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PREHNITE-PUMPELLYITE FACIES METAMORPHISM OF THE NEW BAY FORMATION, EXPLOITS ZONE, NEWFOUNDLAND

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Abstract

The New Bay Formation is a thick (~2000 m) wedge of andesitic volcaniclastic sediments interpreted to have been deposited in an early Paleozoic arc-trench gap. The sediments have been metamorphosed to prehnite-pumpellyite facies, but pumpellyite is not common. A characteristic mineral assemblage is albite + calcite + quartz + prehnite + chlorite + epidote. Field relations and mineral assemblages are interpreted as indicating metamorphism at temperatures on the order of 300-400°C and load pressures less than 1 kb. The high temperatures were produced by injection of numerous thick dykes and sills which were feeders to the overlying Lawrence Head pillow lavas.

Introduction

A number of recent studies have recognized zeolite and prehnite-pumpellyite facies metamorphism in a wide age range of rocks from many parts of the world. Recognition of these facies in the Appalachians of North America was late in coming, until Coombs *et al.* (1970) reported prehnite-pumpellyite facies in Ordovician-Devonian eugeosynclinal strata of northern Maine. Subsequently, Mossman & Bachinski (1972) described zeolite facies assemblages from Devonian rocks on Chaleur Bay, New Brunswick.

This paper is the first description of prehnite-pumpellyite facies in the Appalachians of Newfoundland's Central Paleozoic Mobile Belt, although Marten (1971, p. 80) mentions the occurrence of "secondary prehnite" in intrusive rocks of the Western Arm Group on the Springdale Peninsula. Prehnite-pumpellyite assemblages have been reported from Precambrian strata of the Avalon Platform, Zone H, (Papezik 1972 and this issue), and Williams & Malpas (1972) reported prehnite-pumpellyite metamorphism of ophiolites tectonically emplaced on the western Precambrian platform, Zone A.

Geologic Setting

The island of Newfoundland has been divided into three large-scale tectonic zones (Fig. 1): (1) a western Precambrian platform underlain by Grenville basement (Zone A), (2) Central Paleozoic Mobile Belt (Zones C-G), characterized by Ordovician-Silurian volcanic and associated sedimentary rocks, and (3) Avalon Peninsula (Zone H), an eastern platform of Precambrian and early Paleozoic sedimentary and volcanic rocks (Williams 1969, Williams *et al.* 1972, 1974).

The rocks herein described lie within Zone E (Exploits Zone) of the Central Mobile Belt (Fig. 1) and belong primarily to the New Bay Formation of the middle Exploits Group (Helwig 1969). The rocks are exposed south of the Lukes Arm Fault along the shores of New Bay and the Bay of Exploits north of Botwood. North of the Lukes Arm Fault are basic volcanic rocks of the Lush's Bight Terrane (Zone D) which have been interpreted as remnants of Paleozoic ocean crust (Smitheringale 1972; Bird & Dewey 1970).

The New Bay Formation is an eastward-thickening wedge of volcaniclastic sedimentary

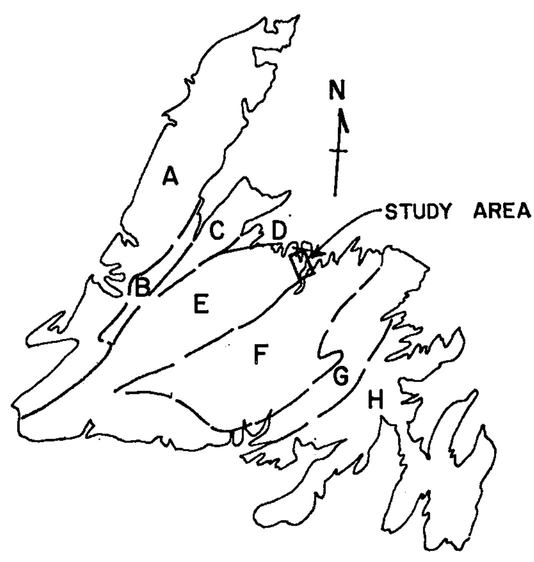

FIG. 1. Location of the study area. Zones A-H are the tectonic-stratigraphic zones of Williams, Kennedy, Neale (1972): A—Lomond Zone or western platform; C-G — Central Paleozoic Mobile Belt; H—Avalon Platform.

rocks. To the west, the formation is interpreted to be in facies relationship with submarine and subaerial(?) volcanic rocks of the Wild Bight Group (Horne & Helwig 1969) and to the east is in tectonic contact with the Dunnage *mélange*, interpreted by Bird & Dewey (1970) as a Paleozoic subduction zone. The New Bay Formation is interpreted as an early Paleozoic arc-trench gap deposit (Franks & Helwig 1973).

Stratigraphy

The New Bay Formation is part of the Ordovician Exploits Group as redefined by Helwig (1969). Earliest Caradocian graptolites in the Lawrence Harbour Shale (Fig. 2) indicate a pre-Upper Ordovician age for the New Bay Formation, and crinoid stems in limestone pods between pillows of the Tea Arm Volcanics indicate only a post-Cambrian age.

The New Bay Formation is composed of volcanogenic sandstones and conglomerates deposited by a variety of resedimentation mechanisms (*e.g.*, turbidity currents, grain flows, debris flows). Clastic beds range in thickness from less than a cm to tens of m and are interbedded with black argillite except in the upper 500m or so where red and green argillite predominate.

The formation is approximately 2100 meters thick at the type section along the east shore of New Bay and thickens to the east along strike. On the west shore of the Bay of Exploits the formation exceeds 3880 meters (the base is not exposed). Numerous basic sills and dykes comprise approximately twenty-one per cent (450 meters) of the formation in the type section and thirty-one per cent (1160 meters) of the Bay of Exploits section. The average thickness of intrusive bodies in the Exploits section is approximately fifty-five meters.

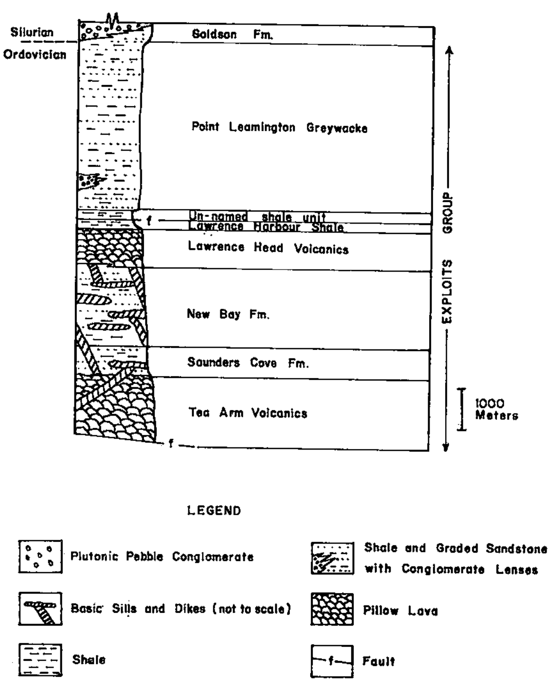

FIG. 2. Stratigraphic section of the New Bay area. Adapted from Helwig (1969).

Structure

Since structural relationships are used later in this paper as a means of interpreting the timing of intrusion, a brief summary of folding in the area is presented below.

Two major fold episodes have affected strata of the New Bay Formation. The earlier (F_1) fold axes trend north to slightly west of north, and S_1 cleavage is poorly developed except in pelitic rocks near F_1 fold axes (Helwig 1967). Helwig (1967, 1970) has shown that F_1 folds are restricted to pre-Point Leamington strata, but an unconformable relationship between the Point Leamington greywackes and underlying strata is neither implied nor observed in the field. The stratigraphic section indicates continuous deep-water sedimentation. The F_1 tectonic episode is reflected in the Point Leamington greywacke by abundant sedimentary slump folds which are interpreted as contemporaneous with and genetically related to the F_1 folds in the underlying formations (Helwig 1970, p. 177; see figure 7, p. 182).

Acadian (F_2) folds clearly post-date F_1 structures and are accompanied by regional development of S_2 slaty cleavage which cuts across axial planes of F_1 folds. These later fold axes trend northeast and affect the entire stratigraphic section shown in Figure 2.

Petrology

Detrital petrology

Modal analyses of thirty sandstones of the New Bay Formation show low quartz content in all samples (usually less than 10% of the framework grains), and the ratio of lithic fragments (L) to feldspar (F) varies from 0.15 to 0.97. In general, the L/F ratio increases with increasing grain size. Plagioclase is very common, potassium feldspar being rare. Lithic fragments are primarily dacitic, andesitic, and basaltic volcanic clasts. No plutonic or metamorphic fragments have been observed, and sedimentary clasts are predominantly shale chips of intrabasinal origin. Clinopyroxene is not a characteristic detrital component of the sandstones but, where present, may form up to 30% of the framework grains.

Total matrix often makes up 20 to 25% of the sandstone, but primary matrix was certainly significantly less and may have been as low as 5 to 10%. *X*-ray diffraction analyses indicate iron-rich chlorite to be the major phyllosilicate in the matrix, with lesser amounts of illite. Preliminary results indicate a rough positive correlation between the percentage of secondary matrix (pseudomatrix and epimatrix of Dickinson 1970), and an increase in chlorite/illite ratio, suggesting that most of the chlorite forms as a result of decomposition of basic volcanic debris within the sandstone whereas the illite represents the detrital clay component (orthomatrix). This contention is supported by the much lower chlorite/illite ratio in the interbedded shales.

Metamorphic petrology

The metamorphic products in the New Bay Formation are (1) albite, (2) chlorite, (3) calcite, (4) white mica, (5) prehnite, (6) epidote, (7) sphene, and (8) pumpellyite in approximate order of abundance. Although many sandstones exhibit extensive mineralogic readjustments in thin section, the rocks generally appear unaltered at the outcrop, and original sedimentary structures and textures are commonly preserved.

Albitization of calcic plagioclase is the most widely recognized metamorphic alteration. Although relict crystals occur with normal and oscillatory zoning, the bulk of the plagioclase had been altered to cloudy albite which commonly contains alteration patches of one or more of the following: chlorite, sericite, prehnite, epidote, and/or calcite. No obvious relationship exists between degree of albitization and geographic or stratigraphic position of the sample.

Chlorite, like albite, is a ubiquitous phase in the New Bay sandstones. It most commonly occurs as a cement or matrix replacement but is also very common as an alteration product of aphanitic and vitric volcanic clasts, plagioclase feldspar, and quartz. The chlorite varies in colour from pale yellow to green. Interference tints are low first order, and anomalous "Berlin blue" interference tints are common. *X*-ray diffraction analyses show a strong enhancement of even-ordered reflections, suggesting that the phase is iron-rich.

Calcite is present as an alteration product of plagioclase, as irregular patches in the clayey matrix, as veins, and as pore fillings. Although calcite is present to some extent in virtually all sandstones examined, it rarely forms more than two per cent of the rock by volume.

Sericitization of feldspar is common. The micaceous phase occurs as tiny laths (.004 to .03 mm) and fan-shaped clusters scattered through plagioclase crystals. No relationship was found between degree of sericitization and stratigraphic position.

Prehnite is the most common index mineral in the New Bay Formation, occurring in more than half the sandstones examined. It is also recognized by *x*-ray diffraction in very fine-grained green, cherty tuffs in the upper and lower parts of the formation. Although prehnite commonly forms only a few per cent of the rock volume, tuffaceous sandstones at some localities are converted into quartz-prehnite rocks. Observed occurrences of prehnite are as:

(1) an alteration product of plagioclase
(2) a lining on walls of veins where it is accompanied by quartz and/or calcite
(3) finely disseminated or ovoid porphyroblasts within clayey matrix
(4) an alteration product of basic glass fragments
(5) white reaction rims on basic volcanic conglomerate pebbles

Epidote is common in the New Bay sandstones but is always subordinate to prehnite. It occurs as both irregular patches in the matrix and as radiating crystal aggregates, often associated with "pools" of chlorite. Epidote also occurs as an alteration product of plagioclase and less commonly as veins. Typically, the epidote is pale yellow to yellow-green and shows slight yellow-green pleochroism. Epidote is observed only in sandstones containing prehnite although not all prehnite-bearing sandstones contain epidote.

Sphene is present as sub-rhombic to somewhat globular masses ($<$0.06mm) of very high relief. In the New Bay sandstones, sphene is almost invariably associated with "pools" of chlorite.

Pumpellyite is not common in the New Bay Formation. It has been identified optically in only three samples of more than one hundred examined. Pumpellyite-bearing sandstones also contain prehnite and epidote. An *x*-ray diffractogram of a heavy mineral fraction has peak positions and relative intensities almost identical to that of pumpellyite from Calumet, Michigan, described by Coombs (1953). The pumpellyite shows strong blue-green pleochroism and anomalous brown and blue interference tints as well as low first order grey. It is most often intimately mixed with chlorite, but the best examples are crystals on quartz phenocrysts in felsitic volcanic rock fragments. Pumpellyite-bearing sandstones occur within the lower and upper 500m of the New Bay Formation, thus no depth (*P-T*) control is apparent.

Sandstones of the Point Leamington are generally more quartz rich and less volcanogenic than those of the New Bay Formation. No prehnite, pumpellyite, zeolites, or authigenic epidote has been observed in preliminary petrographic examination of the Point Leamington Sandstones. Sandstones from the lower part of the formation, which are petrographically similar to New Bay Sandstones, contain albite, calcite, chlorite, and celadonite as metamorphic products.

Chemical Composition

Chemical analyses of sixteen New Bay Sandstones reveal a range in composition from those approximating calc-alkaline high-alumina basalt to those approaching a dacitic composition (Fig. 3). The mean composition is close to tholeiitic andesite. Significant features are the low K_2O content (mean = 1.22) and high Na_2O/K_2O (mean = 4.90) compared with data given by Pettijohn (1963) for the average greywacke (2.00 and 1.45 respectively). The low K_2O and high Na_2O/K_2O are reflected mineralogically in the abundance of albitized feldspar, virtual absence of K-feldspar, and the predominance of chlorite over illite in the phyllosilicate phase.

Discussion

Three observations must be considered in deciphering the metamorphic history of the New Bay Formation:

(1) There is no evidence that the metamorphic phases are stratigraphically (depth) controlled within the New Bay Formation.
(2) Preliminary petrographic examination of overlying formations reveals neither prehnite-pumpellyite nor zeolite facies assemblages.
(3) Coexisting prehnite-epidote is common and pumpellyite rare in the New Bay sandstones.

Two different models are considered here to explain the observed mineral assemblages and field relations.

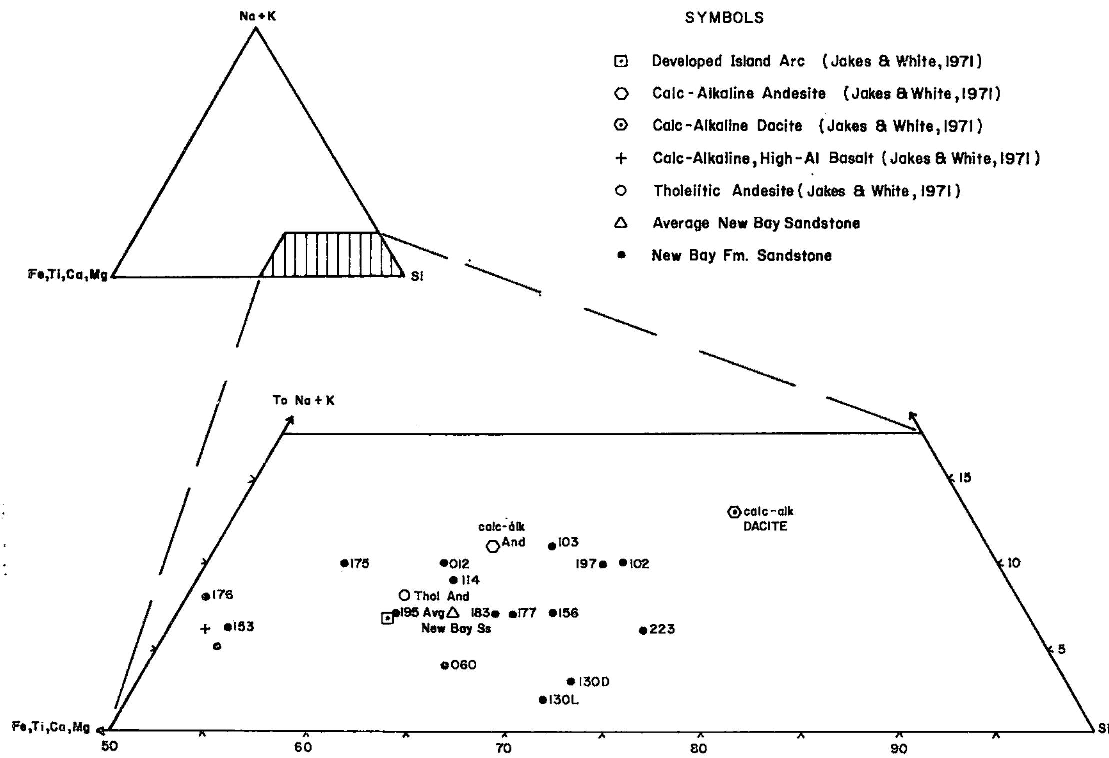

FIG. 3. Chemical composition of seventeen sandstones from the New Bay Formation. Shown for comparison are probable igneous parent rocks.

Burial model

The lack of any relationship between degree of metamorphism and depth within the New Bay Formation could be due to the limited thickness of the sequence. That is, the variation of pressure and temperature (due to burial) over 2000 meters may have been insufficient to produce detectable mineralogic differences. This alone, therefore, does not rule out a burial model. However, the P/T conditions required by a simple burial model are such that either prehnite-pumpellyite or zeolite assemblages are expected in the overlying strata.

Five km of an incomplete Ordovician through Lower Silurian section overlie the New Bay Formation. Hence, minimum load pressure within the formation is estimated at 1.5 - 2.1 kb. This pressure may, in fact, be close to the maximum value since uncomformable relationships exist between Ordovician and Silurian strata in nearby areas (Kay 1967). Recent experimental work (Liou 1971) shows the prehnite-pumpellyite facies to be stable in the temperature range 250-380°C at pressures exceeding 2kb and Nitsch (1971) indicates a stability field for prehnite + epidote + chlorite + quartz (without pumpellyite) from 320-360°C at pressures less than 2.5kb. Based on these data, a geothermal gradient in excess of 40°C/km is required to produce the mineral assemblage observed in the New Bay Formation, assuming a burial model. This is a high but not unreasonable gradient. However, a gradient exceeding 40°C/km would produce temperatures of more than 150°C at the base of the Point Leamington Greywacke, well within the range in which the zeolite facies is developed in classical zeolite facies terranes (Boles & Coombs, in press). Preliminary examination of andesitic volcanogenic sandstones (similar to those of the New Bay Formation) from the lower part of the Point Leamington has revealed neither zeolites, prehnite, pumpellyite, nor epidote.

In summary, observations (1) and (2) above are interpreted as evidence against a simple burial model. On the basis of the data in Nitsch (1971) and Liou (1970) which indicate a stability field for pumpellyite-bearing assemblages at higher pressures and/or lower temperatures than that for prehnite-bearing assemblages, observation (3) may indicate metamorphism at lower pressures and higher temperatures than those which produce pumpellyite-bearing assemblages. The rare occurrences of pumpellyite suggest that temperatures locally were less than that necessary for the reaction:

pumpellyite + quartz → prehnite + chlorite + epidote

shown by Nitsch (1970, p. 254). These observations are interpreted to support a model in which heat for metamorphism is supplied by numerous shallow intrusions rather than by burial alone.

Intrusive heat model

The New Bay Formation and underlying sequences are pervasively intruded by thick basic dykes and sills. In the type section along the shores of New Bay, approximately 20 per cent of the exposed section is composed of intrusions, and along the west shore of Exploits Bay approximately 30 per cent of the section is made up of dykes and sills. Field evidence indicates that these sills and dykes were injected into relatively unconsolidated sediments shortly after their deposition:

(1) Aquagene tuffs and autobrecciated lavas are found in the upper and lower parts of the formation.
(2) Sills and dykes are affected by an early period of folding (F_1) which affects only pre-Point Leamington units.
(3) Xenoliths of contorted sediment found in sills suggest the sediment was not completely lithified at the time they were incorporated.

This evidence, particularly (2), strongly suggests that the sills and dykes are feeders to the Lawrence Head Volcanics overlying the New Bay Formation. I believe that the tremendous quantity of heat released by these intrusions had the cumulative effect of significantly raising temperatures within the sedimentary column.

Assuming a model in which the heat for metamorphism was supplied largely by magmatic intrusions feeding the overlying volcanics, the depth at the time of metamorphism can be evaluated and an estimate made of the temperatures attained. The maximum overburden during metamorphism is represented by the thickness of the Lawrence Head Volcanics and the New Bay sediments. This indicates burial depths of 0.8 to 2.8 km ($<$ 1 kb). Jaeger (1959) has calculated that a sheet with a fixed melting point of 1000°C and a thickness (x meters) intruded into wet sediments (with 20% porosity) can raise the temperature of the sediments (x meters from the contact) almost 250°C, assuming no movement of pore waters. It is likely that movement of pore water in the semi-consolidated sediments reduced gradients and resulted in a more even dispersal of the heat. From the numbers and thicknesses of the sills and dykes in the New Bay Formation, it is estimated that temperatures were raised above 300°C over much of the formation by the cumulative effect of the intrusions. This is supported by the common occurrence of quartz-prehnite veins which are interpreted by Coombs *et al.* (1959, p. 83) to form at temperatures of 300°C or more.

There is no clear-cut evidence of progressive metamorphic zonation related to a particular dyke or sill. However, a thin zone of hornblende hornfels (~5-10 cm) is commonly found adjacent to some intrusions, and at one locality textural evidence in tuffaceous sandstones suggests increasing metamorphism approaching the intrusion:

> no prehnite→prehnite alteration of plagioclase→prehnite replacing plagioclase and disseminated in matrix→prehnite replacing plagioclase and abundant in matrix with numerous quartz-prehnite veins.

At the temperatures and pressures suggested by the intrusive heat model (>300°C and <1 kb), wairakite might be expected to be the stable calcium alumino-silicate. Wairakite is found in areas of extreme geothermal gradients such as at Wairakai, New Zealand (Steiner 1955) and The Geysers, California (Steiner 1958), and experimental work suggests a stability field for wairakite at the temperatures and pressures suggested in this model (Liou 1970). However, the equilibrium boundary between wairakite and prehnite stability fields has not been established and, in fact, coexistence of these two calcium silicates in some areas (Seki *et al.* 1969; Donnelly 1962) indicates the possibility of overlapping stability fields. Surdam (1973) has shown by calculation that, within an appropriate range of temperature and pressure, the stability fields of hydrous calcium aluminosilicates (prehnite, pumpellyite, epidote, laumontite or wairakite) can be related to the activities of Ca^{++}, SiO_2, and H^+ ions in solutions. The predominance of prehnite and apparent absence of wairakite in the New Bay Formation may be due to high log $a_{Ca^{++}}/a_{(H^+)}^2$ relative to log a_{SiO_2} (see Surdam 1973, p. 1917).

The common occurrence of prehnite with epidote instead of with pumpellyite in the New Bay Formation may reflect the low pressure conditions of metamorphism and/or the ratio of partial pressure of CO_2 to that of H_2O. Surdam (1973) noted a correlation between the presence of $CaCO_3$ and the absence of pumpellyite in rocks of the Karmutsen Group, British Columbia, and thus suggested that epidote is favoured over pumpellyite in high $\mu CO_2/\mu H_2O$ environment. The common occurrence of calcite in New Bay sandstones may be cited as evidence that the $\mu CO_2/\mu H_2O$ hindered crystallization of pumpellyite.

Nitsch (1971) on the basis of experimental work suggests the assemblage chlorite + epidote + prehnite + quartz is stable in the range of about 320-360°C at 1 kb and less. At higher pressures pumpellyite appears. Thus, either or both of these factors may have played an important role in limiting the development of pumpellyite in the New Bay Formation.

Summary and Conclusions

Prehnite-pumpellyite facies metamorphism is developed in the pre-Caradocian volcanogenic sandstones of the New Bay Formation. Pumpellyite is rare, and the characteristic assemblage is prehnite + chlorite + quartz + epidote. Albite is ubiquitous and calcite is a minor but persistent phase. Neither occurrence of hydrous calcium alumino-silicates nor degree of albitization is related to depth. Preliminary evidence suggests that metamorphism is restricted to the New Bay and underlying formations, and it is concluded that the metamorphism is a pre-Caradocian event brought about by temporary high heat flow related to the pervasive injection of basic dykes and sills into the New Bay sediments. Subsequent deposition and burial at a normal or subnormal geothermal gradient prevented the development of prehnite-pumpellyite or zeolite facies metamorphism in the overlying strata. However, a more detailed examination of these sequences is needed to confirm this interpretation.

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