metamorphic zones described by Barrow and thought by him to reflect changing intensity of thermal metamorphism, could in fact result from subtle but systematic compositional changes in the pelitic rocks concerned.

Precursors

If, as the evidence from the metamorphic mineral assemblages associated with stratiform ores suggests, metamorphic minerals may represent essentially in situ transformations of earlier sedimentary-diagenetic materials, what might those precursor materials have been? There are a number of possibilities, some of which, particularly in the case of some of these simpler “low-grade” metamorphic minerals, are already well recognized.

The chlorite of many metamorphic rocks may have been incorporated in the original sediments as fine chloritic detritus, or it may have originated as fine volcanic glass that was subsequently converted to montmorillonite and then, by iron and magnesium fixation, to chlorite. Sericite and muscovite may have been contributed to the original sediments as fine illite, or it may represent sea floor and diagenetic illitization of kaolinite and other clay minerals. The biotite of metasedimentary rocks may have been detrital, derived by erosion from granitic and older metamorphic rocks; or pyroclastic, derived from dacitic and related volcanism; or it may be derived by potassium fixation and structural reordering from marine glauconite (Stanton, 1976). It has already been suggested (Stanton, 1976; Stanton & Roberts, 1978; Stanton & Williams, 1978) that at least many of the almandine garnets of metamorphosed sediments may derive from marine chamosites, much of the zoning in the garnet stemming from the original oolitic structures of the chamosites. Although garnet contains a little more silica than do most chamosites, dispersed fine chemical silica within chamosite grains could readily supply the balance (Figure 5) (Stanton, 1982a, p.20, Figure 4). Possible precursors of staurolite (and cordierite) are by no means obvious, but marine degradation of, for example, calc-alkaline volcanic hornblendes might well yield mixed-layer clay-chlorite minerals similar to some of those noted in volcanic clay deposits of Japan (Osada & Sudo, 1961). Granules of such materials, with finely admixed chemical silica, as in the case of the chamosites above, in turn may be converted during compaction and metamorphism to cordierite.

The aluminium silicate (Al_2SiO_5) polymorphs may in turn be derived from kaolinite, halloysite and related alumino-silicate clays, sometimes

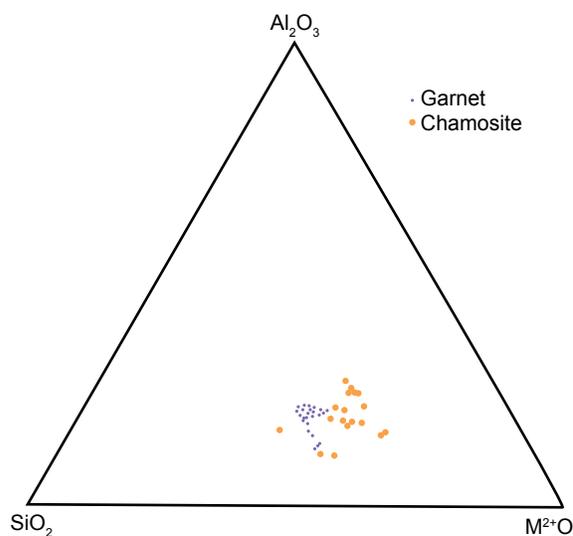


Figure 5. Al_2O_3 - SiO_2 - M^{2+}O relations in garnets from Broken Hill and Mount Misery (purple) and in chamosites from Mount Misery and in the literature (yellow).

in combination with hydrothermal-sedimentary diaspore, boehmite, and gibbsite. It has previously been suggested (Segnit, 1961; Stanton, 1976) that sillimanite might be generated by desilication and dehydration of kaolinite. It is possible, however, that fibrolite, which may in some cases be a precursor of sillimanite, is derived preferentially from the fibrous or tubular member of the kaolinite family, halloysite. This clay mineral is generated particularly in volcanic areas as the result of degradation of feldspars by acid (sulphate-bearing) hydrothermal solutions (Weaver & Pollard, 1975) and has been found in abundance in a number of the Japanese volcanic hydrothermal clay deposits. Development of sillimanite from halloysite might occur by a desilication-dehydration process analogous to that indicated for kaolinite, or by the ordering of halloysite with associated gibbsite, or with excess gibbsite in its structure.

In work on minerals present in the metamorphosed “alteration zone” associated with the Geco orebody (Ontario, Canada), Stanton (1983) found three materials, whose identities were not obvious under the microscope, that commonly occurred in association with sillimanite, and electron microprobe analyses indicated that these were alumino-silicates. The most abundant of these alumino-silicate materials associated with the sillimanite occurs as dark, extremely fine-grained clots, which give low analytical totals (90–98%) indicative of some water content, and plot on an Al_2O_3 - SiO_2 diagram as shown in Figure 6. A lighter colored, less fine-grained member of the trio gives even lower analytical totals and plots very close to the position of halloysite.

There seems no likelihood that these materials reflect weathering or hydrothermal breakdown of

sillimanite to clay minerals, since the drill core in which they occur comes from deep beneath a heavily glaciated, and little-weathered, terrain. Neither is there any evidence of alteration in associated sulfide or silicate minerals (such as biotite), and the microcrystalline material tends strongly to occur at the centers, not the peripheries, of aggregates of clear, sharp sillimanite crystals. Similarly, there is no evidence of retrogression in associated biotite, almandine and staurolite. Thus the fact that these microcrystalline alumino-silicate materials plot in an unmistakable trend intermediate between halloysite/kaolinite and sillimanite seems to give a strong indication that here preserved in an incomplete state is evidence of the prograde transformation of halloysitic/kaolinitic precursor materials to sillimanite.

On this general basis it may be suggested that the three Al_2SiO_5 polymorphs, sillimanite, kyanite, and andalusite, may in some cases each owe their development in metamorphic rocks to nucleation and growth from a specific clay mineral of the kaolinite group, perhaps with additional influence imposed by associated aluminum hydroxides—gibbsite, boehmite, and diaspore. If this were the case, the occurrence of particular Al_2SiO_5 polymorphs would thus be substantially a reflection of the compositions and crystal structures of precursors, and would have little or no pressure-temperature connotation. This does not, however, contradict the careful consideration of the problem of the Al_2SiO_5 polymorphs (Fyfe, 1969; Pitcher, 1965, or experiments Richardson, Bell, & Gilbert, 1968; Richardson, Gilbert, & Bell, 1969) which may be accepted as impeccable. Nevertheless, this evidence does strongly suggest that there are

alternative ways of generating these minerals, just as there are alternative ways of producing many other minerals.

Stanton (1989b, pp.A554–602) has provided numerous examples of minerals found in metamorphic rocks that have been, or can be, produced from simple or complex precursors of near identical compositions, and even at low temperatures. Consequently, the development of a particular metamorphic mineral assemblage can thus be seen to have devolved from constitutional features in the widest sense, that is, not only from simple “bulk chemistry,” but from this in combination with the detailed features of the precursor crystal structure or mixtures of structures. The nature of such structures, and particularly of the mixed layering of clays—chlorites—Al/Fe oxides/hydroxides—zeolites, and of the admixture of these with amorphous SiO_2 and silica/alumina gels, is likely to be just as important as, or even more important than, “bulk composition” in the development of a particular metamorphic mineral.

Possible Reasons for the Extensive Assemblages Associated with some Stratiform Ores

Having established that metamorphic mineral assemblages, can be, indeed must be, derived by transformation in situ from simple and complex precursors as exemplified in the metasedimentary sheaths surrounding stratiform sulfide ores, it is now necessary to explain how these remarkably extensive metamorphic mineral assemblages of the stratiform ore environments develop, and the reasons for the great variations in composition of the original sediments that these mineral assemblages reflect.

It appears that most stratiform ores are formed by the contribution of mineral-bearing hot springs to the sea floor in areas of volcanic activity. The waters of such hot springs today are, of course, at a relatively high temperature, are also slightly acidic, and have a high dissolved solid content and low Eh. As they discharge onto the sea floor they encounter the water of the sea which is cold, slightly alkaline, possesses relatively low dissolved solids, and which may or may not have a low Eh (oxidation potential). Added to this, the output of the hot springs is likely to be somewhat pulsatory, and the motion of the sea water likely to vary with variation of the slow bottom currents of the locality concerned, these two factors leading to a fluctuating interplay between the warm, acidic, and concentrated waters of the hydrothermal regime and the cold, alkaline, and dilute waters of the normal marine regime. It is this interplay, the encounter of warm, concentrated hydrothermal solutions with cold, dilute sea water, that leads to the precipitation of the ore minerals, and it is its fluctuating nature that leads to the development of the bedding of the stratiform ores.

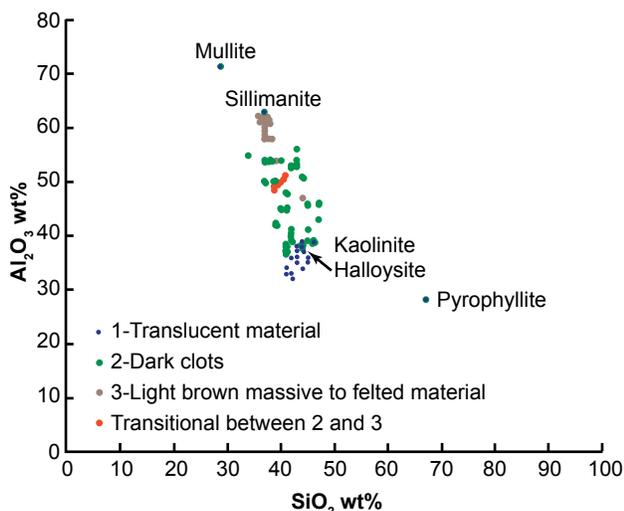


Figure 6. Al_2O_3 - SiO_2 weight percent relations in the three classes of hydrous “alumino-silicate” materials intimately associated with sillimanite in the Geco Mine, Manitouwadge, Ontario. Points for kaolinite, halloysite, pyrophyllite, sillimanite, and mullite are included for reference.

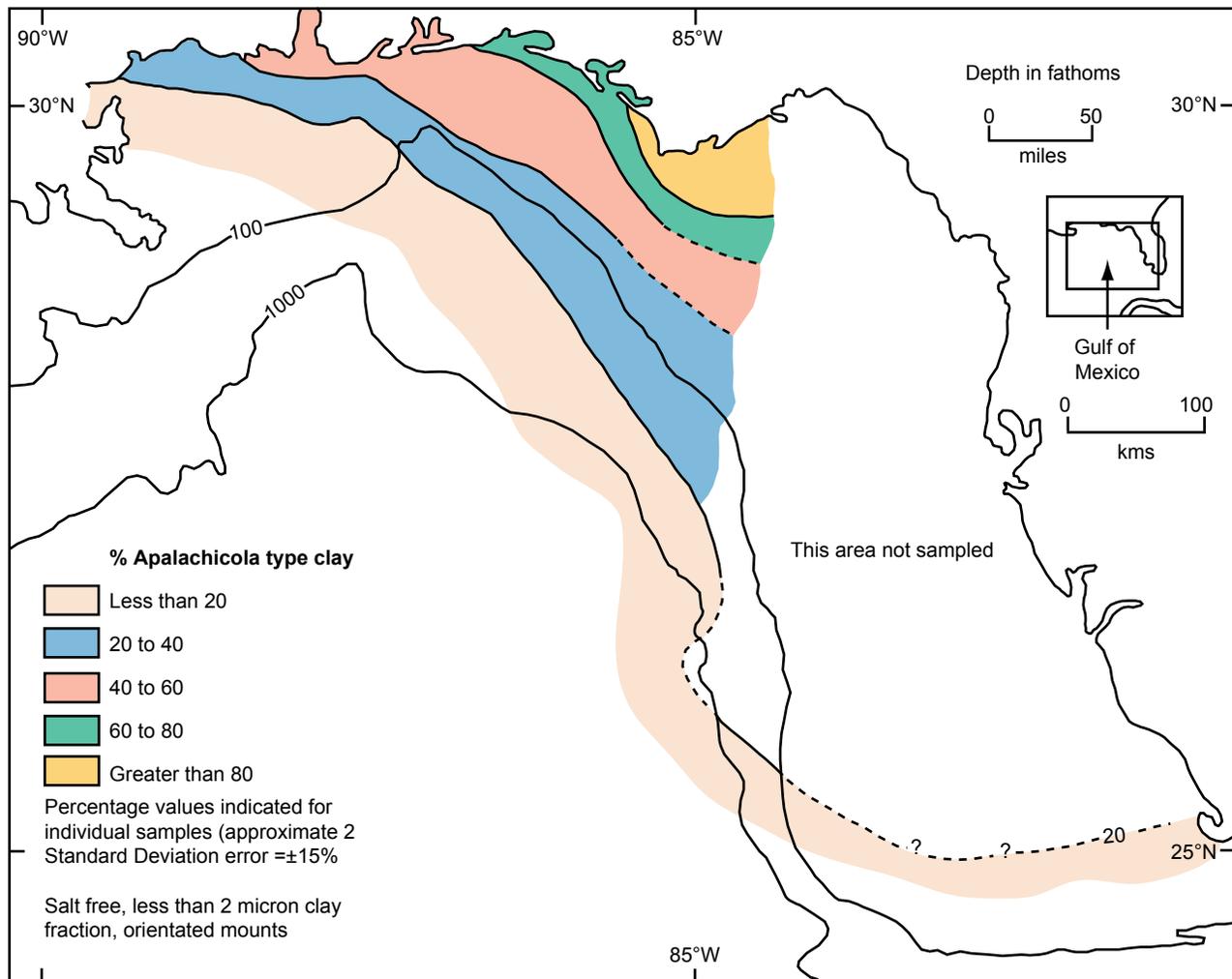


Figure 7. Zonal pattern of mixing of different clay types around portion of the coast of the Gulf of Mexico. “Apalachicola-type clay” refers to the clay mineral suite contributed to the Gulf by the Apalachicola River, as distinct from those contributed by the Mississippi and Mobile Rivers.

However, the contribution of the springs involves more than the ore minerals. As well as iron, calcium and other metal compounds, it usually includes substantial quantities of silica, alumina, and silica-alumina gels, the basic materials of the clay minerals and, through its acidic nature, it also involves the variable breakdown of detrital feldspars and other minerals to a variety of clays within the surrounding sea floor sediments. This activity may continue on well after the deposition of the stratiform orebody itself, and may thus lead to the accumulation of sediments not only of highly varying chemical composition, but also containing a wide variety of clay and associated chemical/detrital minerals.

Thus, sea-floor hydrothermal environments of ore formation, involving as they inevitably do, rapid fluctuations in the chemical and physical state of the mud-water interface, are likely to produce short-range changes of substantial chemical and crystal-structural significance in the sediments to which they

are contributing, particularly to rapid variations in clay mineral assemblages, as sediments accumulate. Changes between dominantly kaolinitic, halloysitic, illitic, chamositic, montmorillonitic, chloritic, glauconitic, and related clay mineral sedimentation, changes that usually take place only over substantial distances and over substantial stratigraphic intervals in “normal” marine sedimentation, may take place with extreme rapidity, and on a very local scale, in the marine-hydrothermal regime. Thus if individual metamorphic minerals are essentially direct derivatives of specific clay, chlorite, mixed-layer clay and mixed-layer clay-chlorite and zeolitic mineral precursors, the sea-floor hydrothermal regime may generate over very small distances and over minute stratigraphic intervals the beginnings of a wide range of metamorphic minerals, such as is usually observed to develop only over substantial distances and over substantial stratigraphic intervals in “normal” marine pelitic sequences.

Clay Mineral Facies in the Marine-Shelf Environment

The small-scale sedimentary environments of stratiform ores such as those described thus indicate that the larger-scale regional metamorphic zones in pelitic rocks could have stemmed in many cases from semi-regional variations in clay and related mineral assemblages consequent upon the variations in the nature and conditions of sedimentation.

The tendency of the clay and related layered silicate minerals to develop zonal patterns of distribution during shelf sedimentation is well established. Smoot (1960), working in the Chester Series of the Mississippian sediments of Illinois, observed that clay minerals were distributed in a regular pattern of essentially concentric zones which developed outwards from what he interpreted as a delta onto an open marine shelf. He considered this distribution of clay minerals to be essentially a depositional, rather than a diagenetic, feature, the coarser kaolinite having settled closer “in-shore,” whereas the finer material remained suspended for some distance “out to sea,” thus adsorbing K^+ and being “transformed” to illite, which settled as sediment “further from the shore.” Thus Millot (1970) and de Segonzac (1970) both supported the suggestion that kaolinite, in tending to deposit as larger crystals closer to its interpreted continental source, may be a paleogeographical indicator of supposed old shorelines.

In considering the development of glauconite by the marine degradation of detrital biotite, Galliher (1935) pointed out that in the sediments of Monterey Bay, California, biotite-rich sandy sediments laid down in near-shore zones were facies of glauconite muds deposited further out to sea. Similarly, in studying clays being delivered to the present Gulf of Mexico, Griffen (1962) showed that a combination of current action and clay particle size led to an ordered distribution of the different clay species, which in turn yielded a gradation facies pattern of clay minerals parallel to the coastline. Figure 7, which shows the degrees of mixing of clay types from several rivers flowing into the Gulf of Mexico, illustrates the scale and nature of clay mineral zoning in the near-shore, modern sediments of the Gulf.

The Liassic (Jurassic) chamositic ironstones of England and Germany have been noted as occurring as a boundary facies between sandstone and shales, giving way laterally to sandstones on what has been interpreted as the shallower margin, and to silty shales towards what has been interpreted as deeper water (Hallam, 1966). Thus it has been proposed that the ironstones developed as a near-shore facies, and that they were an accompaniment to pronounced delta formation, the chamosite-rich zones representing the pro-delta facies. Ellison (1955), in his interpretation

of the Middle Silurian sediments of the eastern USA, suggested that a ferruginous facies occurred near-shore between the presumed palaeoshoreline and a carbonate reef facies. This ferruginous facies constitutes a clear zonal development of iron-rich sediment containing abundant chamosite as well as iron oxides. In a detailed study of the clay minerals of the iron-rich facies, Schoen (1964) showed that chamosite, illite, and chlorite were all abundant, the illite being detrital, the chlorite diagenetic, and the chamosite a primary, syngenetic precipitate. Similarly, Porrenga (1967) found that the iron-rich minerals in the modern sediments of the Niger delta of West Africa displayed a clear zoning of goethite, chamosite, and glauconite parallel to the shoreline. This is clearly significant, because it is the “clay minerals,” chamosite, and glauconite, that are the possible precursors to garnet and biotite respectively.

Along the South American shelf receiving sediments from the Amazon River, Gibbs (1977) found a clear zoning of clay minerals developed both along and across the shelf, which he attributed quite simply to sorting by size. Jeans (1978) likewise found distinctive zoning of clay mineral assemblages amongst the sedimentary megafacies in the Triassic Keuper Marl, Tea Green Marl, and Rhatic Sediments in England. Two principal assemblages were recognized:—

1. a detrital assemblage of mica with minor chlorite which occurred throughout the sediments investigated; and
2. a “neoformed” assemblage of magnesium-rich clay minerals with a limited occurrence apparently related to certain megafacies cycles that had presumably resulted from the interpreted transgression and regression of lighter, normal marine waters over heavier, highly saline Mg-rich waters of a restricted hypersaline environment.

Thus, whatever the cause—variation in the nature of the source materials being eroded; differential settling due to systematic differences in particle size or of flocculation; systematic variations in adsorption and “neof ormation”, sea-floor alteration and agradation; variations in climatic conditions and temperatures during sedimentation; or marine transgression or regression—it is clear that the incidence of different clay minerals in near-shore, and presumed near-shore, marine sediments commonly acquires distinct zoned patterns. The details of these patterns are not entirely constant, and there is considerable overlap, but there does seem to be a widespread tendency for the sediments to develop broad facies patterns not only in the size and nature of their coarser components, but also, though less obviously, in the nature of the clay minerals that these sediments contain.

The facies of clay mineral sedimentation on volcanic shelves appear to be poorly studied, but it

is envisaged that volcanic contributions to adjacent shelf areas may well modify and enhance features of clay mineral distribution, and hence may have considerable significance in the metamorphic response of the sediments concerned. In areas of sedimentation adjacent to calc-alkaline volcanism and hydrothermal activity, it is likely that kaolinite is joined by halloysite and one or more of gibbsite, diaspore and boehmite. Considerable hydrothermal iron could also be added to the sediments, and this presumably would favor the generation of chamosite and glauconite in sedimentary facies, similar to the pattern found in the Niger delta. Erosion of deeply weathered hinterlands, particularly those characterized by extensive laterite-bauxite, would also lead to the gross contribution of ferriferous and aluminous material, and the addition of chamositic and glauconitic, and iron-rich chlorite, zones to the more common kaolinite-, illite-, and smectite-rich clay mineral facies patterns.

Thus with the superimposition of a substantial component of iron, in somewhat greater-than-usual amounts of aluminous matter, on what might be referred to as “normal” patterns of clay mineral sedimentation, we may visualize the development of a clay mineral zoning during sedimentation such as is depicted in Figure 8(a). It should now be recalled that all of these minerals in this pattern have been proposed as principle precursor materials of the common metamorphic index minerals. Figure 8(b) shows the metamorphic mineral zonation that would, if these pre-cursor-product relationships are valid, derive from the sedimentary clay mineral zonation depicted in Figure 8(a). It should be noted that under such circumstances the given mineralogical zone may be confined to a single stratum on a local scale, a single stratum may encompass several zones, and that mineralogical (metamorphic) zones may develop at a high angle to bedding and hence cut across later developed fold structures. For the pelitic rocks, on this basis, metamorphic facies may reflect sedimentary facies, as the latter manifest themselves in subtle variations in clay mineral assemblages.

A Creationist Alternative to the Uniformitarian Interpretation

As was noted at the outset, the concept of regional metamorphic zones and facies was initially developed by Barrow, and later by Kennedy, their interpretation of the metamorphic mineral zonation in the Dalradian of the Scottish Highlands being depicted in a somewhat simplified fashion in Figure 2. It would appear that Barrow was, very reasonably, conscious of the intrusive igneous rocks that cut the Dalradian rocks further to the north, and interpreted the somewhat concentric zonation as a thermal effect. However, there were in fact two possible explanations,

not one, that he could have utilized, namely:—

1. that the zones reflected increasing grades of metamorphism of rocks of constant composition, as he concluded, or
2. that they reflected a more or less constant metamorphism of rocks of systematically, but subtly, changing constitution.

Whether Barrow saw only one possibility, or whether he saw the two and deliberately chose the first, we shall never know.

However, there is now this further evidence provided by stratiform ore environments that suggests that the second alternative merits very serious consideration. In the Pegmont deposit (north-west Queensland), for example, Stanton & Vaughan (1979) have presented what seems clear evidence that progressive change in metamorphic mineral assemblages and metamorphic mineral chemistry are, in those instances at least, a direct consequence of sedimentary facies. Changes in principal element abundances, as revealed in a series of drill-holes, from the centre to the edge of the Pegmont Basin represent a pattern of chemical sedimentation that must have developed in a shallow depression on the sea floor. The original materials of the chemical sediments were probably iron-rich clays and chlorites such as greenalite, minnesotaite, and chamosite, together with goethite, and minor sulfide increasing in abundance towards the centre of the basin. Stanton & Vaughan show how this original constitutional pattern has given rise to a progressive change in mineralogy from basin centre to basin edge. Proceeding outwards from the basin edge, the rocks become quartz-muscovite, quartz-muscovite-biotite, and quartz-muscovite-biotite-feldspar assemblages. That is, a “high-grade” assemblage at the basin centre grades out to garnet-biotite quartzite, and eventually to a “quartz-mica schist” around the periphery. “Grading” of the metamorphic mineral assemblages is clearly a simple consequence of a pre-existing sedimentary facies pattern in this small basin.

Implications—Zones of Precursor Materials

As has now been shown, the evidence of some stratiform ore environments indicates that, even within a restricted and relatively uniform group of rocks such as the pelites, there may be sufficient constitutional variation to induce the development of a wide range of metamorphic minerals, indeed virtually all of the metamorphic minerals known, at a given temperature and pressure. This is precisely the conclusion reached by Yoder (1952) from experimental evidence on the $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ system. Clearly, the system investigated by Yoder is very much simpler than the natural ones under consideration here, yet Yoder showed that at 600°C and 15,000psi it was possible to have assemblages within that restricted

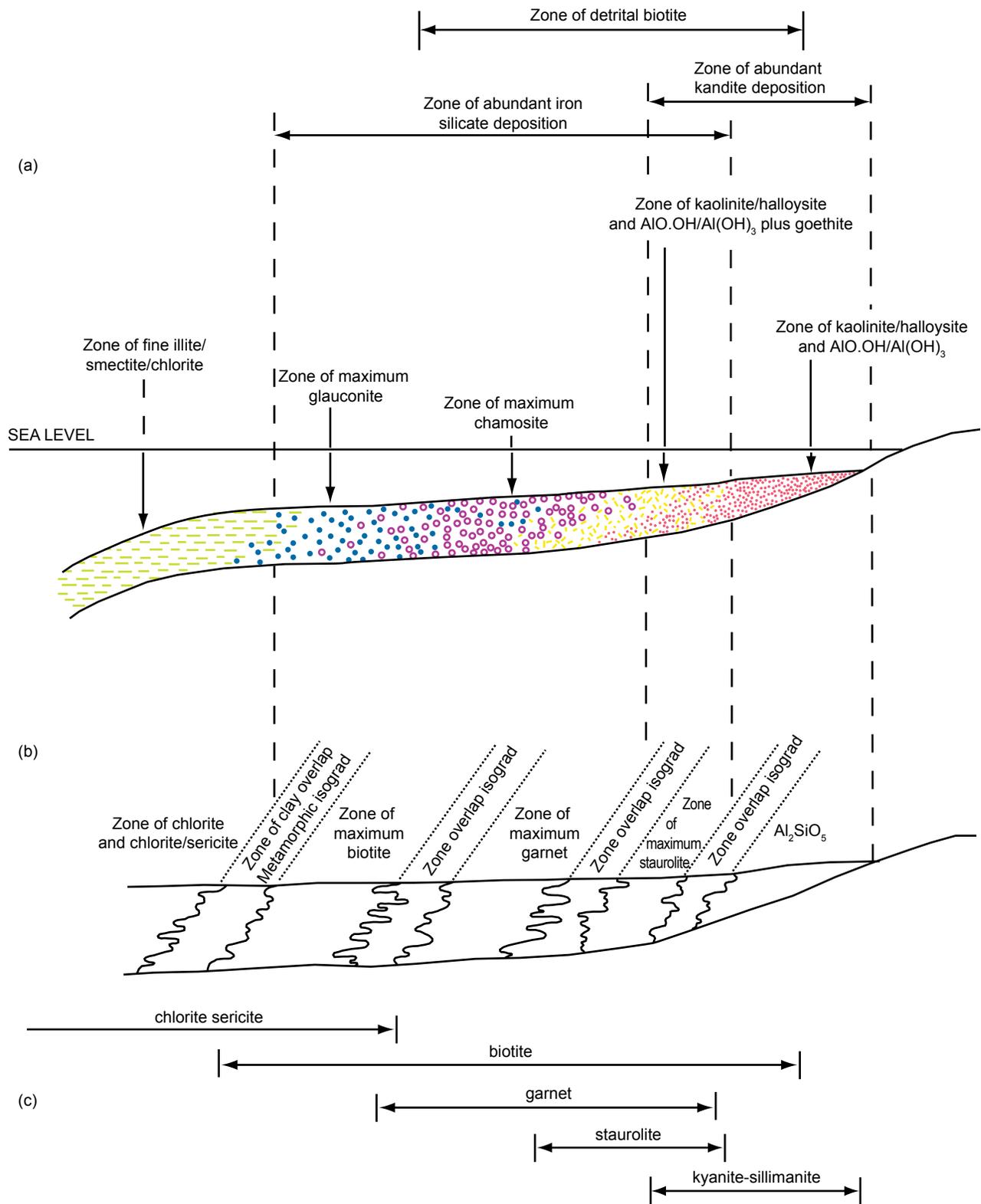


Figure 8. (a) Idealized representation of a pattern of notably aluminum- and iron-rich clays and clay-type materials that might develop in the warm waters of a tropical shelf to which seboard calc-alkaline volcanic and hydrothermal activity were contributing. (b), (c) Similarly idealized representation of metamorphic mineral zones that might result from essentially isochemical regional metamorphism, with concomitant precursor→metamorphic mineral transformation of the original pattern of detrital, sedimentary, and diagenetic clays, as in (a). Note that the original clay mineral facies boundaries and their derived metamorphic zones cut across bedding, and hence would be transgressive to later fold structures.

system corresponding to every one of the accepted metamorphic facies in stable equilibrium. He pointed out that earlier investigators such as Eskola (1920) had based their identification of metamorphic zones and facies on the assumption that the rocks they had chosen were an isochemical group. However, Yoder noted that his experiments showed that changes of a few percent in composition (including water) may produce great differences in mineralogy, and that mineralogical differences interpreted by Eskola and others as resulting from changes in temperature-pressure conditions might actually be, for the most part, results of subtle changes in bulk composition.

Having thus stated explicitly that observed mineralogical differences between rocks of different metamorphic facies might be “the result of variation in bulk composition and need not represent variations of pressure and temperature,” it now seems ironic that Yoder should have gone on to say, “This conclusion, based on experimental fact, appears to be at variance with field observations.” The metapelitic rocks associated with many stratiform ores now clearly indicate, as did Yoder’s experiments, that differences in metamorphic mineral assemblages may be due entirely to variation in the constitution of the rocks, and need not, and at least in some cases do not, represent variations in pressure and temperature. The “field evidence” is there in the metasedimentary sheaths of stratiform ores. Far from being “at variance” with Yoder’s experimental results, it appears to confirm them.

Thus the evidence suggests that there may well be an alternative, in the general sense, to Barrow’s interpretation which has become almost unassailable dogma in the geological literature. At least in some cases metamorphic mineral zones may reflect no more than subtle, but systematic, variations in the clay mineral assemblages of the original pelitic sediments, variations consequent upon sedimentary facies in turn stemming from the filling and shallowing of sedimentary basins and shelves, and from transgression and regression associated with epeirogenic changes in shelf and basin depths. Additional factors effecting such clay mineral assemblages may have been the contribution of particularly copious quantities of aluminum and iron compounds through nearby calc-alkaline volcanism, and the prevailing climate. Warm waters, as in the tropics today for example, may have favored the development of abundant chamosite in the appropriate facies, and hence, during subsequent metamorphism, the development of a pronounced and extensive garnet zone. Indeed, one suspects that it may be the sediments of calc-alkaline volcanic shelves developed under warm water (today’s tropical) conditions that eventually yield the clearest metamorphic mineral zonations.

In such a context the broad zoning and separation of metamorphic minerals in “normal” sedimentary sequences, as compared with the tiny, “compressed” sequences of stratiform ore environments, has been on a scale large enough to be compatible with, and indeed to suggest, that the mineralogical changes stem from regional changes in temperatures and pressures. However, this breadth of scale has probably misled us, and the clue to this possibility that we have probably been misled is provided by the stratiform ores. This line of thought indicates:—

1. early-developed sedimentary/diagenetic precursor materials of the kind postulated may lead to the regional development of metamorphic mineral zoning mimicking that due to prograde metamorphism.
2. in some cases an interplay between early, cryptic zoning of such sedimentary/diagenetic precursors, and later zoning of true prograde metamorphic temperature-pressure conditions may lead to confusing patterns of mineralogical zonation including apparent grade reversals.
3. the “patchy” rather than zonal distribution of the various metamorphic mineralogies so often found in the field, and instances in which patterns of metamorphic mineral occurrences appear to bear no relation to either structural or intrusive features, may be attributable to primary precursor patterns rather than to variations in metamorphic grade.

None of the foregoing should be misconstrued to imply that prograde metamorphism is not a response to increased temperatures and pressures within a given volume of sedimentary and/or other rock strata. That such metamorphism is indeed a *P-T-X* response (particularly a temperature-composition response) on a regional scale has been taken as well established and therefore self-evident. However, what has been emphasized is that development of metamorphic minerals may result not so much from the “bulk chemistry” of the parent pelitic material, as from the crystal structures and chemical compositions of the innumerable individual particles of which it is composed. If (a) regional metamorphism is substantially a response of these preexisting crystalline particles to a rise in temperatures, (b) the different crystal structures respond at different temperatures, and (c) such temperatures vary in space and time, then it may be expected that the various relevant metamorphic daughter products will develop in ordered patterns in space and time. That is, regional metamorphism may proceed to different “grades” that may reveal themselves by the areal distribution of different mineral assemblages and paragenetic sequences.

At first sight this may appear to be exactly the current conventional view of regional metamorphic

grade and mineral zonation. This, however, is not the case, and the principle involved may be illustrated by a re-examination of the Dalradian metamorphic terrain of Scotland (Figure 2) and the regional metamorphic zones there as mapped and interpreted by Barrow. Those zones are currently regarded (and have been so regarded for one hundred years) as reflecting the progressively changing response of pelitic rocks of essentially uniform bulk chemical composition to a rise in temperature that itself exhibited an ordered increase in space. Thus the mineralogical zonation from south-southeast to north-northwest of chlorite-to sillimanite-bearing assemblages is interpreted as indicating a general increase in regional metamorphic temperatures in a north-northwest direction. However, on the basis of the precursor principle as proposed by Stanton (1982a, 1989b) and discussed here, metamorphic temperatures may not have been significantly different over the entire terrain affected; they may simply have been sufficiently high to convert all members of a group of precursor minerals, arranged in zones of premetamorphic origin, to their respective daughter products (Figure 8).

The words “sufficiently high” are chosen deliberately. It would be very surprising indeed if all precursors converted to their relevant metamorphic daughter products at similar temperatures. There can be little doubt that the various transformations, as distinct from simple grain growth being the mechanism involved, would take place at different temperatures. If this were indeed the case, then the different grades of metamorphism would be marked by the temperatures of precursor transformations rather than temperatures of intermineral reactions as conventionally visualized. Clearly, the interplay between zonal sedimentary/diagenetic patterns of precursor occurrence on the one hand, and different temperatures (and pressures) of transformation of these precursors on the other, may well be complex. It is likely, for example, that neofomed chlorite will assume a high degree of crystallinity, and illite transform to muscovite, at lower temperatures than siliceous chlorites might transform to almandine, or kaolinite-gibbsite mixed layers re-order to sillimanite Stanton (1989b, p.A627). However, the place of other potential transformations in terms of the “standard” pattern of regional metamorphic zonation (chlorite-biotite-garnet-kyanite-sillimanite) is quite unknown at this stage. Indeed, temperatures of any particular transformation may be influenced substantially by kinetic factors, as has already been suggested in the cases of sillimanite (Stanton, 1983) and cordierite (Stanton, 1984), and this, together with paleogeographical factors, might induce reversals and other deviations from “normal” zoning patterns.

Implications—Only Up to Moderate Temperatures Required

We noted earlier that Stanton & Williams (1978) found significant differences in garnet compositions developed and preserved from one thin bed to the next on a scale of 1 mm or less in a finely laminated garnet-quartzite in the Broken Hill metamorphic terrain, New South Wales. Furthermore, whereas garnet compositions varied grossly across bedding, they were completely uniform along beds, indicating that the observed finely layered compositional arrangement was a direct reflection of original bedding. In other words, they maintained that a chemical sedimentary feature of the finest scale had been preserved through a proposed period claimed to be at least 1.8 billion years, including a very high-grade metamorphic episode. However, it strains credulity to suppose that this original pattern of chemical sedimentation could have been preserved with the “utmost delicacy,” through a presumed period of 1.8 billion years through the claimed high temperatures and pressures of very high-grade metamorphism.

What is equally amazing is the discovery by Stanton (1989b, p.A543–A544) of distinctly hydrous “quartz” in well-bedded quartz-muscovite-biotite-almandine-spinel rocks also in the Broken Hill metamorphic terrain. Stanton comments that it seems “remarkable” that this silica could still retain such a notably hydrous nature (7–10% water) after 1.8 billion years that included relatively high-grade (that is, high temperatures and pressures) metamorphism! He also insists that this well-bedded unit in part represents chert that exhibits delicately preserved fine bedding in spite of being involved in high-grade metamorphism.

So the quartz in this Broken Hill metamorphic rock unit was originally chemically-sedimented silica, deposited as a product of sea-floor hydrothermal exhalation as hydrous silica gel, that with diagenesis and aging dehydrated and transformed in situ to quartz—a metamorphic mineral. Thus it has not been produced by any metamorphic reaction, being derived directly from an ancestral hydrous form of silica. Even any induced variable grain growth and coarsening due to presumed metamorphic heating has in no way obliterated the fine bedding. However, this is wishful thinking, that some of this hydrous quartz, that is supposed to be transformed in situ to quartz merely with the low temperatures of diagenesis and aging, should not only survive intact through a presumed period of 1.8 billion years, but the high temperatures and pressures of high-grade metamorphism. Surely, if this “remarkable” discovery proves anything at all, then it is that metamorphic quartz has not only been produced by dehydration and transformation in situ of precursor silica gel and/or chert, but that the

temperatures, pressures and timescales postulated are not necessarily required. Indeed, this discovery indicates that, since quartz does form from its hydrous silica precursor at the low temperatures of diagenesis, these claimed high-grade metamorphic rocks may not have suffered high temperatures and pressures at all!

Stanton (1989b, p.A638) has concluded that if the regional metamorphic silicates do develop principally by transformation and grain growth, the problem of the illusive metamorphic reaction in the natural milieu is resolved. Preservation of what appear to be disequilibrium concentration gradients and mineral assemblages follows naturally if the materials formed at low temperatures and pressures, particularly in wet sedimentary and sedimentary-hydrothermal depositional regimes, simply undergo early water loss followed by in situ solid-solid transformation with rising temperatures and pressures. There is no destabilizing of large chemical domains (“bulk chemistries”) leading to extensive diffusion, no widespread reaction tending to new equilibria among minerals that develop as groups in accordance with the requirements of the Phase Rule. Puzzled speculation that some metamorphic rocks might attain their mineral assemblages directly rather than through a series of mineral reactions, and hence without passing through each successive grade, appears to be answered. The common lack of evidence that “high-grade” zones have passed through all the mineral assemblages of the “lower-grade” zones, an inevitable corollary of the “progressive” nature of the conventional understanding of metamorphism, seems accounted for. The real metamorphic grade indicators are then not the hypothetical inter-mineral reactions usually postulated, but the relevant precursor transformations, which may be solid-solid or in some cases gel-solid. Of course, 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. Nevertheless, such phenomena appear not to have anything like the dominating importance in regional metamorphism that is currently assumed, and the role of metamorphic reactions in generating the bulk of regional metamorphic mineral matter is probably, quite contrary to present belief, almost negligible.

The other key factor in elucidating regional metamorphic grades, zones and mineral compositions besides precursor mineral/sediment compositions would thus be the temperatures of precursor transformations, rather than the temperatures of presumed “classical” metamorphic mineral reactions. It is therefore highly significant that hydrous “quartz,” which should have been totally dehydrated at relatively low temperatures, is still found today

with its water content in a “high-grade” metamorphic terrain. This is not an isolated occurrence. Many such examples indicate that such transformations do occur at low to moderate temperatures and pressures, and that the timescales involved may not have been as long as suggested. Thus it is conceivable that regional metamorphic terrains with their zones of “classical” index minerals could have been produced as a result of catastrophic sedimentation, burial, and tectonic activities over short timescales, the zones only being a reflection of variations in original sedimentation, as can be demonstrated in continental shelf depositional facies today.

Regional Metamorphism

Within the Creationist Framework

In the creationist framework of earth history there is more than one episode capable of producing large regions of zoned metamorphic rocks. During the creation week it is not clear when the first rocks were created and formed, although of course the Scriptural record clearly states that dry land was formed and covered in soils ready for plants to grow in during day three. The earth itself was created on day one, but we are only told that it was then covered in water. We can only speculate whether there was a rocky earth beneath differentiated at that point of time into a core, mantle and rocky exterior crust (Austin et al., 1994). Furthermore, the nature of any such early-formed rocky crust would be difficult to decipher from today’s surface exposures, because the rocks there have undergone changes due to the catastrophic events since. Nevertheless, we can clearly infer from what we are told in Genesis 1 that the formation of the dry land on day three must have involved both earth movements (tectonism), erosion of the emerging land surface due to the retreating waters, and deposition of sediments in the developing ocean basins. So at the very least there is here sedimentation capable of producing zones of sediments with subtle differences in bulk chemistry and mineralogy that would be precursors for accompanying or subsequent regional metamorphism. It is because tectonism accompanied this sedimentation that we cannot preclude the possibility that with such earth movements, plus deep burial of some of these sediments, some metamorphism in some regions may have accompanied this day three regression.

Of course, there is no reason to assume that this sedimentation did not continue on into, and through, the pre-Flood era. Furthermore, any volcanism and tectonism that occurred during the creation week may also have continued on into the pre-Flood era, but obviously with an intensity and frequency subdued enough so as not to generate impossible living conditions for the residents of the pre-Flood world.

Thus the pre-Flood continental shelves and ocean basins would have continued to accumulate a variety of sediments with zonal patterns of different clay and other minerals, perhaps not too dissimilar to those observed today and described earlier (for example, see Figure 7). There also seems no reason not to suppose that there was also sea-floor hydrothermal activity, with hot springs issuing forth a variety of chemicals to interact with the normal marine sedimentation. After all, the Scriptural record does say that at the time the Flood began the fountains of the great deep were broken up (Genesis 7:11), which could be read to imply that fountains already in existence were broken up, to then catastrophically issue forth voluminous water, dissolved chemicals/minerals, and probably accompanying molten rock. That these fountains did exist prior to the Flood could be inferred from Revelation 14:7, which speaks of the Creator Who made the heaven, the earth, the sea, and the fountains of waters. Thus in the pre-Flood era there is wide scope for the development of sedimentation patterns that may have subsequently been metamorphosed, due to heat released and burial at the outset of the Flood producing temperatures sufficient to induce precursor transformations and regional zones that would mimic conventional “grades.” Nevertheless, it is suggested that the scope for metamorphism itself would have been somewhat limited in the pre-Flood era.

It is, of course, the Flood event itself which provides perhaps the greatest scope for regional metamorphism within the creationist framework of earth history. With water eventually again covering the whole earth, catastrophic sedimentation occurred as the pre-Flood land surface was eroded away. The vast thicknesses of fossil-bearing strata are mute testimony to the deep burial of large volumes of sediments. The rock record also testifies to vast outpourings of lavas, so that volcanism on a global scale ensured the release of copious amounts of hydrothermal waters during sedimentation, and the sediments would also have included volcanic components (Austin et al., 1994). Tidal resonance of the global ocean’s waters would have ensured an episodic nature to sedimentation, (Clark & Voss, 1990, 1992) and rapid deformation and tectonism would have ensured both elevated temperatures and pressures in thick sediment piles, as well as the potential for repeated cycles of sedimentation, metamorphism, erosion, sedimentation, and then metamorphism again in regions that overlapped as this catastrophic activity shifted geographically (Tyler, 1990). Add to this the possibility of rapid plate tectonics with thermal run-away subduction, rapid rifting, and “rapid” continent-continent collisions as per conventional plate tectonics minus the evolutionary timescale,

(Austin et al., 1994; Baumgardner, 1986, 1990) and one has a sufficient scenario for the various settings required for regional metamorphism. The range of induced pressures would have, of course, been short-lived, and the timescales would have only allowed for moderate temperatures to be reached. However, as we have seen, the evidence presented now indicates that composition is the primary factor in metamorphism, and that the zoning of index minerals found across regionally metamorphosed terrains is dependent upon the presence and compositions of precursor minerals, and the temperatures at which those precursors are transformed.

This overall scenario may be somewhat simplistic, but it does provide the “skeleton” of a creationist explanation for regional metamorphism. As was noted at the outset, the biggest problem creationists face with the conventional scenario for regional metamorphism is the heat presumed to have been involved, (Wise, 1986) given that even with rapid burial beneath kilometers of sediments time is needed to produce that heat within the sediment pile. However, we have now seen that only moderate temperatures may be needed to transform the precursors into the index minerals of the zones of regional metamorphism, and such moderate temperatures would have conceivably been generated in the short timescale in the Flood event described above, both due to the thicknesses of the sediment piles catastrophically accumulated, and due to the increased heat flow from the mantle because of rapid plate tectonics (Austin et al., 1994). This higher heat flow during the Flood also would have progressively raised ocean water temperatures. This has been confirmed by oxygen isotope analyses of foraminifera fossilized in the lowermost deep-sea sediments in today’s post-Flood ocean basins (such fossilized foraminifera building their tests in equilibrium with the waters at the time they lived, which would have been at the end of the Flood/beginning of the post-Flood era) (Vardiman, 1994). So the waters trapped in the Flood sediments would have been warmer than the waters being trapped in sediments today, thus giving the buried sediments a “head start” in reaching the temperatures required for diagenesis, and then the moderate temperatures required for regional metamorphism.

This demonstrated necessity for only moderate temperatures to transform precursors, even at the highest conventional “grades,” also alleviates the conventional need, raised as an objection against Flood geology by Young (1977), to bury sediments under loads up to 16–19kms thick to produce the presumed high temperatures and high pressures conventionally thought necessary for regional metamorphism. These conventionally postulated overlying thicknesses Young also posed as another problem, as they

need to be then eroded away subsequent to that metamorphism so that the metamorphosed strata are now exposed at the earth's surface again. Thus, given the primary importance of precursors and zones of different precursors in the sediments, it has now been demonstrated that the creationist framework with its short timescale, and particularly the Flood event, appears to be able to cope with the moderate temperatures, pressures and depths of burial, plus the catastrophic loading and unloading (burial and erosion), required for regional metamorphism, and for the distribution of regionally metamorphosed rocks and their constituent "grade" zones that we see exposed on the earth's surface today.

Some Remaining Problems to be Solved

It would be misleading to give the impression that no problems remain to be solved. Far from it. While the "skeleton" of this creationist scenario for regional metamorphism, based as it is on observational and experimental realities, is both conceivable and feasible, the "bones" need "fleshing out" and the principles enunciated here need to be applied specifically from region to region of metamorphic rocks across the earth's surface today, and vertically and time-wise down through the rock record.

And some problems about the rocks and minerals themselves also remain to be resolved. For example, at what specific temperatures and pressures are the various precursors transformed? Obviously, the answer to that question will enable quantification of the temperatures, pressures and depths of burial required for regional metamorphism within the creationist framework. Also, how do porphyroblasts develop in the many cases where diffusion has been restricted? Are they

1. products of transformation of large particles, for example, impure chamosite oolites and particles in the case of garnet,
2. products of transformation of concretions and related products developed by post-sedimentation and diagenetic processes, a derivation that would account for many "spotty" porphyroblasts, and porphyroblasts that straddle bedding planes, or
3. products of later inhibition-dependent and orientation-dependent coarsening? (Stanton, 1972)

These processes would readily account for porphyroblasts of a given mineral in a matrix of its own kind, for example, quartz porphyroblasts in quartz-rich metapelites, and for porphyroblasts that straddle bedding planes. These mechanisms would also account for porphyroblasts related to, or developed after, tectonic deformation.

Another group of problems lies in relationships between metamorphic minerals and phases of deformation. It seems likely that some interpretations

of metamorphic microstructures may require revision, although there has been some recent vigorous discussion on some aspects of this issue (Vernon, 1978; Bell, 1985; Bell, Rubenach, & Fleming, 1986; Bell, Forde, & Hayward, 1992a; Bell et al., 1992b; Bell & Johnson, 1989, 1992; Passchier, Frouw, Zwart, & Vissers, 1992). However, it remains to be seen whether or not apparent sequences of development of metamorphic minerals may be attributed, more simply, to differences in their deformational behavior and in their variable propensity to anneal and to undergo secondary grain growth in the metallurgical sense. Thus there is still a lot of work for creationists to do in dealing with many of the mineralogical and textural issues in metamorphic petrology from the short timescale perspective, including conventional experimental studies on mineral stabilities and reactions. Only then will we have developed a comprehensive explanation of regional metamorphism within the creationist framework for earth history.

Conclusions

A careful search of the metamorphic petrology literature reveals that in recent years doubts have been expressed regarding the basic assumptions of the "classical" or conventional explanation for regional metamorphism. Precise microscope and electron microprobe studies now indicate that there are severe limits on the distances involved in metamorphic diffusion, which in turn imposes severe constraints on both the extent of supposed mineral reactions and the opportunity for equilibration of mineral assemblages. Even where different minerals are found side-by-side, that conventional wisdom would expect to have reacted, no evidence of such mineral reactions can be found.

Furthermore, the preservation of very fine scale zoning patterns within single crystals indicates that, even at the supposed highest grades of metamorphism, equilibrium has not been attained even within single crystals. One is thus forced to conclude that the chemical components of a metamorphic grain now occupying a given small domain are derived directly from those chemical components occupying that domain immediately prior to the onset of metamorphism—in other words, the metamorphic mineral must represent the in situ growth and/or transformation of a pre-metamorphic material of similar overall composition.

These conclusions are strikingly confirmed by the array, assemblages and compositions of metamorphic minerals found within and surrounding stratiform sulfide orebodies. Since these ores have now been demonstrated to have formed due to hydrothermal springs on the sea-floor, the enclosing rocks with their metamorphic assemblages must represent original

pelitic sediments produced in concert with “normal” marine sedimentation. Studying the assemblages of mineral species and their compositional variations in these metasedimentary sheaths shows that original sedimentary features even at the finest scale (1 mm or less) have been preserved through claimed millions of years and the supposed highest “grades” of metamorphism. Furthermore, there is no clear micro-structural evidence of mineral reactions and metamorphic equilibrium has not been established. Indeed, the whole spectrum of index minerals characteristic of the presumed zones of regional metamorphism occurs within centimeters of each other. It is thus concluded that the key factor in the development of a particular set of metamorphic minerals is the composition, not just the bulk chemistry, of the pelitic rock, and the detailed features of precursor materials, their crystal structures and their compositions.

Therefore, these stratiform ores and their metamorphic assemblages reflect original sedimentation in sea-floor hydrothermal environments mixing with “normal” marine sedimentation, the clay and other minerals in the sediments being the precursors to the metamorphic assemblages now present. Extension of this precursor principle to wider zones of sedimentation reveals that both in present-day marine shelf environments and in the depositional environments reflected in a number of “ancient” sedimentary basins, there are wide zones of pelitic sediments containing different clay and related mineral assemblages, such that if these were metamorphosed they would result in metamorphic mineral assemblages that would mimic the zones of regional metamorphism with their characteristic index minerals.

Furthermore, it has been demonstrated that these transformations of precursor minerals/materials into metamorphic mineral assemblages can occur at low to moderate temperatures. Some of these metamorphic minerals have been found with remnants of their precursor materials alongside, the two coexisting in rocks that are supposed to have experienced the highest “grade” of metamorphism.

The most extreme example, the presence of distinctly hydrous “quartz” in high-grade metamorphic rocks, even after 1.8 billion years and such metamorphism, can only mean that temperatures were low to moderate and the timescale was very short. Thus it is feasible to conclude that the classical zones of regional metamorphism represent zonal patterns of the original sedimentation, and that the precursor clay and associated minerals have undergone transformation to metamorphic mineral assemblages at low to moderate temperatures and pressures. Furthermore, this implies that the depths of burial

required were considerably less, and consequently the timescales as well.

Creationists can therefore 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, particularly during the Flood, but also during the tectonism, erosion and sedimentation of the emerging land surface on day three of the creation week. Volcanism on a global scale, and thus the release of copious amounts of hydrothermal waters, during sedimentation would have produced zones of different precursor materials, and also provided heat for metamorphism during the Flood year. Catastrophic erosion caused by the retreating Flood waters would also have left previously-buried metamorphic rocks exposed at the earth’s surface today.

Thus the major objections raised, on the basis of the conventional explanation of regional metamorphism, against the young-earth creation-Flood model of earth history are answerable, and an alternative creationist explanation has been outlined on the basis of observational and experimental realities. Further work is, of course, needed to quantify the conditions required for precursor transformations, while various mineralogical and textural issues in metamorphic petrology, and in microstructural analysis of phases of deformation, need to be dealt with to make this creationist explanation comprehensive.

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