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KÜBLER ILLITE "CRYSTALLINITY" INDEX OF THE CRETACEOUS GYEONGSANG BASIN, KOREA: IMPLICATIONS FOR BASIN EVOLUTION

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Abstract—Thermal maturity of the Lower Cretaceous Sindong and Hayang groups in the Gyeongsang Basin, Korea, was investigated using the Kübler illite "crystallinity" index (KI) which is based on the numerical expression of the 10-Å peak width after calibration to the Crystallinity Index Standard scale. The metamorphic grade of the Sindong and Hayang groups ranges from late diagenetic zone to high anchizone. Depth of burial was not a major factor controlling KI variation in the basin because Hayang mudrocks have higher thermal maturity than the underlying Sindong mudrocks. Short-lived heating by the emplacement of the Upper Cretaceous plutonic rocks is responsible for the higher thermal maturity in the Hayang mudrocks. A linear NNE-SSW trending belt is drawn by connecting the lowest KI values, and it seems to reflect a hidden fault trace beneath the Hayang Group. Emplacement of Upper Cretaceous plutonic rocks and introduction of hydrothermal fluids along the inferred fault may have been the main cause of the lowering of KI values along this belt. This inferred fault is interpreted to represent the buried eastern boundary of the Nagdong Trough, which was the main depositional site for the Sindong Group in the western part of the Gyeongsang Basin. Deposition of the Hayang Group occurred in the enlarged basin when the basin extended eastward. This study provides an example that KI values can be used in the reconstruction of an early history of basin evolution.

Key Words—Gyeongsang Basin, Illite Crystallinity (Kübler Index), Korea, Low-Grade Metamorphism.

INTRODUCTION

The illite 001 X-ray diffraction reflection (10-Å peak) gradually sharpens as metamorphic grade increases. The Kübler illite "crystallinity" index (KI), introduced by Kübler (1967a, 1967b, 1968), is the numerical expression for the 10-Å peak width, and is used to define diagenetic and low-grade metamorphic zones in argillaceous sediments: the diagenetic zone, anchizone, and epizone. KI is a commonly used method to determine metamorphic zones because of the abundance of illite and ease of measurements despite arguments that KI cannot be used as an accurate geothermometer (Essene and Peacor, 1995). Abundance of illite in most mudrocks in a siliciclastic basin makes it possible to measure thermal maturity in a basin-wide scale and to detect potential heat sources.

KI is also used to determine the timing and characteristics of geologic events of a sedimentary basin. KI is especially useful in reconstructing structural and metamorphic history in very low- to low-grade pelitic rocks (*e.g.*, Frey *et al.*, 1980; Roberts and Merriman, 1985; Frey, 1988; Roberts *et al.*, 1996; Warr *et al.*, 1996; Lee and Ko, 1997). Also, the spatial variation in sediment thickness (*e.g.*, Awan and Woodcock, 1991) and the existence of concealed plutons (*e.g.*, Roberts *et al.*, 1990) can be examined on the basis of KI variation. In this study, KI was used to reconstruct an early history of sedimentary basin development by detecting a major fault related to the initiation of basin formation.

We measured the KI variation of the mudrocks in the Lower Cretaceous Sindong and Hayang Groups in the Gyeongsang Basin, Korea (Figure 1). The Gyeongsang Basin consists of Lower Cretaceous sedimentary strata, which are gently dipping toward the basin center, and Upper Cretaceous volcanic and plutonic rocks. This study provides an example of the application of KI to detect thermal maturity and its controlling factor(s) in a sedimentary basin that has undergone little tectonic disturbance and was affected by igneous activity soon after sedimentation.

GEOLOGICAL SETTING

The Gyeongsang Basin is a Cretaceous nonmarine sedimentary basin developed in the southeastern part of Korea (Figure 1). Oblique subduction of an oceanic plate beneath Asia during Early Cretaceous time developed an Andean-type continental margin with many arc-parallel strike-slip faults, within which the Gyeongsang Basin formed (Chun and Chough, 1992).

Early Cretaceous sedimentation in the Gyeongsang Basin deposited the Sindong and Hayang Groups (Figure 1). The Sindong Group, lower in the sequence, is composed of sandstones, mudrocks, and minor conglomerates derived from a plutonic/metamorphic provenance in the northwest (Choi, 1986; Koh, 1986). Outcrops of the Sindong Group are limited to the western part of the Gyeongsang Basin. Chang (1987) suggested that the Sindong Group was deposited within the NNE-SSW trending, long and narrow "Nagdong Trough", which was developed along the western part of the present Gyeongsang Basin. Deposition of the Hayang Group accompanied the basin extension to the east along with sporadic volcanism in and around the

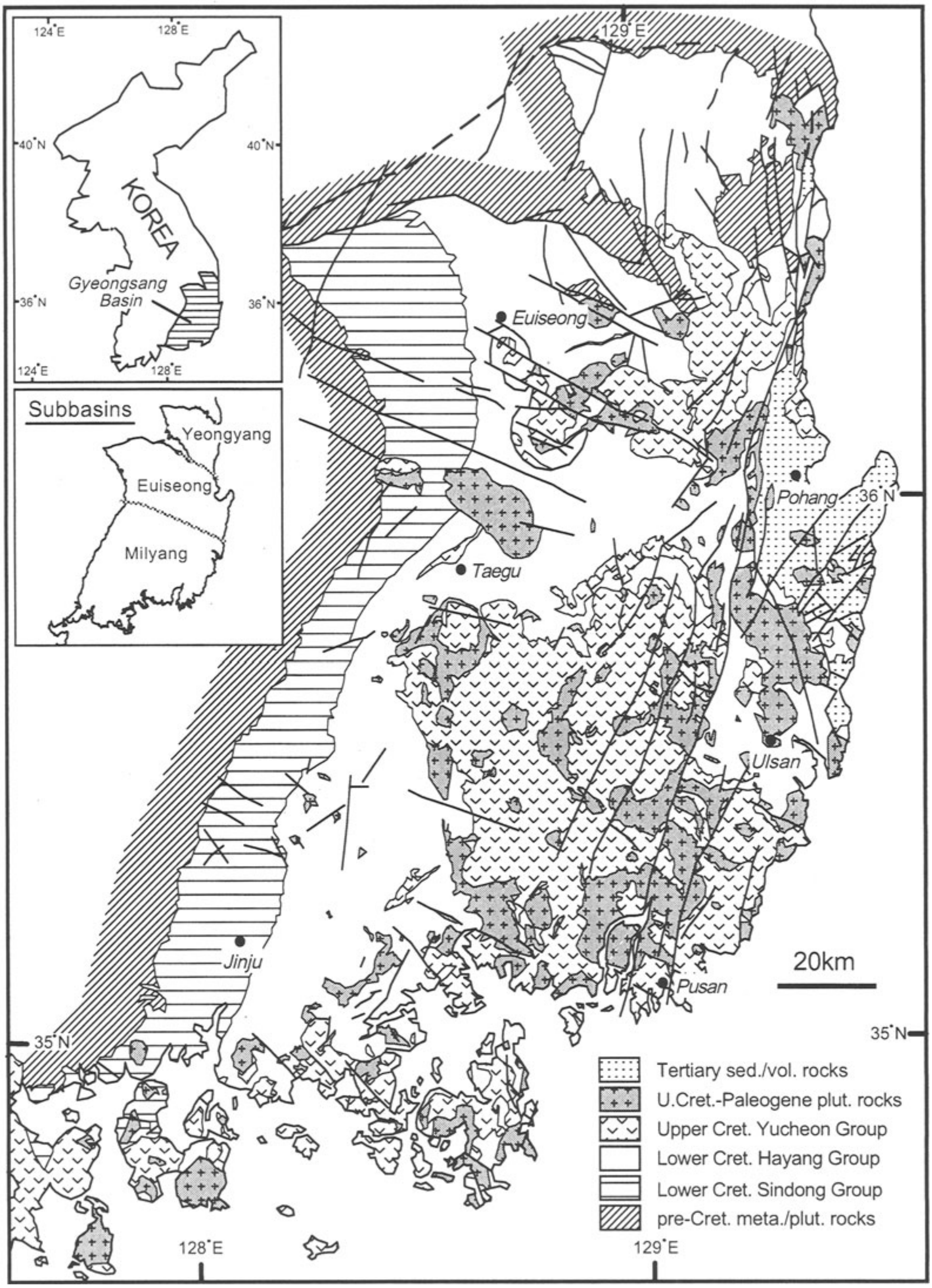

Figure 1. Geologic map of the Gyeongsang Basin. Location of the Gyeongsang Basin and its subbasins are shown in insets.

basin (Chang, 1970, 1987). Sediments were derived from both the volcanic and plutonic/metamorphic provenances (Lee and Lee, 2000).

During the Hayang deposition, the Gyeongsang Basin was divided into three subbasins with different subsidence histories and sedimentary environments (Figure 1). Consequently, different lithostratigraphy has been applied to each subbasin; the Milyang, Euiseong, and Yeongyang subbasins from south to north (Chang, 1968, 1975; Figure 1). The mudrocks in the Milyang and Euiseong subbasins are considered in this study.

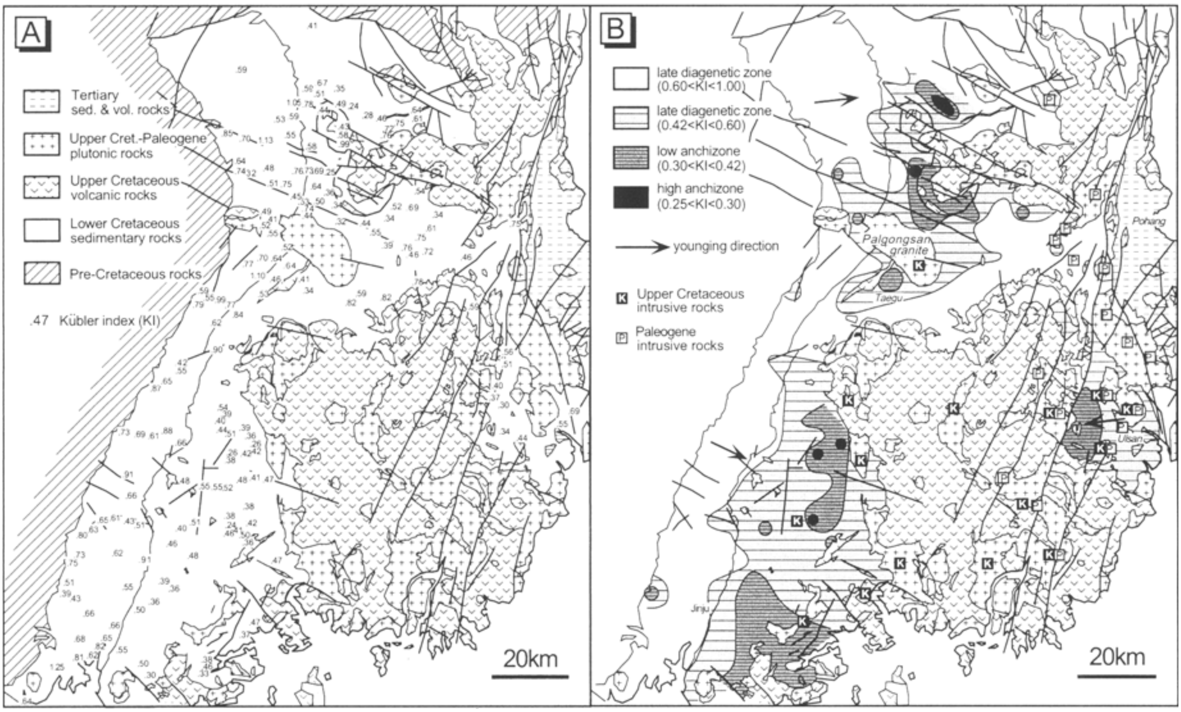

Figure 2. (A) Kübler index of mudrocks of the study area. (B) Contoured metamorphic map of the Gyeongsang Basin.

In Late Cretaceous time, continental arc volcanism and plutonism dominated the basin and sedimentation terminated (Lee *et al.,* 1987; Won, 1987; Pouclet *et al.,* 1995). Also, the relative motion between the oceanic and continental plates changed from oblique to normal (Engebretson *et al.,* 1985). The volcanic and volcaniclastic rocks of this period are named the Yucheon Group, and the mostly acidic plutonic rocks are called the Bulgugsa Granite. Isotopic ages of granite intrusions in the Gyeongsang Basin generally range from ~120 to 40 Ma, and most of them are clustered between 85–70 Ma (Shin and Jin, 1995).

SAMPLES AND ANALYTICAL METHODS

Mudrock samples of the Sindong and Hayang Groups were collected from areas covering the Milyang and Euiseong subbasins of the Gyeongsang Basin to investigate the overall thermal maturity and the location and type of the heat source. Oriented clay aggregates of the <2-μm fraction from 187 samples were prepared for X-ray diffraction. Diffraction data were collected with a Rigaku Geigerflex RAD 3-C automatic horizontal goniometer equipped with a scintillation counter and using Ni-filtered CuKα radiation. Samples were scanned from 2 to 30 °2θ at a scan speed of 2 °2θ/min, a step-width of 0.02°, three slits of 1°, 0.15 mm, and 1°, and a time constant of 1 s at 40 kV and 30 mA. The presence of expandable clays was examined for samples treated with ethylene glycol at 60°C for 8 h. The KI was measured from air-dried samples. Measured KI values were calibrated to the Crystallinity Index Standard (CIS) scale using the procedure and standards of Warr and Rice (1994). For each CIS sample, three oriented clay-aggregate samples were prepared and the mean KI values for air-dried samples were used in calibration. The lower and upper anchizonal boundaries were set at KI values of 0.42–0.25 Δ°2θ, respectively (Kübler, 1967a).

RESULTS

KI values and isocryst lines in the study area are shown in Figure 2. Sindong and Hayang mudrocks generally belong to late diagenetic zone to anchizone. Increase of KI values upsection is expected in a sedimentary basin that experienced burial diagenesis. In the Gyeongsang Basin, however, KI variation shows a complex pattern that does not depend on stratigraphic positions. Some lower KI values are found with a close spatial relationship with the Upper Cretaceous plutonic rocks, and this is best seen near the Palgongsan Granite and in the southeastern part of the Gyeongsang Basin (near Ulsan) (Figure 2B). In other parts of the basin, however, the distribution of the lowest KI values is not found in mudrocks adjacent to plutonic rocks. The lowest KI values in the Milyang and Euiseong subbasins constitute a NNE-SSW trending belt (Figure 2B), implying the former presence of a linear heat source. Besides the NNE-SSW belt, an area with low KI values is extended along some fault traces trending WNW-ESE in the Euiseong Subbasin.

In contrast to Upper Cretaceous plutonic rocks, a decrease of KI values near Paleogene plutonic rocks is not found. These plutonic rocks are mainly distributed along the eastern part of the Gyeongsang Basin (Figure 2B).

DISCUSSION

Controlling factors of KI

Among major factors controlling KI values such as temperature, strain, lithology, and presence of interstratified clay minerals (Kisch, 1987), temperature seems to be the most important for the Gyeongsang Basin. Strain energy can also be important in the aggradation of illite crystallites (Roberts and Merriman, 1985; Roberts *et al.,* 1990, 1996; Merriman *et al.,* 1990). In the Gyeongsang Basin, however, no prominent fold or thrust is found within the basin. Thus, the effect of strain energy caused by tectonic movement can be ignored. The effect of lithology on KI was minimized by using only fine-grained mudrock samples. Few mudrocks contain Reichweite (R), R = 3, illite-smectite (I-S) clays and their KI values were not measured.

Elevated temperature from burial does not seem to be the major factor controlling the KI variations in the Gyeongsang Basin. Lower KI values in the stratigraphically younger Hayang Group suggest that the KI values cannot be explained by a simple burial model. Both the Sindong Group and upper part of the Hayang Group east of Taegu have similar KI values (Figure 2B). The similarity in metamorphic grades between these lowest and highest strata suggests that burial was not the main control that caused KI variations. Emplacement of plutonic rocks seems to be more responsible for the KI-value variation in the study area. The occurrence of the anchizone around the Upper Cretaceous granitic rocks (Figure 2B) suggests that elevated temperatures caused by the intrusion of granitic rocks of Late Cretaceous time might have resulted in lower KI values.

A line connecting the area of the lowest KI values follows a NNE trend (Figure 3). This linear trend cannot be related to the structural updoming around plutons (*e.g.,* Warr *et al.,* 1991) because there is no evidence of disturbance in the dip direction of the strata. Rather, these data seem to delineate a hidden fault trace along which plutonic rocks were emplaced and through which hydrothermal solutions passed. Low KI values have been associated with hydrothermal solutions and the formation of ore deposits (*e.g.,* Panno and Moore, 1994; Bertrand *et al.,* 1998). Hydrothermal ore deposits in the Gyeongsang Basin have a close relationship with Late Cretaceous granitic rocks (Chang, 1997), and hydrothermal solutions seem to have affected the KI variation also.

Comparison of KI with other thermal indicators

Vitrinite reflectance (VR) of the Sindong Group mostly ranges from 2.5 to 4.0% Ro with an average of 3.14% Ro (Son *et al.,* 1994; Oh *et al.,* 1996; Cheong *et al.,* 1997). This value corresponds to the anthracitic coal rank and the maturation temperature of ~260°C (Barker, 1988; Bostick *et al.,* 1978). Fission-track analysis on detrital zircon grains in sandstones implies that the Sindong Group was heated to the zircon partial annealing zone (210–310°C) at ~80 Ma (Lim, 1999). When assuming a 'normal' geothermal gradient of 25–30°C/km, the transition from the diagenetic zone to the anchizone occurs at ~200°C in burial metamorphic condition (Merriman and Frey, 1999). KI values in the Sindong Group mostly correspond to the diagenetic zone. Thus, the maturity suggested by our KI study is much lower than that implied by organic maturity and fission-track analysis.

The discrepancy between KI and VR is caused by the lag in clay diagenesis compared with organic maturation for short-lived heating (Kisch, 1987; Olsson, 1999), which often has been reported in basins influenced by magmatic activity (see examples in Kisch, 1987). These results agree with the interpretation that KI variations in the Gyeongsang Basin were affected by plutonic emplacement.

Inferred fault: eastern margin of 'Nagdong Trough'?

The limited distribution of the Sindong Group in the western part of the Gyeongsang Basin, and the deposition of the Hayang Group on pre-Cretaceous basement rocks in areas other than the western margin of the Gyeongsang Basin, suggests that the Sindong Group was deposited in the NNE-trending 'Nagdong Trough' located in the western part of the Gyeongsang Basin (Chang, 1975, 1987). Although the presence of the Nagdong Trough is supported by stratigraphy, the location of the eastern boundary of the Nagdong Trough has not been defined. The eastern boundary of the Nagdong Trough is covered by the Hayang Group.

We suggest that the inferred fault beneath the Hayang Group (Figure 3) is the location of the eastern boundary of the Nagdong Trough. The lack of disturbance of the overlying sedimentary rocks over the inferred fault trace suggests that movement of the fault ceased before the deposition of the Hayang Group. However, the fractured basement around the fault trace may have allowed emplacement of plutonic rocks and the introduction of hydrothermal fluids along the fault trace during Late Cretaceous time. The NNE-SSW trend of the fault trace supports the idea that the fault was a part of a NNE-SSW fault system that occurred in the eastern continental margin of Asia during Early Cretaceous time (Maruyama *et al.,* 1997).

Evolution of the Gyeongsang Basin and the development of major faults (Figure 4) can be considered.

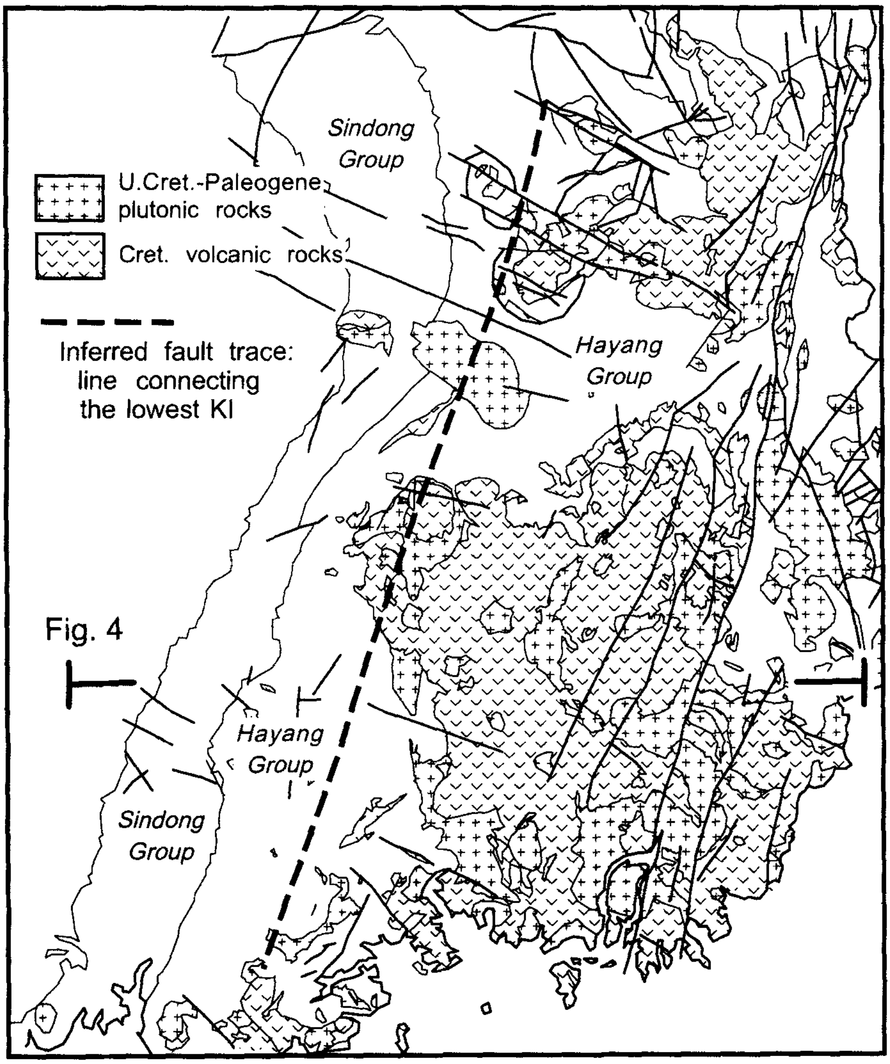

Figure 3. Line connecting the lowest KI values in the study area, except the Ulsan area. This NNE-SSW trending linear heat source seems to reflect an emplacement of plutonic rocks and hydrothermal fluids along a fault trace which was active before the deposition of the Hayang Group. The inferred fault trace is interpreted to be the eastern boundary of the Nagdong Trough. Also shown is the approximate position of the cross section in Figure 4.

The Sindong Group was deposited in the Nagdong Trough that formed in the western part of the future Gyeongsang Basin (Figure 4A). Although major deposition occurred within the Nagdong Trough, limited sedimentation also occurred outside the eastern part of the trough (Um *et al.*, 1983; Chang *et al.*, 1990). Later, the basin widened eastward and the Hayang Group was deposited in the extended basin (Figure 4B). The eastern boundary of the basin is inferred to have been a "wrench" fault similar to those developed in the eastern continental margin of Asia during the Cretaceous. There is no evidence for the location of a fault along the eastern boundary of the Gyeongsang Basin because this part was detached from Korea during the opening of the East Sea (Sea of Japan) in the Miocene and is covered by thick Tertiary sediments. During Late Cretaceous time, magmatic activity culminated in the Gyeongsang Basin, and emplacement of plutonic rocks and associated hydrothermal fluids caused higher thermal maturity in Lower Cretaceous sedimentary strata near the plutonic rocks (Figure 4C).

CONCLUSIONS

The metamorphic grade of the Lower Cretaceous Sindong and Hayang mudrocks of the Gyeongsang Basin ranges from the late diagenetic zone to anchizone. In general, illite in the Hayang Group mudrocks has better "crystallinity" (*i.e.*, lower KI values) than those in the underlying Sindong Group mudrocks. The KI values were decreased by the temperature increase

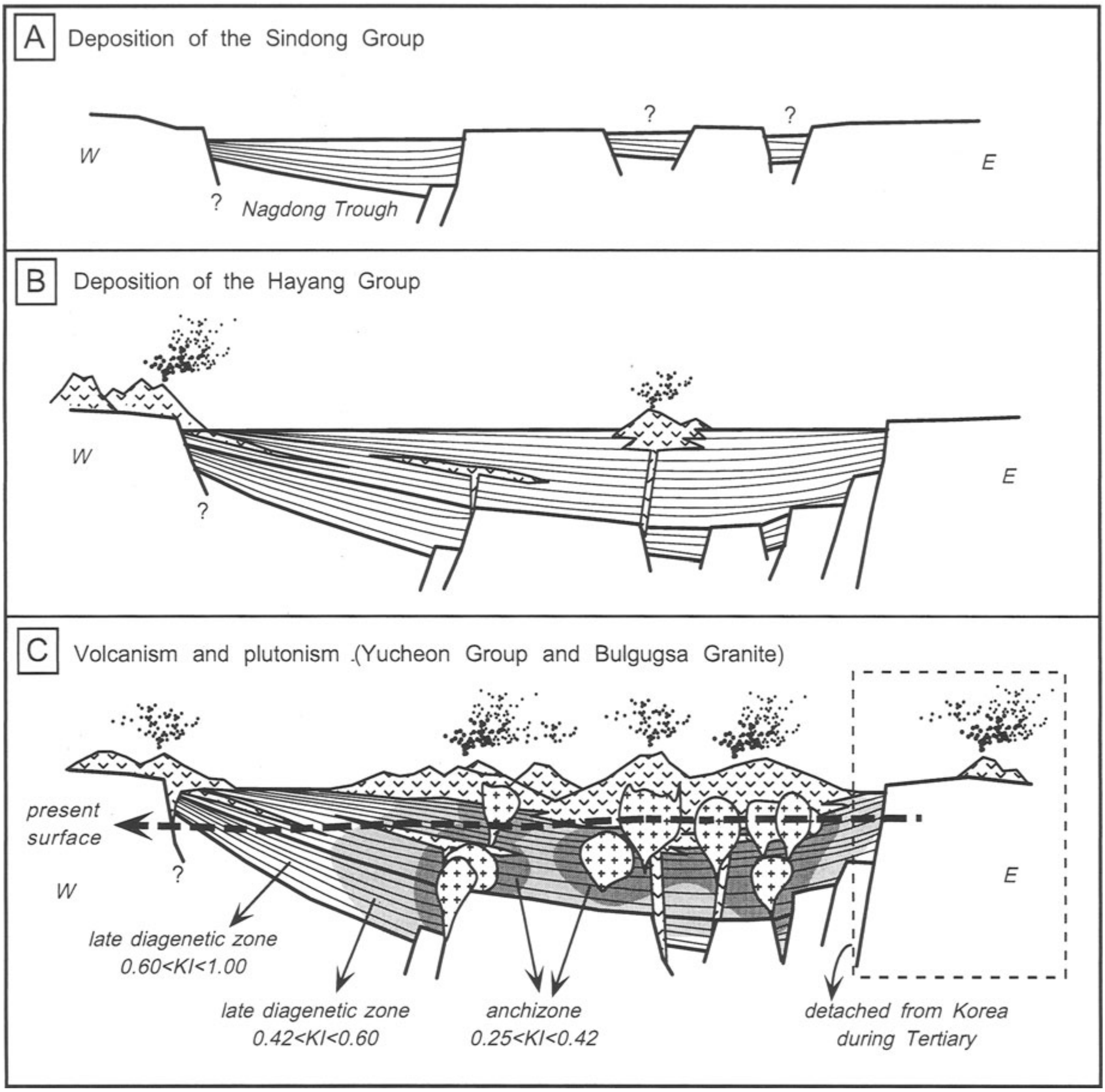

Figure 4. Reconstruction of the evolution of the Gyeongsang Basin during Cretaceous time. See Figure 3 for position of the cross section.

caused by the emplacement of Upper Cretaceous plutonic rocks and introduction of hydrothermal fluids. Thermal maturity as suggested by the KI study is much lower than that indicated by vitrinite reflectance and fission-track analysis because the slow reaction rate of clay minerals could not respond rapidly to the short-lived thermal event.

The lowest KI values, in the middle of the Hayang Group, constitute a linear belt with a NNE-SSW trend. A fault that was active before the deposition of the Hayang Group is inferred, and it is interpreted to represent the eastern boundary of the Nagdong Trough, the main depositional site for the Sindong Group. The boundary fault was covered by the Hayang Group, and was one of main conduits for the emplacement of Upper Cretaceous plutonic rocks and the introduction of hot fluids.

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REFERENCES

Awan, M.A. and Woodcock, N.H. (1991) A white mica crystallinity study of the Berwyn Hills, North Wales. *Journal of Metamorphic Geology,* **9,** 765–773.

Barker, C.E. (1988) Geothermics of petroleum systems: Implications of the stabilization of kerogen thermal maturation after a geologically brief heating duration at peak temperature. In *Petroleum Systems of the United States,* L.B. Magoon, ed., U.S. Geological Survey Bulletin 1870, Washington, D.C., 26–29.

Bertrand, R., Chagnon, A., Heroux, Y., and Savard, M.M. (1998) Hydrothermal alteration of clay minerals and organic matter within and outside the Jubilee carbonate-hosted Zn-Pb deposit, Cape Breton Island, Nova Scotia, Canada. *Economic Geology,* **93,** 746–756.

Bostick, N.H., Cashman, S.M., McCulloh, T.H., and Waddell, C.T. (1978) Gradients of vitrinite reflectance and present temperature in the Los Angeles and Ventura basins, California. In *Low Temperature Metamorphism of Kerogen and Clay Minerals,* D.E. Oltz, ed., Pacific Section SEPM Special Symposium, 65–96.

Chang, B.-U. (1997) A study on the lead isotopic compositions of ore deposits and igneous rocks in the Gyeongsang Basin, southeast Korea. Ph.D. thesis, Seoul National University, Seoul, Korea, 100 pp.

Chang, K.H. (1968) An introduction to the stratigraphy of Gyeongsang (Kyongsang) Group, Gyongsang province, southern Korea. *Journal of the Geological Society of Korea,* **4,** 39–42. (in Korean).

Chang, K.H. (1970) Geology of Upper Mesozoic strata, N. Gyeongsang province, southern Korea. *Journal of the Geological Society of Korea,* **6,** 1–12. (in Korean).

Chang, K.H. (1975) Cretaceous stratigraphy of southeast Korea. *Journal of the Geological Society of Korea,* **11,** 1–23.

Chang, K.H. (1987) Cretaceous Strata. In *Geology of Korea,* D.-S. Lee, ed., Geological Society of Korea, Kyohak-Sa, Seoul, 157–201.

Chang, K.H., Woo, B.-G., Lee, J.-H., Park, S.-O., and Yao, A. (1990) Cretaceous and Early Cenozoic stratigraphy and history of eastern Kyongsang Basin, S. Korea. *Journal of the Geological Society of Korea,* **26,** 471–487.

Cheong, T.J., Oh, J.H., Son, J.D., Bong, P.Y., Lee, H.Y., Ryu, B.J., Son, B.K., Kwon, Y.I., Hwang, I.G., Lee, Y.J., and Kim, H.Y. (1997) Petroliferous basin analysis in Taegu area (II). In *Petroleum Resources Assessment,* KIGAM Research Report KR-97(C)-18, Korea Institute of Geology, Mining & Materials, Taejon, Korea, 193–313. (in Korean).

Choi, H.-I. (1986) Sandstone petrology of the Sindong Group, southwestern part of the Gyeongsang Basin. *Journal of the Geological Society of Korea,* **22,** 212–223.

Chun, S.S. and Chough, S.K. (1992) Tectonic history of Cretaceous sedimentary basins in the southwestern Korean Peninsula and Yellow Sea. In *Sedimentary Basins in the Korean Peninsula and Adjacent Seas,* S.K. Chough, ed., Korean Sedimentology Research Group Special Publication, Seoul, Korea, 60–76.

Engebretson, D.C., Cox, A., and Gordon, R.G. (1985) *Relative Motions Between Oceanic and Continental Plates in the Pacific Basin.* Geological Society of America, Special Paper 206, 59 pp.

Essene, E.J. and Peacor, D.R. (1995) Clay mineral thermometry—a critical perspective. *Clays and Clay Minerals,* **43,** 540–553.

Frey, M. (1988) Discontinuous inverse metamorphic zonation, Glarus Alps, Switzerland: Evidence from illite "crystallinity" data. *Schweizerische Mineralogische und Petrographische Mitteilungen,* **68,** 171–183.

Frey, M., Teichmüller, M., Teichmüller, R., Mullis, J., Künzi, B., Breitschmid, A., Gruner, U., and Schwizer, B. (1980) Very low-grade metamorphism in external parts of the Central Alps: Illite crystallinity, coal rank and fluid inclusion data. *Eclogae Geologicae Helvetiae,* **73,** 173–203.

Kisch, H.J. (1987) Correlation between indicators of very low-grade metamorphism. In *Low Temperature Metamorphism,* M. Frey, ed., Blackie, Glosgow, 227–300.

Kübler, B. (1967a) La cristallnité de l'illite et les zones tout à fait supérieures du métamorphisme. In *Etages Tectoniques, Colloque de Neuchâtel 1966,* Université Neuchâtel, à la Baconnière, Neuchâtel, Switzerland, 105–121.

Kübler, B. (1967b) Anchimetamorphisme et schistosité. *Bulletin Centre Recherche Pau-SNPA,* **1,** 259–278.

Kübler, B. (1968) Evaluation quantitative du métamorphisme par la cristallnité de l'illite. *Bulletin Centre Recherche Pau-SNPA,* **2,** 385–397.

Koh, I.S. (1986) Study on the Source Rocks of the Nagdong Group. *Journal of the Geological Society of Korea,* **22,** 233–256. (in Korean).

Lee, J.I. and Lee, Y.I. (2000) Provenance of the Lower Cretaceous Hayang Group, Gyeongsang Basin, southeastern Korea: Implications for continental-arc volcanism. *Journal of Sedimentary Research,* **70,** 151–158.

Lee, S.-M., Kim, S.-W., and Jin, M.-S. (1987) Igneous activities of the Cretaceous to Early Tertiary and their tectonic implications in South Korea. *Journal of the Geological Society of Korea,* **23,** 338–359.

Lee, Y.I. and Ko, H.K. (1997) Illite crystallinity and fluid inclusion analysis across a Paleozoic disconformity in central Korea. *Clays and Clay Minerals,* **45,** 147–157.

Lim, H.S. (1999) Thermal history and provenance study of the Sindong Group by using a zircon fission track method. M.S. Thesis, Seoul National University, Seoul, Korea, 88 pp.

Maruyama, S., Isozaki, Y., Kimura, G., and Terabayashi, M. (1997) Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750 Ma to the present. *Island Arc,* **6,** 121–142.

Merriman, R.J. and Frey, M. (1999) Patterns of very low-grade metamorphism in metapelitic rocks. In *Low-Grade Metamorphism,* M. Frey and D. Robinson, eds., Blackwell, Cambridge, 61–107.

Merriman, R.J., Roberts, B., and Peacor, D.R. (1990) A transmission electron microscope study of white mica crystallite size distribution in a mudstone to slate transitional sequence, North Wales, UK. *Contributions to Mineralogy and Petrology,* **106,** 27–40.

Oh, J.H., Kwak, Y.H., Son, J.D., Cheong, T.J., Ryu, B.J., Son, B.K., Hwang, I.G., Lee, Y.J., Kim, H.J., and Ko, J. (1996) Petroliferous basin analysis in Jinju area (II). In *Petroleum Resources Assessment,* KIGAM Research Report KR-95(C)-24, Korea Institute of Geology, Mining & Materials, Taejon, Korea, 185–301.

Olsson, I. (1999) Regional burial heating vs. local magmatic heat influence of the Röstånga area, Scania, southern Sweden, *GFF,* **121,** 209–214.

Panno, S.V. and Moore, D.M. (1994) Mineralogy of the clay-sized fraction of the Davis Shale, southeast Missouri: Alteration associated with a Mississippi Valley-type ore deposit. *Economic Geology,* **89,** 333–340.

Pouclet, A., Lee, J.-S., Vidal, P., Cousens, B., and Bellon, H. (1995) Cretaceous to Cenozoic volcanism in South Korea and in the Sea of Japan: Magmatic constraints on the opening of the back-arc basin. In *Volcanism Associated with Extension at Consuming Plate Margin,* J.L. Smellie, ed., Geological Society of London, Special Publication 81, 169–191.

Roberts, B. and Merriman, R.J. (1985) The distinction between Caledonian burial and regional metamorphism in metapelites from North Wales: An analysis of isocryst patterns. *Journal of the Geological Society of London,* **142,** 615–624.

Roberts, B., Morrison, C., and Hirons, S. (1990) Low grade metamorphism of the Manx Group, Isle of Man: A comparative study of white mica 'crystallinity' techniques. *Journal of the Geological Society of London,* **147,** 271–277.

Roberts, B., Merriman, R.J., Hirons, S.R., Fletcher, C.T.N., and Wilson, D. (1996) Synchronous very low-grade metamorphism, contraction and inversion in the central part of the Welsh Lower Palaeozoic Basin. *Journal of the Geological Society of London,* **153,** 277–285.

Shin, S.-C. and Jin, M.-S. (1995) *Isotope Age Map of Plutonic Rocks in Korea.* Korea Institute of Geology, Mining and Materials, Taejon, Korea.

Son, B.-K., Cheong, T.-J., Oh, J.-H., and Kwak, Y.-H. (1994) Thermal maturation and diagenesis of the Gyeongsang Supergroup, Euiseong area, SE Korea. *Korean Journal of Petroleum Geology,* **2,** 83–90. (in Korean).

Um, S.-H., Choi, H.I., Son, J.D., Oh, J.H., Kwak, Y.H., Shin, S.C., and Yun, H.S. (1983) *Geological and Geochemical Studies on the Gyeongsang Supergroup in the Gyeongsang Basin.* KIER Bulletin, 36, Korea Institute of Energy and Resources, 124 pp. (in Korean).

Warr, L.N. and Rice, A.H.N. (1994) Interlaboratory standardization and calibration of clay mineral crystallinity and crystallite size data. *Journal of Metamorphic Geology,* **12,** 141–152.

Warr, L.N., Primmer, T.J., and Robinson, D. (1991) Variscan very low-grade metamorphism in southwest England: A diastathermal and thrust-related origin. *Journal of Metamorphic Geology,* **9,** 751–764.

Warr, L.N., Greiling, R.O., and Zachrisson, E. (1996) Thrust-related very low grade metamorphism in the marginal part of an orogenic wedge, Scandinavian Caledonides. *Tectonics,* **15,** 1213–1229.

Won, C.K. (1987) Triassic to Paleogene igneous rocks. In *Geology of Korea,* D.-S. Lee, ed., Geological Society of Korea, Kyohak-Sa, Seoul, 313–326.

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