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ILLITE CRYSTALLINITY AND FLUID INCLUSION ANALYSIS ACROSS A PALEOZOIC DISCONFORMITY IN CENTRAL KOREA

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Abstract—Illite crystallinity and fluid inclusion techniques are used to understand the thermal histories of rocks on either side of the disconformity between the Lower and Upper Paleozoic strata in South Korea. Illite crystallinity studies show that the metamorphic grade of the upper strata of the Lower Paleozoic Joseon Supergroup, platform carbonates with subordinate siliciclastics, belongs to the epizone and that of the lowermost strata of the Upper Paleozoic Pyeongan Supergroup, paralic to nonmarine clastics, belongs to the anchizone. The maximum mode of homogenization temperature for fluid inclusion of the uppermost strata of the Joseon Supergroup is 260 to 270 °C and that of the lowermost strata of the Pyeongan Supergroup is 240 to 250 °C. These data reveal a difference in thermal histories of strata below and above the unconformity, suggesting that, in contrast to the previous supposition of a period of non-deposition, at least a 1-km thick section of sediment was removed by erosion during development of the unconformity. Burial and heat flux from a proposed hot spot are suggested as the dominant factors causing differences in a metamorphic grade for the Joseon Supergroup before the deposition of the Upper Paleozoic strata.

Key Words—Disconformity, Illite Crystallinity, Korea, Low-grade Metamorphism, Paleozoic Strata, Thermal History.

INTRODUCTION

The interest in the thermal histories of sedimentary rocks and basins has grown rapidly since the 1970s owing to increased interest in predicting the timing of oil generation (McCulloh and Naeser 1989). Studies of vitrinite reflectance, conodont color alteration, fission tracks, clay mineral assemblage and fluid inclusions have been used to understand the thermal history of sedimentary basins. For example, the thermal history of a discontinuous sedimentary succession of Early Permian to Tertiary age in southern Israel was reconstructed by using vitrinite reflectance and fission track analysis (Feinstein et al. 1989). Vitrinite reflectance was used to estimate the thickness of sediments removed at unconformities (Armagnac et al. 1989). Illite crystallinity (IC) has also been used to distinguish between the burial and regional metamorphism within orogenic areas (Roberts and Merriman 1985).

Diagenetic changes occur in mud and shale in the temperature range of 20 °C to nearly 200 °C (Dunoyer de Segonzac 1970; Boles and Franks 1979). The greenschist facies, the beginning of "true" metamorphism, generally starts at temperatures above 350 °C (Frey and Kisch 1987). Very low-grade metamorphism occurs in the temperature range of 150–200 to 350–400 °C (Frey and Kisch 1987). Illite crystallinity is used as the main indicator of metamorphic grade, including anchimetamorphism (or anchizone) and epimetamorphism (or epizone) for very low- and low-grade metaclastites (Kubler 1968; Frey 1987).

In Korea, the Early Paleozoic sedimentary rocks, the Joseon Supergroup, are disconformably overlain by the Late Paleozoic Pyeongan Supergroup. The disconformity between the 2 supergroups represents a geological time gap of more than 100 my. It is generally believed that after deposition of the uppermost strata of the Joseon Supergroup during the Middle to Late Ordovician, the marine sedimentary basin was uplifted due to epeirogeny and remained without further sedimentation (Reedman and Um 1975). A new basin developed within the same region during the Late Carboniferous Period and subsequently deposited the Pyeongan Supergroup above the unconformity.

Most of the Korean Peninsula is considered to be part of the North China platform (Sino-Korean platform). North China and Korea have similar Paleozoic stratigraphic sequences (Sun et al. 1989; Hu et al. 1989; DS Lee 1987; Reedman and Um 1975; Zhang and Zhen 1991) and this unconformity is also seen in North China.

The purpose of this study is to examine the thermal histories of the Lower Paleozoic and Upper Paleozoic strata across the disconformity to provide information about the process of sediment thermal alteration, which can be examined in North China. On the basis of IC and fluid inclusion data, the Lower Paleozoic strata are inferred to contain higher thermal grades than the Upper Paleozoic strata, indicating a difference in the thermal evolution of these 2 strata across the unconformity.

GEOLOGIC SETTING

The study area is located northeast of the Ogcheon belt (in the strict sense, Ogcheon intracontinental orogenic belt; Cluzel et al. 1990, 1991) in the east-central Korean Peninsula (Figure 1). Presently this supposed

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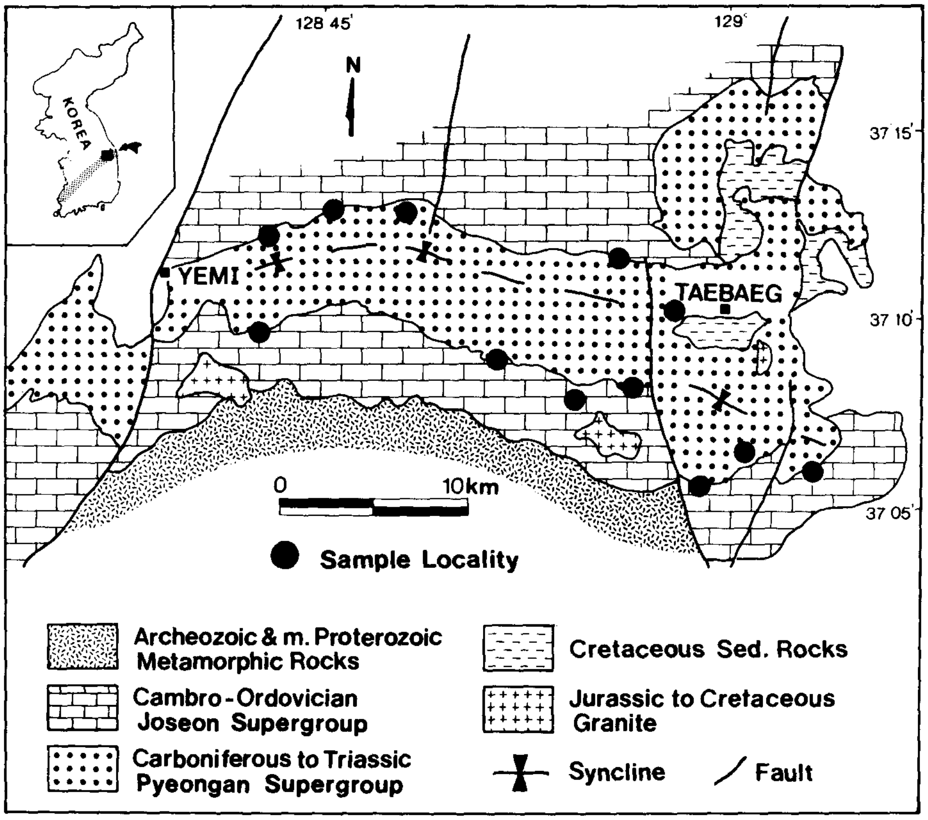

Figure 1. Simplified geological map of the study area. The Ogcheon belt is marked by the shaded area in the inset.

AGE			FORMATION	
Cretaceous			Jeoggagri	
Triassic (?)			Donggo	Pyeongan Supergroup
Permian	Late		Kohan Dosagok	Pyeongan Supergroup
Permian	Early		Hambaegsan Changseong	Pyeongan Supergroup
Carboniferous	Late		Geumcheon Manhang	Pyeongan Supergroup
Ordovician	Late	Sangdong Group	Duwibong	Joseon Supergroup
Ordovician	Middle	Sangdong Group	Jigunsan	Joseon Supergroup
Ordovician	Middle	Sangdong Group	Maggol	Joseon Supergroup
Ordovician	Early	Sangdong Group	Dumugol	Joseon Supergroup
Ordovician	Early	Sangdong Group	Dongjeom	Joseon Supergroup
Cambrian	Late	Samcheog Group	Hwajeol	Joseon Supergroup
Cambrian	Middle	Samcheog Group	Daegi	Joseon Supergroup
Cambrian	Middle	Samcheog Group	Myobong	Joseon Supergroup
Cambrian	Early	Samcheog Group	Jangsan	Joseon Supergroup

Figure 2. Stratigraphy of the Baegunsan syncline area where the Paleozoic Joseon and Pyeongan supergroups are exposed (modified after Kobayashi 1966; Cheong 1969).

orogenic belt is in fault contact with the study area; the Ogcheon belt is not thought as part of the Sino–Korean platform (Cluzel et al. 1990, 1991; Kobayashi 1966). The study area is covered mainly with the Lower Paleozoic Joseon and the Upper Paleozoic Pyeongan supergroups with the E–W trending Baegunsan syncline running through the middle of it (Figure 1). The Joseon Supergroup ranges in age from Lower Cambrian to Upper Ordovician and has been classified into 2 groups consisting of 9 formations (Kobayashi 1966; Cheong 1969).

The Jigunsan and Duwibong formations form the upper strata of the Joseon Supergroup (Figure 2). The Jigunsan Formation overlies the Maggol Formation conformably and is characterized by fossiliferous dark gray to black shales. The Jigunsan Formation is about 50 to 100 m thick. The shales are often calcareous and nodular in the upper part, whereas limestone beds are well-developed in the lower part of the formation. The Jigunsan conodont fauna are closely correlated with Llanvirnian to Llandeilian stages in Europe (Lee 1977).

The Duwibong Formation is the uppermost stratum of the Joseon Supergroup. The depositional environment of this formation is interpreted as a shallow carbonate ramp (Hyeong 1990). This formation consists

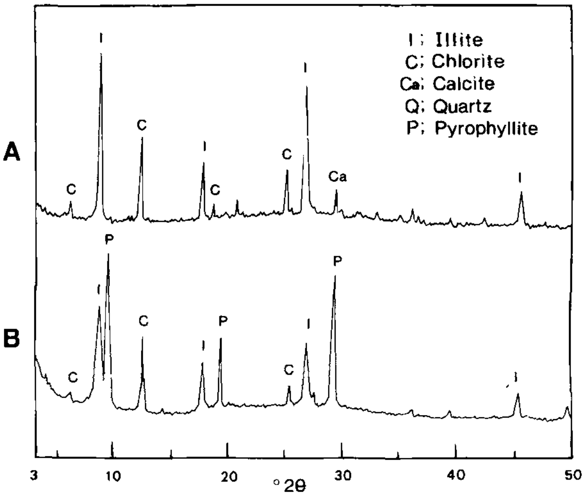

Figure 3. Typical XRD patterns representative of the air-dried <2-μm fraction of shales from the Jigunsan (A) and Manhang (B) formations. The Jigunsan shales contain illite and chlorite, while the Manhang shales contain illite, chlorite and pyrophyllite.

mainly of light gray to gray limestones. The Duwibong conodont fauna corresponds to the Llandeilian to lower Caradocian stages in Europe (Lee 1977). The thickness of the Duwibong Formation is 50 to 100 m, and it is unconformably overlain by the Manhang Formation, the lowermost strata of the Pyeongan Supergroup (Carboniferous to ?Triassic). The unconformity between the Duwibong and Manhang formations represents a hiatus ranging from Late Ordovician to Late Carboniferous (Figure 2).

The Manhang Formation comprises red or greenish-gray shale and sandstone, mottled coarse sandstone, fine-pebble conglomerate with minor intercalations of light-colored limestone beds in the upper part (HS Lee 1987). The thickness of the Manhang Formation is 200 to 300 m, and this formation is overlain conformably by the black shale, the Geumcheon Formation. Due to the presence of plant fossils in the lower part and of marine fossils in the upper part of the Manhang Formation, this formation is interpreted to have been deposited in a paralic setting (HS Lee 1987).

The Paleozoic strata in the Baegunsan syncline area had undergone deformation during the Triassic Songnim Disturbance and again during the Jurassic to Cretaceous Daebo orogeny. These tectonic events introduced the large-scale folding, faulting and overthrusts in the Baegunsan syncline area (Cheong 1976).

METHODS

Argillaceous samples were collected at 12 localities throughout the Baegunsan syncline area (Figure 1). At least 20 fresh rock samples were collected from each locality with intervals of 1 to 2 m from outcrops of the Jigunsan and Manhang formations. Oriented <2 μm clay fractions were analyzed by X-ray diffraction (XRD) using a Rigaku Model RAD-3C diffractometer with Ni-filtered Cu$K\alpha$ radiation. Altogether, 77 samples (Jigunsan Fm, 46; Manhang Fm, 31) were analyzed for IC. The IC was determined by both the Weaver index (WI; Weaver 1960) and the Kubler index (KI; Kubler 1968). In general, as metamorphic grade increases, IC increases also. The WI is best applied to unmetamorphosed sediments because of the error in determining the sharpness ratio on very narrow, high-crystallinity peaks (Blenkinsop 1988), whereas KI is widely used to estimate the metamorphic grade.

For KI, IC was determined by Δ °2θ converted from the measured half-height width of the 10-Å peak. Instrument settings were a time constant at 2 s and a scan rate at 0.5 °2θ/min (Robinson et al. 1990). The lower boundary values for anchizone and epizone used in this study are KI 0.37 Δ °2θ and 0.21 Δ °2θ (Kisch 1990).

Illite polytype was determined on the dried <2-μm fraction after gently grinding in an agate mortar. Samples were scanned from 3 to 50 °2θ at the settings of 35 kV, 20 mA, and a scanning rate of 1 °2θ/min. The *2M* polytype percentage was determined following the procedures of Maxwell and Hower (1967).

Expandable layers in illites were determined on glycolated samples (Środoń 1984). Samples heated at 300 °C for 2 h were used to check illite expandability. Both heated and glycolated samples were scanned from 3 to 50 °2θ at the scanning rate of 4 °2θ/min. Also, several samples were heated to 550 °C to positively determine the presence of kaolinite (Brown and Brindley 1980).

Calcite samples were collected from the Duwibong and Manhang formations. These samples are calcite cements of a meteoric to shallow burial origin that filled fossil molds and solution cavities. About 100 fluid inclusions were measured from doubly polished and knife-cleaved calcite cements. To minimize error due to stretching or distortion of the host crystal from experimental overheating, a single inclusion or a group of cogenetic inclusions within a single crystal was used for temperature measurements in each thin section segment. The homogenization temperatures were measured by using a United States Geological Survey (USGS) Type Gas Flow Heating and Freezing System. Replicate measurements of fluid inclusions indicate an error of approximately 1 °C at homogenization temperatures of 200 °C.

RESULTS

Clay Mineralogy

The clay mineral assemblage of the Jigunsan Formation consists of illite and chlorite (Figure 3a); no mixed layering was detected. The Manhang shale

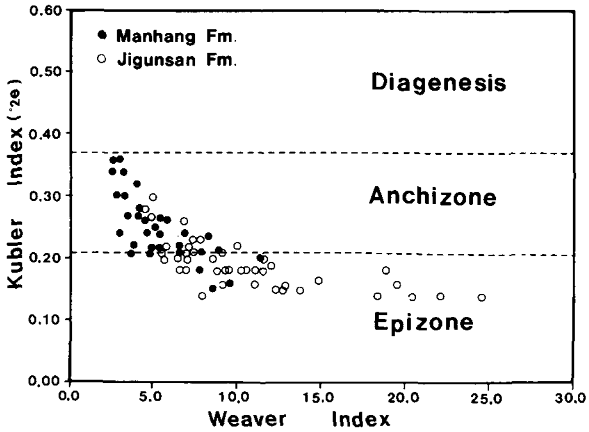

Figure 4. Illite crystallinity values of the Jigunsan and Manhang illites.

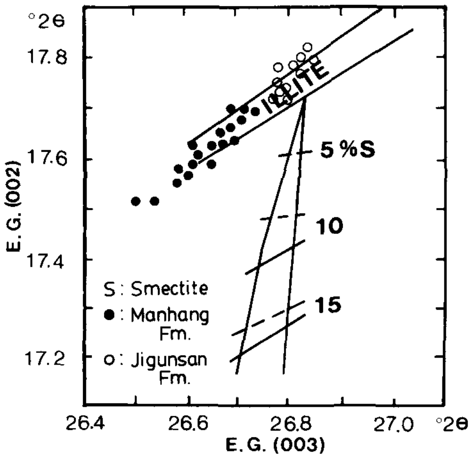

Figure 5. Diagram for determining illite/smectite ratio from (002) and (003) reflections (Środoń 1984). Samples from the Jigunsan and Manhang formations are plotted in separate areas in the illite field.

comprises illite, chlorite and pyrophyllite (Figure 3b) and no apparent mixed layering was determined. Illite and chlorite occur in all Manhang samples, whereas pyrophyllite occurs in approximately half the samples. Chlorite in both the Jigunsan and Manhang formations is of the *llb* polytype. Kaolinite was not observed.

Illite Crystallinity

IC of the Jigunsan Formation ranges from 4.48 to 32.5 in WI and from 0.30 to 0.14 Δ °2θ in KI. Figure 4 shows the IC and corresponding incipient metamorphic grade of the Jigunsan Formation. Most KI values in this formation are less than 0.21 Δ °2θ and fall within the epizone field with some illites plotting in the anchizone. Comparing the IC between the southern and northern regions of the Baegunsan syncline, both regions show similar values close to a mean of 0.19 ± 0.03 (± values are 1 standard deviation) Δ °2θ in KI.

The IC of the Manhang Formation ranges from 2.39 to 9.43 in WI and from 0.36 to 0.15 Δ °2θ in KI. Most of the Manhang IC values fall within the anchizone field and few samples fall within the epizone (Figure 4). The mean IC of the Manhang samples is 0.26 ± 0.05 Δ °2θ in KI.

Illite Expandability

Although the mixed-layer illite/smectite (I/S) is not evident from the XRD patterns of the Jigunsan and Manhang samples, the existence of the mixed-layer I/S in illite was investigated. A plot of the positions of the (002) versus (003) reflections from the XRD patterns of glycolated samples is presented in Figure 5. Samples from both the Jigunsan and Manhang formations plot within the illite field. However, the illites plot separately from each other. The intensity ratio (Ir), defined as the ratio of air-dried to ethylene glycolated intensity ratios of (001) and (003) reflections (Środoń and Eberl 1985), of illite from the Jigunsan samples is approximately 1, whereas Ir of the Manhang samples is greater than 1 (Figure 6). This relation indicates that the Jigunsan illites are pure illites and that the Manhang illites may contain some I/S.

The measurements of the joint breadth (2θ) of (001) illite and adjacent I/S reflections (BB1) as well as that of (004) illite and adjacent I/S reflections (BB2) (Środoń 1984) show that values of BB1 and BB2 of the Manhang illites are smaller than 4 °2θ, indicating that the Manhang illites contain some Kalkberg (ISII) type I/S.

Figure 7 shows the differences in KI values of the 10-Å peak before and after heat treatment. The Jigun-

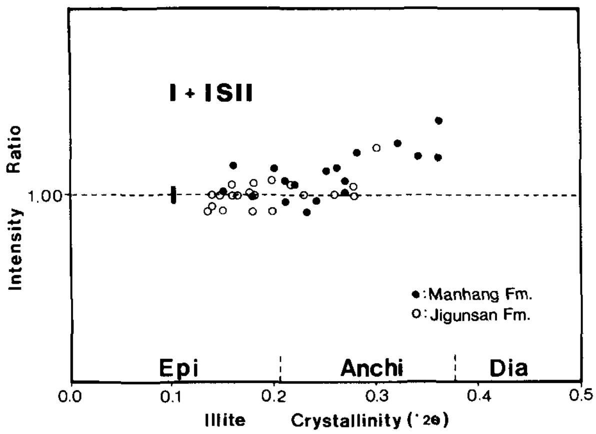

Figure 6. Relationship between illite crystallinity (Kubler index) and Intensity ratio (Ir). The Ir values of the Jigunsan illites are approximately 1, while those of the Manhang illites typically are larger than 1. Key: I = illite; ISII = Kalkberg-type illite/smectite.

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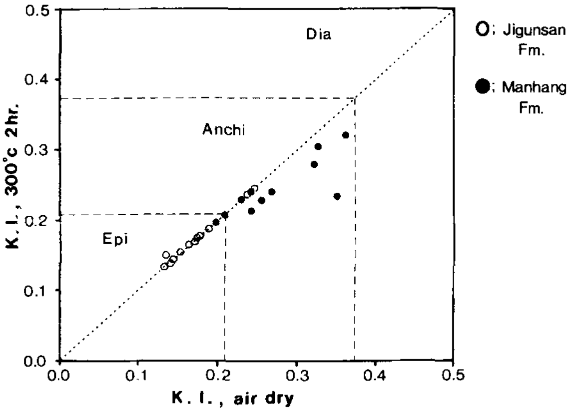

Figure 7. Diagram showing the changes in Kubler index when samples are heated at 300 °C for 2 h. The peak width of the anchizone illites decreases when heated.

san illites do not show any changes in KI values. The KI values of the heat-treated Manhang illites are less than those of the untreated illites, suggesting that some expandable smectite layers are present even though ethylene glycol has little or no effect upon the shape or position of the 10-Å peak.

Illite Polytype

Figure 8 shows that the proportion of the illite *2M* polytype for both Jigunsan and Manhang samples is more than 85%. When comparing polytypes to IC, the proportion of the *2M* polytype increases with IC. The epizone illites consist mostly of 100% *2M* polytype.

Fluid Inclusion

Fluid inclusions contain 2 phases and range in size from about 5 to 15 μm with some as large as 25 μm. They occur as isolated inclusions or in lines confined to a single crystal of calcite. There were no all-liquid inclusions and none with large vapor bubbles that would not homogenize. Homogenization temperature measurements are shown in Figure 9. The homogenization temperatures are uncorrected for pressure. The measured values have a broad temperature range. The Duwibong inclusions have homogenization temperatures ranging from 170 to 290 °C, and the Manhang inclusions range from 160 to 260 °C.

INTERPRETATIONS

The clay mineral assemblages of the Jigunsan and Manhang formations may correlate well with the epizone and anchizone conditions of metamorphism (Hoffman and Hower 1979; Hunziker 1986). Characteristically, pyrophyllite, an indicator mineral of the anchizone (Dunoyer de Segonzac 1970; Frey 1970), also occurs in the Manhang Formation, which is consistent with IC measurements.

The recrystallization of chlorite occurs during deep diagenesis. Although the correlation of chlorite poly-

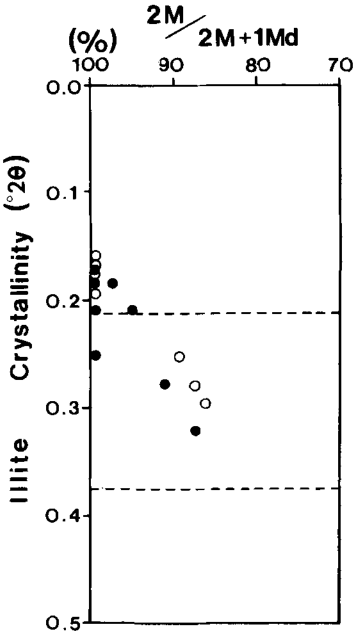

Figure 8. Relationship between illite crystallinity and *2M* polytype %. The proportion of *2M* polytype increases with increasing illite crystallinity.

types and temperature is generally poor, the *IIb* polytype is more stable in the higher temperature range (Hayes 1970; Walker 1989). The chlorites of both the Jigunsan and Manhang formations are the *IIb* polytype, implying temperatures greater than 250 °C (Walker 1989).

The *2M* polytype of illite is stable in lab experiments at temperatures above 200 to 350 °C (Yoder and Eugster 1955). Polytype analysis shows that more than 85% of *2M* polytypes that occur in both Jigunsan and Manhang illites are in general agreement with metamorphic grades in both formations. The presence of Kalkberg-type I/S in the Manhang samples indicates that the thermal grade of the Manhang illites is less than that of the Jigunsan illites.

Some Jigunsan illites plotting in the anchizone field are attributed to the lithology. These samples were collected from the upper, more calcareous part of the Jigunsan Formation. In calcareous lithologies, the recrystallization of illite may be retarded compared with noncalcareous clastics due to a potassium deficiency (Frey 1987). The Manhang illites plotting in the epizone were collected from the locality close to the major fault and thrust area.

As anchizone and epizone are only determined by IC, the temperature range of each zone does not represent specific IC values, and varies with the locality. Based on the mineralogy, the anchizone ranges in temperature from about 200 to 300 °C (Dunoyer de Segonzac 1970; Hunziker 1986). In the southern Appalachians the late-diagenetic zone to anchizone transi-

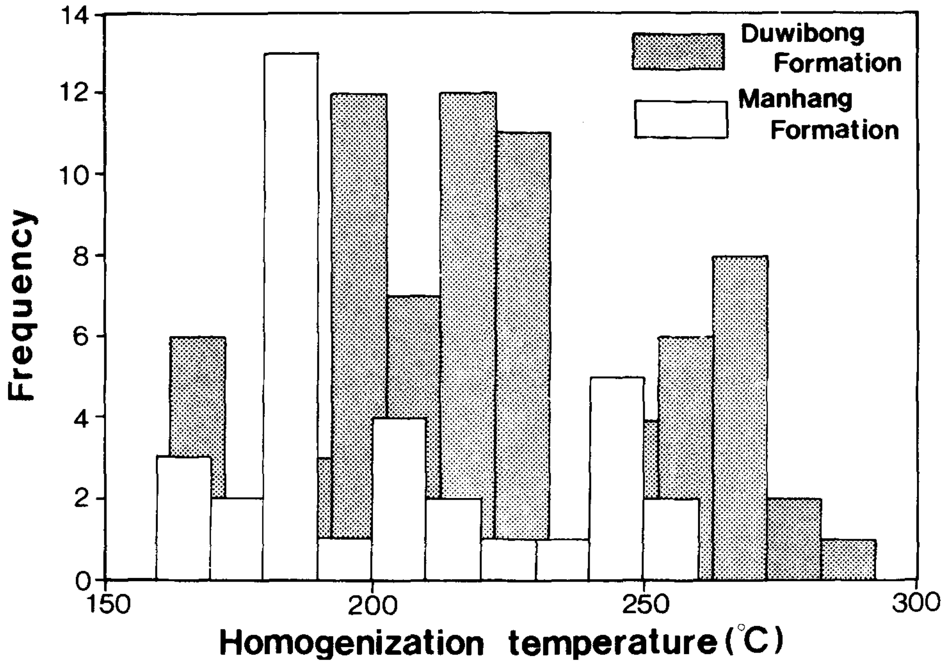

Figure 9. The distribution of homogenization temperatures of fluid inclusions from the Duwibong and Manhang formations.

tion is at approximately 250 to 280 °C (Weaver et al. 1984), which is higher than elsewhere.

This study suggests that the Jigunsan Formation is believed to have reached paleotemperatures of at least 300 °C, and the Manhang Formation from 200 to 300 °C. These temperature ranges are in agreement with conodont color alteration index values of 5 for the Duwibong Formation and 4.5 for the Manhang Formation, suggesting that both formations have been subjected to appreciable thermal metamorphism or have been deeply buried (Epstein et al. 1977).

Fluid inclusions in calcite cements are useful for interpreting diagenetic conditions (Moore and Druckman 1981; Smith et al. 1984). Their fluid inclusion data suggest that calcite cements precipitated from hot, deep-burial brines. However, other methods of study, such as stable isotope geochemistry and cement stratigraphy, have led to an interpretation of a low-temperature, freshwater origin for some of these cements (Goldstein 1986). The discrepancy suggests that some fluid inclusions in calcite cements trapped at low temperatures may re-equilibrate during deep burial. In fact, many fluid inclusions in calcite tend to re-equilibrate when heated to temperatures higher than those of initial entrapment (Goldstein 1986; Prezbindowski and Larese 1987; Barker and Goldstein 1990). Therefore, some homogenization temperatures of fluid inclusions in calcite cements may record near maximum burial temperatures of the host rock. Some fluid inclusions in calcite cements do not re-equilibrate with changing conditions during burial (Goldstein 1986; Prezbindowski and Larese 1987; Barker and Goldstein 1990). The wide distribution of homogenization temperatures in Figure 9 suggests that fluid inclusions show variable degrees of re-equilibration or that they are recording multiple events because of multiple origins. The re-equilibration processes are not reversible. Therefore, for deciphering thermal history of sedimentary rocks, only the maximum mode of polymodal homogenization temperature data or single mode of unimodal data appears to have significance (Barker and Goldstein 1990). The maximum modes of homogenization temperatures for the Duwibong and the Manhang fluid inclusions are 260 to 270 °C and 240 to 250 °C (Figure 9). Such maximum modes of homogenization temperatures are consistent with the results of paragonite geothermometers for both formations (Lee 1993). The difference in the homogenization temperatures between the Duwibong and Manhang formations, separated by an unconformity, cannot be explained by geothermal gradient alone. The fluid inclusions suggest that the Duwibong Formation underwent a higher thermal evolution than the Manhang Formation before the development of the unconformity.

DISCUSSION

Metamorphic-grade temperatures from IC and fluid inclusions for the upper strata of the Joseon Supergroup and the lowermost strata of the Pyeongan Supergroup can possibly be attributed to various heat sources. These sources are: 1) direct heat flux from a nearby igneous body; 2) heat accompanying defor-

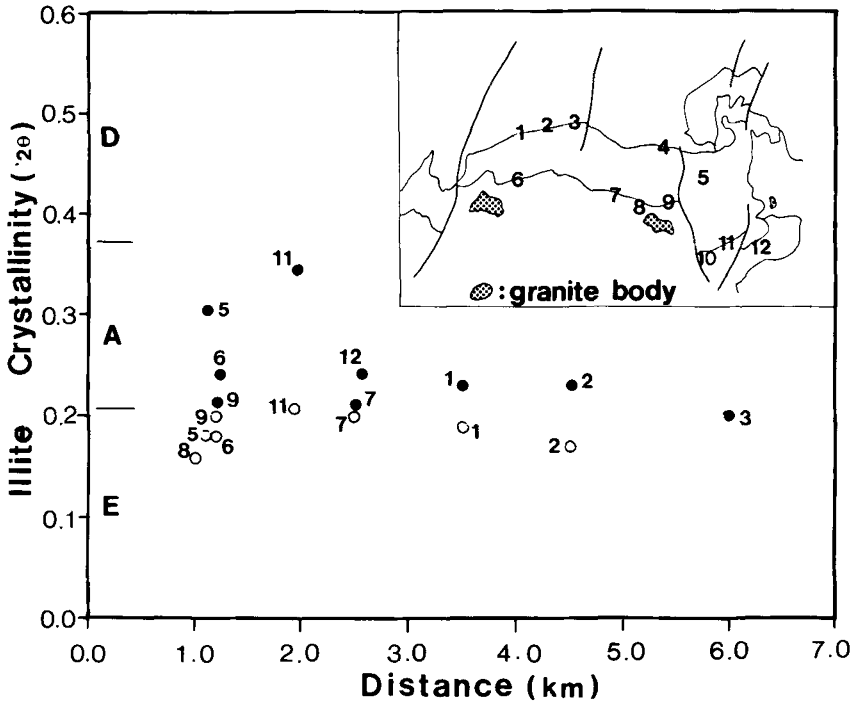

Figure 10. Diagram showing distribution of illite crystallinity according to distance to nearest igneous body. Key: numbers = sampling locality; open circles = Jigunsan Formation; solid circles = Manhang Formation.

mation; 3) deep burial of the sediments; and 4) lithospheric reheating or a hot spot. Among them, the burial and hot spot epeirogeny of the Joseon Supergroup before deposition of the Pyeongan Supergroup might have caused the discontinuity in the thermal grades between the 2 supergroups.

Igneous Body

Mica crystallinity has been used to delineate contact metamorphism around intrusive igneous bodies (Islam et al. 1982; Nadeau and Reynolds 1981). These studies revealed that relatively narrow thermal haloes are detectable around the pluton.

Several intrusive and extrusive igneous bodies from Jurassic to Cretaceous in age are distributed in the Baegunsan syncline area. These are Imok Granite (92 ± 1 Ma; Figure 1: western igneous body), Eopyeong dioritic rocks (107 Ma; Figure 1: center igneous body), hidden granitic rocks in Sangdong area occurring in the middle of Imok and Eopyeong bodies (83 ± 2.6 Ma) and intrusive and extrusive igneous bodies (50–100 Ma) in eastern Taebaeg.

To examine the effects of igneous bodies upon the incipient metamorphism in the Baegunsan syncline area, the variation of IC was examined in relation to distance from nearest igneous body at each sampling locality (Figure 10). There is no change in IC with distance from igneous bodies in the study area. Regardless of proximity to igneous bodies, the ICs of the Jigunsan and Manhang formations fall within the epizone and anchizone. The heat supplied by the igneous body is considered insufficient to cause metamorphic grades of the 2 formations even though some contact metamorphism has been reported around the igneous bodies (Chang 1988; Moon 1985).

The IC of these formations is not related to the distribution of igneous bodies but to stratigraphic age; the younger Manhang Formation exhibits lower-grade metamorphism than the older Jigunsan Formation.

Deformation

The Baegunsan syncline area is thought to have undergone several deformation episodes accompanied by folding and faulting. As deformation throughout the Baegunsan syncline area had occurred after deposition of the Jigunsan and Manhang formations, the deformation should influence 2 formations simultaneously. Assuming that the deformation was the major factor of the incipient metamorphism in the study area, the metamorphic grade of 2 formations should almost be equal in any locality and the grade should be higher in highly deformed localities than in less-deformed localities. However, the metamorphic grade of the 2 formations is not equal at any given locality (Figure 11). Considering the above assumption, if a high degree of the IC is observed in the Jigunsan formation at a certain locality, then the IC of the Manhang Formation should also be high in that locality. Such distribution

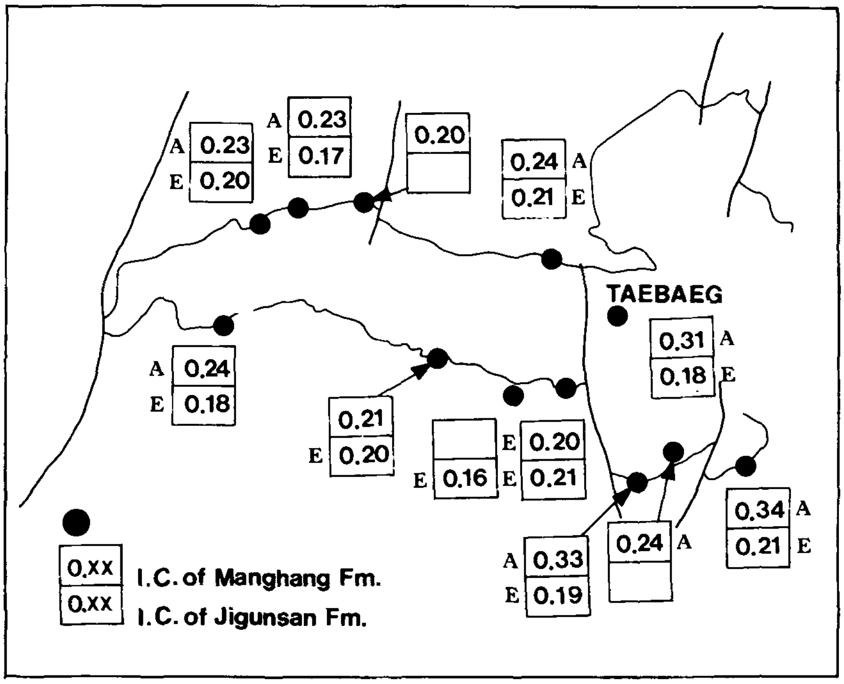

Figure 11. Diagram showing distribution of illite crystallinity values of the Jigunsan and Manhang illites in the Baegunsan syncline area. Illite crystallinity values are the mean of each locality. Key: A = anchizone; E = epizone.

patterns are not evident in the study area. In addition, the Jigunsan Formation is more calcareous and contains more organic matter than the Manhang Formation, which may suggest that the Jigunsan Formation is less sensitive to the deformation than the Manhang Formation. The Manhang samples show the better schistosity. Organic matter richness and calcareous lithology can inhibit illite recrystallization (Kubler 1968). However, the data show that the more calcareous and organic-rich Jigunsan Formation has higher IC than the Manhang Formation (Figure 11). Considering the fact that illites in the Jigunsan Formation were formed in a more calcareous, organic-rich sediments, the IC of the Jigunsan Formation should be even higher. Thus, the difference in the IC between the Jigunsan and the Manhang formations should be even more different. Weaver et al. (1984), in the study of the southern Appalachian, observed that the contours of the porphyroblast mineral zones and the distribution of the cleavage are roughly parallel to the boundary fault, whereas the grade of metamorphism (IC) is aligned at nearly right angles to the fault and overburden. Weaver et al. (1984) concluded that tectonic forces are responsible for the distribution of slate cleavage and that IC is best attibuted to thermal effects.

Therefore, the Jigunsan Formation probably experienced higher temperatures or more prolonged heating than the Manhang Formation in the overall study area. Consequently, the metamorphic processes of the 2 formations did not occur concurrently during the overall deformation of the study area, and the 2 formations were influenced by different metamorphic processes.

Burial/Lithospheric Reheating

Metamorphic grade of the Jigunsan and Manhang formations is more related to the position of the 2 formations within the stratigraphic sequence. The metamorphic grade of the Jigunsan Formation is higher than the Manhang Formation, which implies that the difference in metamorphism of the 2 formations may be due to burial.

The stratigraphic thickness of the Pyeongan Supergroup above the Manhang Formation in the study area is less than 2 km. Considering the maximum paleogeothermal gradients, this stratigraphic thickness is insufficient for metamorphic temperatures of 200 °C, at the onset of the anchizone (Dunoyer de Segonzac 1970; Hunziker 1986), and temperatures estimated from fluid inclusions.

The following mechanism may be assumed: after a considerable amount of sediments was deposited, uplift and severe erosion took place, whereby the younger geological record was removed as demonstrated in several studies (Islam et al. 1982; Friedman and Sanders 1982). Deposition of thick sediments and severe erosion could have occurred during the periods of 2 unconformities in the Baegunsan syncline area.

First, it is assumed that deposition and erosion would have taken place during the period between the

?Triassic Donggo and the Cretaceous Jeoggagri formations, represented by the younger unconformity, after deposition of the Paleozoic strata. In this case, the Jigunsan and Manhang formations would have been buried together and influenced by the same degree of incipient metamorphism. Assuming 30 °C km^{-1} for geothermal gradient and considering the thickness of the Duwibong Formation in-between, the difference in the metamorphic temperature of these 2 formations should be at most 3 °C. The 2 formations should show almost equal metamorphic grade, which is not supported by the present data.

Second, and more probably, deposition and erosion may have occurred between the Joseon and Pyeongan supergroups. Although the Jigunsan and Manhang formations underwent burial together based upon the present stratigraphic record, the Jigunsan Formation was not influenced by such burial because the later burial did not reach or overcome the threshold temperatures that the Jigunsan Formation had experienced.

Assuming that the Jigunsan Formation had already reached the epizone during the period before the development of disconformity, the continuous sedimentation should have occurred after the deposition of the Duwibong Formation. Assuming the geothermal gradient of 30 °C km^{-1} and the paleotemperature of 270 °C, the maximum burial depth of the Jigunsan Formation is calculated to approximately 8.5 km. Even with a higher goethermal gradient, a tremendous amount of sediment had to be deposited and then eroded. No remnants of such sediments are evidenced in the Korean Peninsula and it is unlikely that the Jigunsan Formation was overlain by sediments near 10 km. Such large removal of sediments by erosion is not unusual in an orogenic area (L. Smith 1991, University of Wyoming, written communication): however, such a structural event is not supported by the geology.

Considering the minimum rate of denudation at 10 mm/100 y (Saunders and Young 1983), 1300-m thick sediments might have been eroded during the unconformity period. Such eroded sediment thickness does not help interpret the observed difference in thermal alteration grades between the 2 Paleozoic strata unless different orders of magnitude in denudation rate are involved.

Alternatively, high geothermal gradient in the Lower Paleozoic strata may explain the discrepancy in the thermal grades, providing that erosion of some overlying sediments is inescapable during the unconformity period. In stable cratonic areas, the only heat source causing high geothermal gradient may be a hot spot and crustal rifting. No rifting event is recorded in Sino–Korean platform during the Paleozoic. Broad crustal epeirogeny due to reheating of continental lithosphere by hot spots was well advocated (Crough 1979, 1981). A hot spot swell heat flux from the mantle may result in greater thermal gradient, causing higher thermal anomaly in the overlying sediments compared to those in areas unaffected by hot spots.

Such hot spot epeirogeny is proposed to be an adequate mechanism for an uplift of the Lower Paleozoic strata in the Korean Peninsula. Therefore, burial and higher heat flux due to hot spot activity may explain why the thermal alteration of the Lower Paleozoic strata is higher than the Upper Paleozoic strata before the development of the unconformity. However, at present it is difficult to estimate the thickness of the eroded sediment column due to an epeirogeny. In the case of the Manhang Formation, the main heat source is not presently evident. The metamorphic grade of the Manhang Formation seems to be caused either by burial or by tectonic deformation.

CONCLUSIONS

Thermal histories of the Paleozoic strata below and above major regional disconformity have been used to understand thermal histories of rocks on either side of the unconformity and to infer the thickness of the removed sediment thickness. Clay mineral analysis using IC and fluid inclusion studies upon the Jigunsan and Duwibong formations of the Joseon Supergroup and the Manhang Formation of the Pyeongan Supergroup show:

1) The clay mineral assemblage of the Jigunsan Formation consists of illite and chlorite. The Jigunsan illitic material is pure illite and the proportion of the *2M* polytype is more than 85%. Average IC falls within the epizone.

2) Clay minerals in the Manhang Formation are illite, chlorite and pyrophyllite. Average IC falls within anchizone. Also, the Manhang illites contain some Kalkberg-type I/S.

3) Fluid inclusions in calcite cements from the Duwibong Formation have homogenization temperatures ranging from 170 to 290 °C and the Manhang inclusions, from 160 to 260 °C. The measured temperatures are broadly distributed, suggesting various degrees of re-equilibration during burial. The maximum temperatures are consistent with IC.

4) The Joseon Supergroup contains higher thermal grades than the Pyeongan Supergroup and this is considered to be caused mainly by burial and high geothermal gradient. The effects of igneous activities and deformation are interpreted to be less significant for the metamorphism of the Lower Paleozoic strata. The Joseon Supergroup had been influenced more by thermal activities before the deposition of the Pyeongan Supergroup.

5) The significant burial (more than 1 km) of the Joseon Supergroup coupled with high geothermal gradient due to the heat flux from the mantle via hot spot activity are proposed to have caused higher thermal grades in the Lower Paleozoic strata. Although the un-

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conformity was previously thought to be a non-depositional surface, the unconformity period was characterized by continuous sedimentation and significant removal of sediments by erosion. The results of this study can be applied to other disconformity-bearing cratonic basins.

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