Tectonic history of paleostress from calcite twins in the Joseon and Pyeongan Supergroups, South Korea

Seong Seung Kang[a] and Yuzo Obara[b,*]

[a] Visiting Foreign Researcher, Department of Civil and Environmental Engineering (Associate Professor, Research Institute of Basic Sciences, Sunchon National University, Korea), Kumamoto University
[b] Professor, Department of Civil and Environmental Engineering, Kumamoto University

Abstract

The state of paleostress in the Joseon and Pyeongan Supergroups distributed in the northeastern part of the Ogcheon belt of South Korea was investigated using the calcite strain gauge (CSG) technique, in order to clarify and infer the tectonic evolution of paleostress fields. Combining the results of the relationship between twin strain, twin density and twin width, which are used as indicators of deformation conditions in natural low-temperature deformation of limestone, it is estimated that calcite twins were probably formed at temperatures of 170-200°C in the Joseon Supergroup, and under lower temperatures than 170°C in the Pyeongan Supergroup. In five samples of the Joseon Supergroup and two samples of the Pyeongan Supergroup, two different principal paleostress directions are inferred from calcite twins, while only one direction is inferred in other samples of two Supergroups. This result suggests that deformation occurred during two or more different tectonic events in the Joseon and Pyeongan Supergroups during the Mesozoic era. The most dominant direction of maximum principal paleostress are oriented NW-SE, and NE-SW direction are also shown. These directions of maximum principal paleostress are accordance with the direction of many fault and thrust sets developed in the study area. Putting together the results of paleostress analysis from this and other studies, it is concluded that the direction of maximum principal paleostress in the Joseon and Pyeongan Supergroups had changed from NE-SW during the Songrim disturbance period (late Triassic) to NW-SE during the Daebo orogeny period (early Jurassic to early Cretaceous) in the Mesozoic era. Considering the results of the maximum principal paleostress, the tectonic events related with the Songrim disturbance and Daebo orogeny might have affected this study area.

Key words : tectonic history, paleostress, Joseon Supergroup, Pyeongan Supergroup, Ogcheon belt, calcite strain gauge.

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* Correspondence:
Address: Department of Civil and Environmental Engineering, Kumamoto University, Kumamoto 860-8555, Japan
Phone & Fax: +81-96-342-3686
E-mail: obara@kumamoto-u.ac.jp

1. Introduction

The Ogcheon belt is the biggest mobile belt in Korea, occupying the south central part of Korea (Fig. 1). Paleostress in the Joseon and Pyeongan Supergroups is important for clarifying the stress history and tectonic evolution of the Ogcheon belt and its surrounding area in the Mesozoic era. The Ogcheon belt, which is bounded by the Gyeonggi massif to the northwest and the Ryeongnam massif to the southeast, is a NE-trending fold and thrust belt. The Ogcheon belt can be divided into two zones: the Ogcheon zone to the southwest consists of non-fossiliferous, low to medium grade metasedimentary and metavolcanic rocks, and the Taebaeksan zone to the northeast comprises fossiliferous, non or weakly metamorphosed sedimentary rocks of the Paleozoic to early Mesozoic (Chough et al., 2000). The Taebaeksan zone occupies the northeastern part of the Ogcheon belt and comprises mainly the Joseon Supergroup in the Cambrian to Ordovician and the Pyeongan Supergroup in the Carboniferous to Triassic. Cluzel (1992) and Cluzel et al. (1990, 1991) reported that the Ogcheon belt experienced three orogenic events: the Ogcheon orogeny in the Silurian to Devonian causing D_1 and D_2 deformations, the Songrim orogeny in the late Permian to Triassic producing D_3 deformation, and the Daebo orogeny in the middle Jurassic to early Cretaceous resulting in D_4 deformation (Chough et al., 2000). The Joseon and Pyeongan Supergroups were formed and then deformed thereafter, especially by the Daebo orogeny in the late Triassic to late Cretaceous (Kim et al., 1992; Hwang, 1994; Jang and Kang, 1998, Kang et al., 2005). Furthermore, the Daebo orogeny in the broadest sense can be divided into three stages: pre-Daebo orogeny of the Songrim disturbance in the late Triassic, syn-Daebo orogeny of the Daebo orogeny in the early Jurassic to early Cretaceous, and post-Daebo orogeny of the Bulguksa distrubance in the late Cretaceous (Kim et al., 1992; Kim, 1994, 1996).

In South Korea, the Mesozoic tectonic movements are divided into three main phases: the Songrim disturbance, the Daebo orogeny, and the Bulguksa disturbance (Lee, 1988). In the first event, the whole Korean peninsula was uplifted in the late Triassic. In the second event, the Songrim disturbance passed into the Daebo orogeny of the early Jurassic to early Cretaceous. The Daebo orogeny is known as the most severe orogenic movement in Korea, with which all pre-existing rocks and formations were deformed and also locally metamorphosed. Many faults are accompanied with folding, which is particularly well developed in the Ogcheon belt and is aligned NE-SW in accordance with the Sinian direction. In the final event, the Bulguksa disturbance of the late Cretaceous, intensive volcanism and plutonism occurred, however, deformation was minor with locally developed normal and strike-slip faults. Sinistral strike-slip faults mostly trend NE-SW, while the trend of normal faults varies from NW-SE to NE-SW. These igneous activities and deformations can be related to contemporaneous plate tectonic movements.

The directions and magnitudes of stress can usually be determined by analyzing the fabrics of certain minerals in rocks (Handin and Griggs, 1951; Turner, 1953; Turner and Weiss, 1963). Dislocation density, subgrain size, and dynamically recrystallized grain size have been used to determine the magnitude of paleostress (Pfiffner, 1982; Twiss, 1977; Weathers et al., 1979; Kohlstedt and Weathers, 1980). Such information plays an important role in clarifying the stress history in any tectonic belt, which arises of increasing interest in geotectonic studies (Rocher et al., 1996; Gonzalez-Casado and Garcia-Cuevas, 1999; Lacombe, 2001). Mechanical twinning is commonly observed in deformed calcite (Turner, 1953; Rowe and Rutter, 1990; Burkhard, 1993; Newman, 1994; Ferrill, 1998). The orientations of calcite twin lamellae can be used to determine the direction of paleostress that is the stress field at the time of deformation. Furthermore, twins in calcite grain can be developed

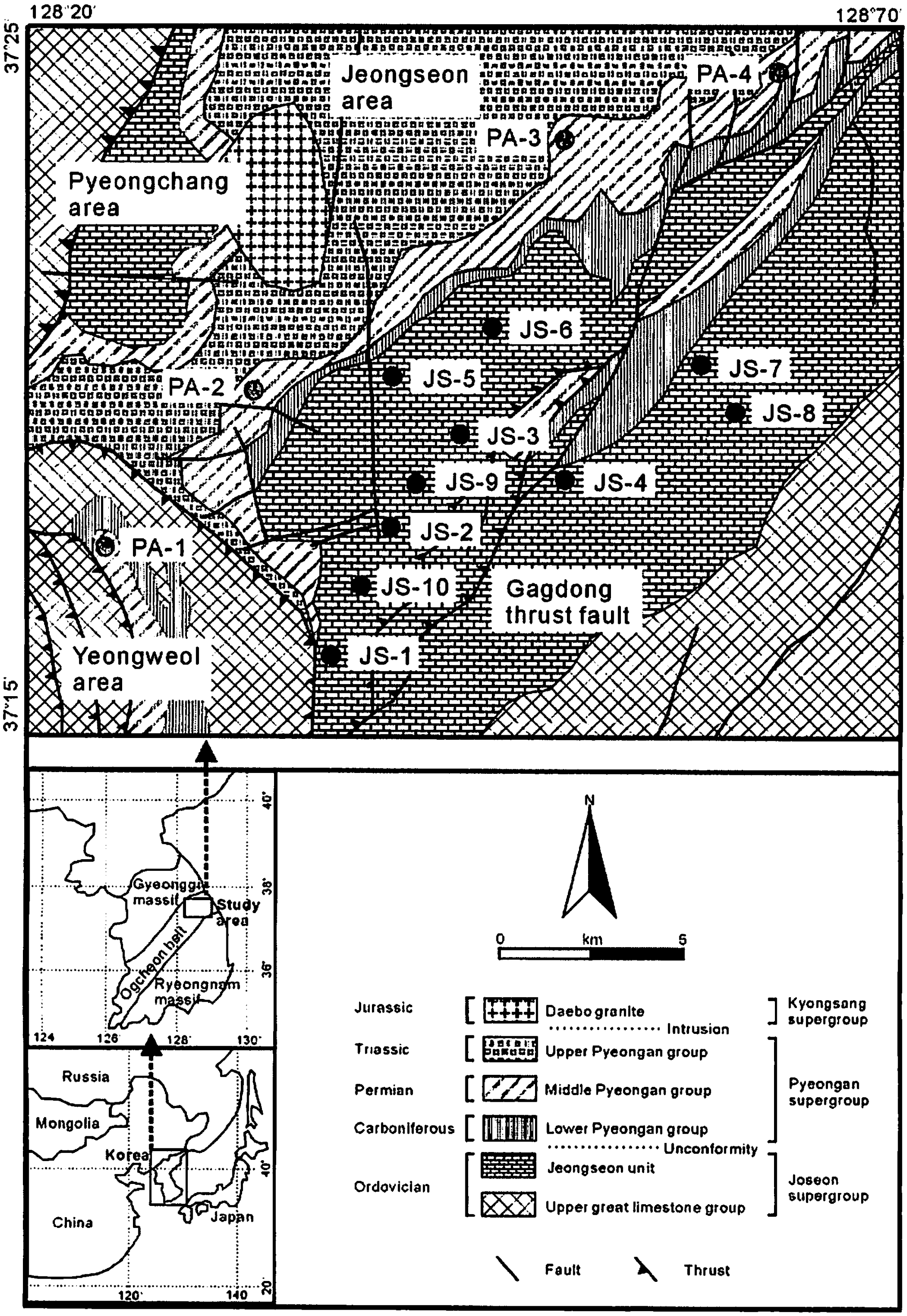

Fig. 1 Location of the study area and sample locations in the Joseon and Pyeongan Supergroups in the northeastern part of the Ogcheon belt, South Korea. The study area lies between longitude 128°20′ and 128°70′ and latitude 37°15′ and 37°25′. The Ogcheon belt is a NE-trending Phanerozoic mobile zone with about 70 km wide and 450 km long in the central part in South Korea.

only if the resolved shear stress equals a critical value (Groshong, 1972; Spang, 1972). The induced twin plane is roughly parallel to the direction of the maximum shear stress. During the twinning process, the c-axis of the twin is flipped into the direction closer to the maximum compressive axis with respect to the c-axis of the host grain. By measuring the orientation of c-axis and the pole of twin lamellae, the number and thickness of the twin, and the width of grain perpendicular to the twin plane, the direction of paleostress fields can be estimated (Groshong, 1972; 1974, Groshong et al., 1984; Evans and Groshong, 1994). This method is termed as the calcite strain gauge (CSG) technique.

The purpose of this study is to clarify paleostress in the Joseon and Pyeongan Supergroups distributed in the northeastern part of the Ogcheon belt of South Korea and to infer the tectonic evolution of paleostress fields. The tectonic history of the Joseon and Pyeongan Supergroups after being deposited and deformed thereafter is not well defined. The results from these paleostress fields provide new information to understand the tectonic evolution during the Mesozoic era.

2. Fundamentals

The CSG technique (Evans and Groshong, 1994) is a method to analyze the directions and relative magnitudes of the principal strain from calcite twin sets, which is measured with a four-axis universal stage (U-stage) mounted on a petrologic microscope and a micrometer ocular. The most probable values of the strain tensor components are then obtained from the shear strain by performing a multiple linear regression analysis with the least square method.

Twin sets in a calcite grain produced by simple shear are parallel to the glide direction g in the ge plane as shown in Fig. 2. The f axis is perpendicular to the ge plane. The dashed lines indicate the outline of the original untwined calcite grain. The shaded areas indicate the twinned lamellas, and the unshaded areas show the host portions (i.e., untwined lamellas) of the calcite grain. Here α is the angle of the rotation of the grain edge from the host portion to the twinned lamellas and is equal to 38° 17′ following Handin and Griggs (1951). The shear strain γ_{ge} in the ge plane is thus given as follows:

$$\gamma_{ge}=\frac{2}{H}\sum_{i=1}^{n} t_i \tan\frac{\alpha}{2} \quad (1)$$

where H is the total thickness of the host and twins, n is the number of twins, and t_i is the thickness of the i-th twin. The strain tensor $[\varepsilon']$ in the crystal coordinate system (g,e,f) is then given as

$$[\varepsilon']=\begin{bmatrix} 0 & \Gamma_{ge} & 0 \\ \Gamma_{ge} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \Gamma_{ge}=\frac{\gamma_{ge}}{2}=\frac{0.347}{H}\sum_{i=1}^{n} t_i \quad (2)$$

The corresponding strain tensor $[\varepsilon]$ in the geographical coordinate system (x,y,z) is expressed as

$$[\varepsilon]=\begin{bmatrix} \varepsilon_{xx} & \Gamma_{xy} & \Gamma_{xz} \\ \Gamma_{xy} & \varepsilon_{yy} & \Gamma_{yz} \\ \Gamma_{xz} & \Gamma_{yz} & \varepsilon_{zz} \end{bmatrix} \quad (3)$$

where ε_{ii} is the normal strain (positive for elongation), and Γ_{ij} is the shear strain $(i,j=x,y,z)$. The geographical coordinate axes are defined here as follows: the x axis is horizontal to the east, the y axis is horizontal to the north, and the z axis is vertical to the zenith. The coordinate transformation matrix $[L]$ from the geographical coordinate system (x,y,z) to the crystal coordinate system $(g,e,$

f) is expressed as

$$[L]=\begin{bmatrix} l_g & m_g & n_g \\ l_e & m_e & n_e \\ l_f & m_f & n_f \end{bmatrix} \tag{4}$$

where l_i, m_i, and n_i are the direction cosines of the crystal axes $i=g,e,f$ with respect to the geographical axes x, y, and z, respectively. The procedure to determine the direction cosines from the azimuth and inclination of the crystal axes measured using a four-axis universal stage is described in detail by Groshong (1972, 1974) and Evans and Groshong (1994). The local strain tensor $[\varepsilon']$ of Equation (2) can thus be written by the coordinate transformation law using Equations (3) and (4) as follows:

$$[\varepsilon']=[L][\varepsilon][L]^T \tag{5}$$

where the superscript T stands for matrix transpose. The shear strain Γ_{ge} is then derived:

$$\begin{aligned}\Gamma_{ge} &= l_g(\varepsilon_{xx}l_e+\Gamma_{xy}m_e+\Gamma_{xz}n_e)\\ &\quad +m_g(\Gamma_{xy}l_e+\varepsilon_{yy}m_e+\Gamma_{yz}n_e)\\ &\quad +n_g(\Gamma_{xz}l_e+\Gamma_{yz}m_e+\varepsilon_{zz}n_e)\end{aligned} \tag{6}$$

In calcite twins, the volumetric strain $\varepsilon_v=\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}$ is zero because deformation is simple shear so that Equation (6) can be rewritten

$$\begin{aligned}\Gamma_{ge} &= (l_gl_e-n_gn_e)\varepsilon_{xx}+(m_gm_e-n_gn_e)\varepsilon_{yy}\\ &\quad +(l_gm_e+l_em_g)\Gamma_{xy}+(m_gn_e+m_en_g)\Gamma_{yz}\\ &\quad +(l_gn_e+l_en_g)\Gamma_{xz}\end{aligned} \tag{7}$$

The shear strains measured from n calcite grains can thus be expressed as

$$\{\alpha_C\}=\{\Gamma_{ge}^1 \quad \Gamma_{ge}^2 \quad .... \quad \Gamma_{ge}^n\}^T \tag{8}$$

where the superscript n denotes the number of calcite grains. The geographical strain vector $\{\varepsilon\}=\{\varepsilon_{xx} \quad \varepsilon_{yy} \quad \varepsilon_{zz} \quad \Gamma_{xy} \quad \Gamma_{yz} \quad \Gamma_{xz}\}^T$ can then be expressed as

$$[A_C]\{\varepsilon\}=\{\alpha_C\} \tag{9}$$

where $[A_C]$ is the $n\times6$ coordinate transformation matrix. The components of the coordinate transformation matrix $[A_C]$ are the functions of the direction cosines and can be computed by Equation (7). The most probable values for the geographical strain vector are obtained by performing a multiple linear regression analysis with the least square method using the normalized expression of Equation (9) as follows:

$$[B_C]\{\varepsilon\}=\{\beta_C\} \tag{10}$$

where $[B_C]=[A_C]^T[A_C]$ and $\{\beta_C\}=[A_C]^T\{\alpha_C\}$. The most probable values of the geographical strain vector can be determined by inverting Equation (10).

$$\{\varepsilon\}=[C_C]\{\beta_C\} \tag{11}$$

where $[C_C]$ is the inverse matrix of $[B_C]$.

Once the six components of the geographical strain tensor in equation (3) for a rock sample are determined by the procedure described above, the magnitudes and orientations (direction cosines) of

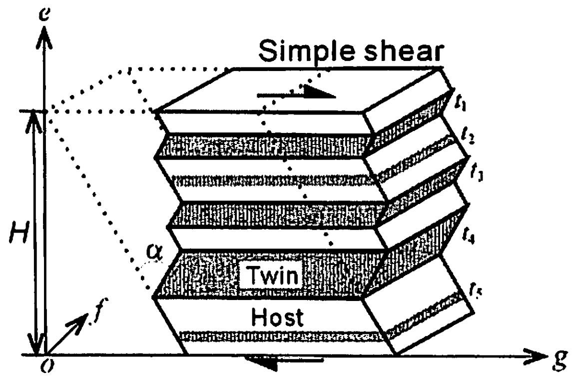

Fig. 2 Geometry of twins in a calcite grain produced by simple shear stress (modified after Evans and Groshong, 1994).

the three mutually perpendicular principal strains ε_1, ε_2, and ε_3 (positive for elongation) can be calculated by means of taking the eigenvalues and eigenvectors of the global strain tensor (Goodman, 1989). Here ε_1 is the maximum principal strain (shortening), ε_2 is the intermediate principal strain, and ε_3 is the minimum principal strain (elongation) so that $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$.

On the basis of the calcite strain gauge technique described above, a computer program was developed by Evans and Groshong (1994). This computer program calculates the average twin thickness, average twin density, negative expected value (NEV), total twin strain, and magnitudes and orientations of the principal strains for each rock sample as well as the calculated expected value of the shear strain for each twin set (Evans and Groshong, 1994). A negative expected value (NEV) of the shear strain implies that the calcite grain is not properly oriented to twin given the computed strain tensor (Groshong, 1972, 1974; Teufel, 1980). The total twin strain is the square root of the second invariant of the geographical strain tensor ($\sqrt{J_2}$). J_2 is calculated from the three principal strains as: $J_2 = -(\varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1 + \varepsilon_1\varepsilon_2)$ (Jaeger and Cook, 1979). They are expressed as %. The scatter (noise) of the twin data in the calculation can be reduced by eliminating 20% of the twin sets that gave the largest deviations removed (LDR) from the calculated expected values (Groshong et al., 1984). The process of 20% largest deviation removal was used here to improve the precision and accuracy of magnitude and direction estimates (Groshong et al., 1984). The deviation means the difference in magnitude between the measured and expected shear strains. All of the expected shear strains should be positive for a single homogeneous deformation because twin gliding in calcite occurs only with a positive sense of shear. A small negative expected value (less than 40%) implies inhomogeneous strain, whereas a large one (more than 40%) implies a complex strain history (Groshong, 1974; Teufel, 1980). Two strains of greatly different orientations were accurately distinguished by computing data with the positive expected values (PEV) separately from data with the negative expected values (NEV).

3. Study area

The study area lies between longitude 128°20′ and 128°70′ and latitude 37°15′ and 37°25′ as shown in Fig. 1. The Joseon and Pyeongan Supergroups are located at the northeastern part of the Ogcheon belt. The Ogcheon belt, which is about 70 km wide and 450 km long in the central part of South

Korea, is a NE-trending Phanerozoic mobile zone bounded by two Precambrian massifs: the Gyeonggi massif to the northwest and the Ryeongnam massif to the southeast. The Ogcheon belt is divided into two parts: northeastern part consisting of unmetamorphosed Paleozoic sedimentary rocks (Joseon and Pyeongan Supergroups) and southwestern part of crystalline schists and phyllites (Ogcheon Group). The early Paleozoic Joseon Supergroup consists of platform carbonate and subordinate siliciclastic rocks. The late Paleozoic to early Mesozoic Pyeongan Supergroup consists of parallic to nonmarine clastic deposits and is disconformably underlain by the Jeongseon units of the Joseon Supergroup. The unconformity between the two sedimentary sequences spans a long hiatus of more than 100 Ma (Lee and Sheen, 1998; Lee and Lee, 2003; Chough et al., 2000). The rocks in the study area are affected by polyphase deformation, and produced discontinuities such as folds, thrusts and faults. General strikes and dips of discontinuities are N30°E and 52°NW. However, strikes and dips of discontinuities, distributed at the Yeongweol area in the western part of the Gagdong thrust fault, are N30°W and 28°SW. The trends of the axial traces of folds related with faults can be classified into the three directions NW-SE, NE-SW and E-W (Kim et al. 1992). In addition, folds and thrusts formed associated with the Songrim disturbance, the Daebo orogeny and the late Cretaceous Bulguksa disturbance have NE-SW, NW-SE and E-W trends, respectively (Kim, 1996; Chough et al., 2000). The regional geologic structure of the study area suggests that the western part (Yeongweol area) is dominated by westward-dipping thrust faults whereas the eastern part (Jeongseon area) is dominated by oblique-slip faults.

4. Samples and measurements

Ten (Joseon Supergroup: JS1~JS10) and four (Pyeongan Supergroup: PA1~PA4) oriented limestone samples were collected in two Supergroups distributed along the northeastern part of the Ogcheon belt of South Korea. Each location of sampling is shown in Fig. 1. If the samples were collected in such folded and faulted terranes, the paleostresses may vary spatially. For example, in a folded layer, the layer-parallel compression prevails in the inner part of a fold hinge, while the layer-parallel extension prevails in the outer part of a fold hinge (Goodman, 1989). Furthermore, in order for the calculated paleostress to be considered as a regional paleostress, the condition that the calculated paleostress did not rotate after the acquisition must be fulfilled. For example, if the calculated paleostress is acquired during layer-parallel shortening at an early stage of folding, and it later rotates due to the fold development, the calculated paleostress orientations are greatly rotated from the regional ones (Rocher et al., 1996; Lacombe, 2001). For these reasons, we have been careful to collect the samples in the flanks of folds in folded terrane.

For precision and accuracy of the measured twin strain magnitudes, two perpendicular thin sections were cut in vertical planes striking north-south and east-west from each sample (Groshong et al., 1984; Ferrill, 1991; Evans and Groshong, 1994). All thin sections were prepared with a thickness of less than 5μm in order to measure twins clearly (Kang et al., 2002). Twins in oriented thin sections were then examined using a petrologic microscope with a four-axis universal stage, and a series of calcite twin measurement data was obtained. The calcite twin measurement data were processed with the CSG technique. Although analysis of 50 calcite grains from a single thin section produces the adequate results for many purposes (Groshong, 1974), 25 grains from each of two mutually perpendicular thin sections give the best results with the most reasonable amount of work (Groshong et al., 1984). In this study, the number, thickness, and orientation of the twins as well as the thickness of the host calcite grains perpendicular to the twins and the c-axis orientation of the host calcite grains were measured in 25 grains from two thin sections.

5. Results

The twinned grains are found to be entirely distributed throughout the calcite grain. In addition, the calcite grains for measuring twins were randomly selected in thin sections. Fig. 3 shows microphotographs of twins from samples (vertical plane striking north-south) collected in the Joseon (Figs. 3(a) and (b)) and Pyeongan (Figs. 3(c) and (d)) Supergroups. According to Ferrill et al. (2004), twin morphologies were defined a spectrum that corresponds to increasing temperature from straight thin twins (type I) at very low temperature to straight thick twins (type II), to curved, tapered and lensoid think twins (type III), and finally to thick patchy twins (type IV). Most calcite grains investigated in the Joseon and Pyeongan Supergroups have one or two twin sets composed of thin or thick straight lines. The appearance of the twins suggests they can be classified as type I (Figs. 3(a) and (c)) and type II (Figs. 3(b) and (d)), implying deformation at relatively low temperatures of approximately under 200°C (Burkhard, 1993; Ferrill et al., 2004).

The calcite twin measurement data were processed using the computer program developed by Evans and Groshong (1994). The results are summarized in Table 1. The five samples (JS-1, JS-4, JS-6, JS-7, JS-8) in the Joseon Supergroup and two samples (PA-1, PA-2) in the Pyeongan Supergroup show large negative expected values (NEV) of approximately more than 40%, so the data were analyzed two values, the positive expected values (PEV) and NEV. The twin strain, twin density and width range from 0.83 to 9.83%, 33.5 to 113.4 twins/mm, and 0.28 to 2.03μm in the

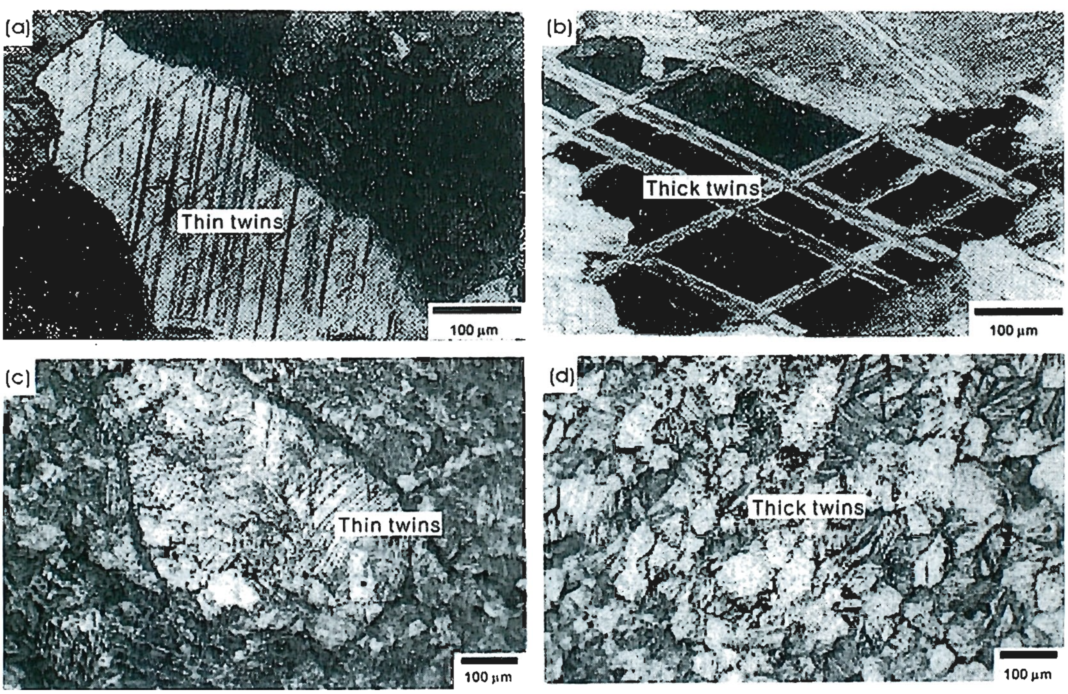

Fig. 3 Microphotographs of one or two twin sets, which appear as thin straight lines (type I) or thick straight lines (type II); (a) and (b): Joseon Supergroup, (c) and (d): Pyeongan Supergroup.

Table 1 Calcite twin data of the Joseon and Pyeongan Supergroups. CP refers to the cleaning procedure. LDR means that the 20% of the twin sets with largest deviations is automatically removed. PEV and NEV represent the positive expected value and the negative expected value, respectively. $\sqrt{J_2}$ is the twin strain, which is the square root of the second invariant of strain.

Name of sample	CP	Elongations of principal strain (%)			Directions of principal paleostress			Twin width	Twin density	Twin strain
		ε_1	ε_2	ε_3	σ_1	σ_2	σ_3	(μm)	(twins/mm)	($\sqrt{J_2}$)
JS-1(P)	PEV	−10.92	2.86	8.11	115°/34°	5°/26°	247°/45°	2.03	67.4	9.83
JS-1(N)	NEV	−9.44	1.02	8.41	225°/18°	323°/24°	102°/59°	1.35	46.1	8.98
JS-2(L)	LDR	−3.64	1.26	2.37	89°/19°	192°/34°	336°/49°	0.56	90.2	3.21
JS-3(L)	LDR	−6.04	0.02	6.02	231°/56°	104°/22°	3°/25°	1.47	57.7	6.03
JS-4(P)	PEV	−4.02	0.80	3.21	214°/34°	310°/9°	52°/54°	1.42	33.5	3.69
JS-4(N)	NEV	−0.80	−0.05	0.86	311°/42°	103°/45°	207°/14°	0.43	35.5	0.83
JS-5(L)	LDR	−3.36	0.50	2.86	299°/37°	182°/31°	65°/37°	0.75	46.7	3.15
JS-6(P)	PEV	−5.10	0.47	4.63	303°/21°	184°/52°	46°/30°	0.54	113.4	4.49
JS-6(N)	NEV	−1.60	0.28	1.31	42°/39°	151°/22°	263°/43°	0.28	75.3	1.48
JS-7(P)	PEV	−6.24	1.39	4.85	173°/33°	271°/13°	19°/54°	1.21	51.8	5.68
JS-7(N)	NEV	−2.16	0.20	1.96	328°/13°	63°/22°	210°/65°	0.57	41.4	2.07
JS-8(P)	PEV	−2.50	−1.13	3.63	256°/35°	129°/40°	10°/30°	0.90	41.8	3.23
JS-8(N)	NEV	−3.50	0.33	3.16	325°/56°	121°/32°	218°/11°	0.59	40.0	3.35
JS-9(L)	LDR	−3.52	−0.02	3.54	342°/28°	80°/15°	195°/57°	0.53	90.2	3.53
JS-10(L)	LDR	−5.56	0.61	6.17	115°/29°	319°/59°	211°/11°	0.99	89.6	5.90
PA-1(P)	PEV	−4.49	1.75	2.73	319°/22°	118°/65°	226°/7°	0.79	60.4	3.92
PA-1(N)	NEV	−1.12	−0.72	1.84	109°/69°	221°/8°	314°/18°	0.47	37.9	1.60
PA-2(P)	PEV	−7.69	−2.73	10.41	75°/2°	190°/81°	334°/6°	1.47	64.4	9.36
PA-2(N)	NEV	−5.24	0.80	4.49	336°/6°	218°/73°	69°/12°	0.63	54.4	4.93
PA-3(L)	LDR	−0.85	−0.07	0.92	180°/32°	24°/53°	277°/12°	0.37	32.3	0.89
PA-4(L)	LDR	−3.13	0.63	2.50	70°/71°	333°/2°	242°/18°	0.55	57.7	2.87

Joseon Supergroup, and 0.89 to 9.36%, 32.3 to 64.4 twins/mm, and 0.37 to 1.47μm in the Pyeongan Supergroup, respectively. The twin width dependens on deformation temperature and strain, furthermore, the twin width and density are usually used as indicators of deformation conditions of limestone (Ferrill, 1991, 1998; Ferrill et al., 2004). Figs. 4(a) to (d) illustrate twin width versus twin strain, twin density versus twin strain, twin density versus twin width, and product of twin width and twin density versus twin strain for each sample. Plots include data obtained from Ferrill (1991). The data obtained from this study is similar in an aspect to those of Ferrill's (1991). According to Ferrill et al. (2004), domains were divided on the graphs by deformation at maximum temperatures <170°C, 170−200°C, and >200°C, respectively (Figs. 4(a) to (c)). As shown in Fig. 4(c), calcite develops thick twins and low twin densities at higher temperatures, on the other hand, calcite develops thin twins and high twin densities at lower temperatures. Fig. 4(d) shows the relationship between product of twin width and twin density versus twin strain. The product is directly proportional to the amount of shear strain, because twin width and twin density together determine the amount of shear strain, a given shear strain can be accommodated by the product of twin width and twin density (Groshong, 1972; Ferrill et al., 2004). As shown in Fig. 4(d), the product of twin width and twin density increases with twin strain. Comparing the results of this and other studies (Ferrill, 1991; Ferrill et al., 2004), it is estimated that calcite twins were produced at temperatures of 170−200°C in the Joseon Supergroup, and under lower temperatures than 170°C in the Pyeongan Supergroup. These results are good agreement with the results of the temperature suggested by the appearance of

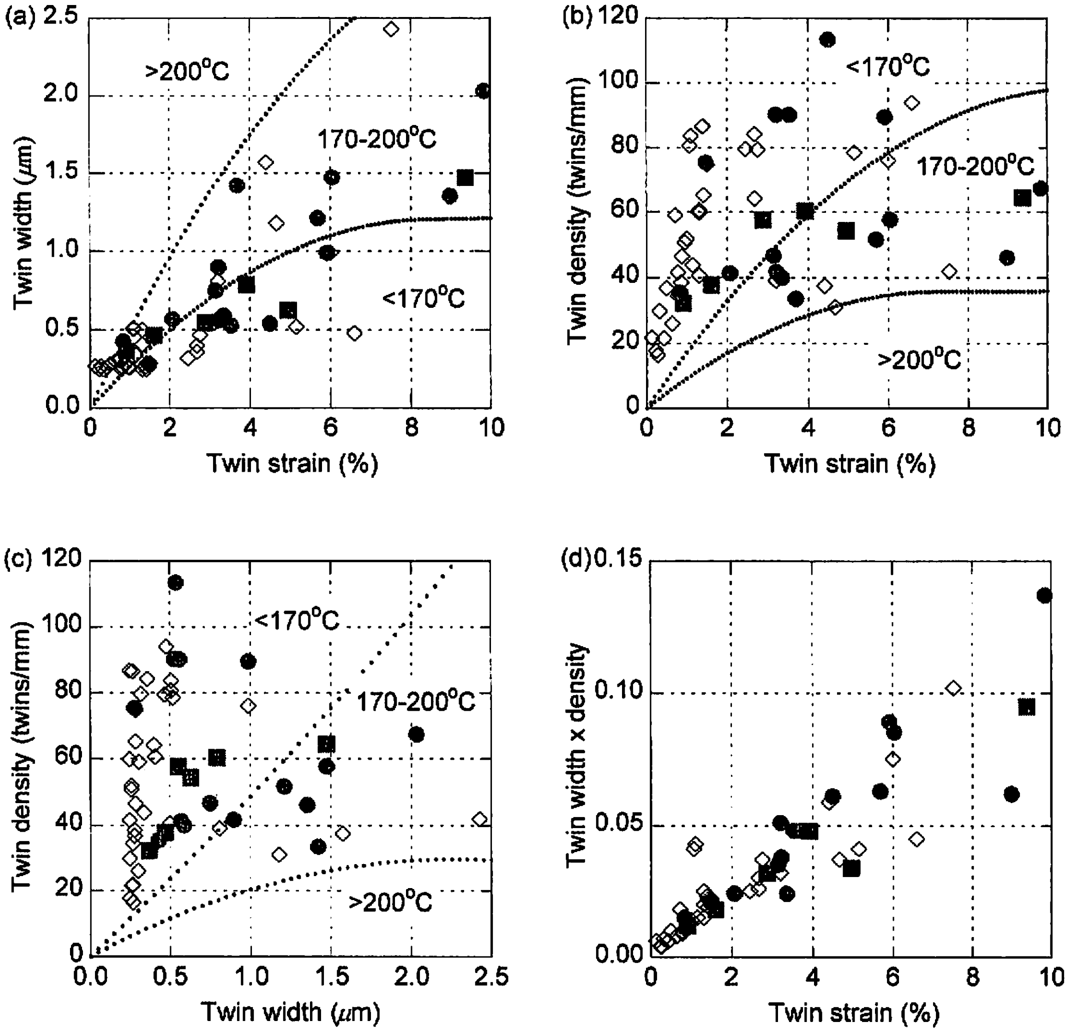

Fig. 4 Graphs of twin parameters. (a) Twin width versus twin strain, (b) twin density versus twin strain, (c) twin density versus twin width, (d) product of twin width and twin density versus twin strain. Plots include data from Table 1 (Ferrill, 1991). The closed circles and rectangles stand for the results from the Joseon and Pyeongan Supergroups, respectively. The open diamonds stand for Ferrill's results (1991). The dotted lines represent the boundaries of maximum temperature expressed by Ferrill et al. (2004).

twins of type I and type II.

The directions of the maximum principal paleostress obtained from calcite twins and discontinuities developed in the study area are plotted on a lower hemisphere equal-area Schmidt stereonet projection, and then presented on a rose diagram in Fig. 5. In five samples (JS-1, JS-4, JS-6, JS-7, JS-8) in the Joseon Supergroup and two samples (PA-1, PA-2) in the Pyeongan Supergroup, two events with different principal directions could produce the observed calcite twins, while only one event is needed to account for the calcite twins in other samples (JS-2, JS-3, JS-5, JS-9, JS-10 in the Joseon Supergroup, and PA-3, PA-4 in the Pyeongan Supergroup) as shown in Table 1. The

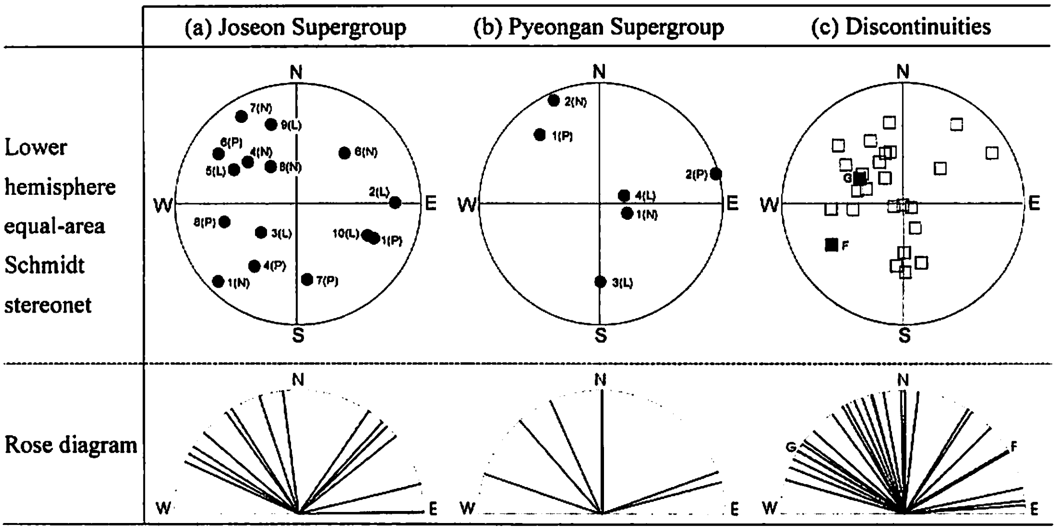

Fig. 5 Stereographic projection of the directions of the maximum principal paleostress calculated from cal-cite twins on a lower hemisphere equal-area Schmidt stereonet, and rose diagram: (a) Joseon Supergroup, (b) Pyeongan Supergroup, and (c) discontinuities. The closed circles represent the results from the Joseon and Pyeongan Supergroups, respectively. The open and close rectangles represent the directions of the Gagdong thrust fault (G), preferred fault (F), and many faults developed in the study area, respectively.

maximum principal paleostress in both Supergroups mainly presented two directions, namely NW-SE and NE-SW. However, the NW-SE direction more concentrates than the NE-SW direction. The directions of the maximum principal paleostress are generally accordance with those of discontinuities distributed in the study area. Comparing the directions of the maximum principal paleostress with those of discontinuities in Fig. 5, the NW-SE direction is accommodated to the direction of the Gandong thrust fault (G, N30°W), and the NE-SW directions is accommodated to the direction of the preferred fault (F, N30°E). The maximum principal paleostresses of the samples JS-1(P) and JS -1(N), JS-2(L), JS-4(P), JS-7(P) and JS-7(N), and JS-9(L) indicate a stress field associated with thrust faulting (compressional tectonic events), which are inclined at a gentle angle to the horizontal. On the other hand, the maximum principal paleostresses of the samples JS-3(L), JS-4(N), JS-5(L), JS-8(N), PA-1(N), and PA-4(L) indicate a stress field compatible with normal faulting (extensional tectonic events), which are inclined at a high angle to the horizontal. Also, appearance of strike-slip faulting is shown in the samples JS-6(P), JS-8(P), JS-10(L), PA-1(P), PA-2(P) and PA-2(N), and PA-3(L). Paleostress regime in the study area shows the complicate state more or less. The direction of the maximum principal paleostress is expressed at each sampling location on a geological map in Fig. 6. The NW-SE trending maximum principal paleostress is compatible with the direction of the Gagdong thrust fault, and the NE-SW trending is accordance with the direction of many faults developed in the study area. The above results suggest that twinning in the study area could be related to more than two different tectonic events.

6. Discussions

Kim et al. (1992) established the deformational sequence in Danyang, which is located in the

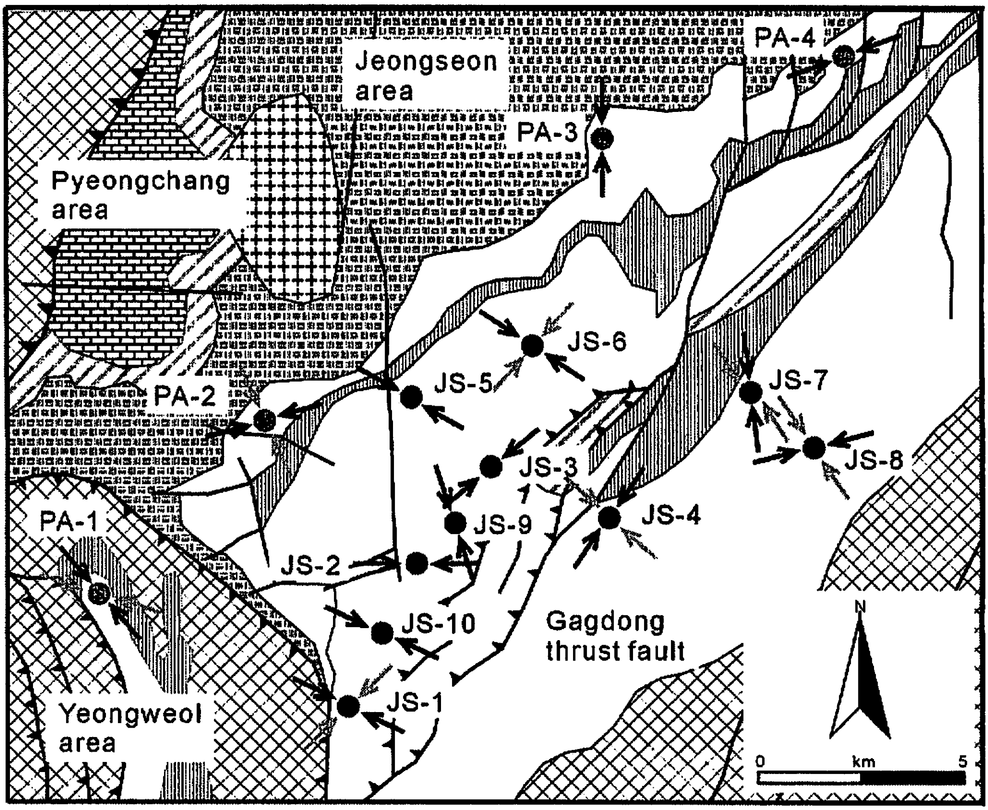

Fig. 6 The directions of the maximum principal paleostress in each sampling location; black arrows: LDR and PEV, gray arrows: NEV.

southeastern part of this study area (Ogcheon belt), by analyzing paleostress tensors within thrust zone using the striations on fault planes. This area was folded and thrusted by polyphase deformation due to several tectonic events. Their study shows that the maximum principal direction was oriented NE-SW during the pre-Daebo orogeny period (late Triassic). It was then rotated NWW-SEE during the syn-Daebo orogeny period (early Jurassic to early Cretaceous). It is finally aligned N-S during the post-Daebo orogeny period (late Cretaceous). Such a change in the direction of maximum principal stress during the Daebo orogeny suggests a major rotation. The direction of the NE-SW trending maximum principal stress is in accordance with one during the Songrim disturbance, and the directions of the NW-SE trending maximum principal stress is accordance with one during the Daebo orogeny. Lee and Chang (1993) studied joint analysis on the marble in the Jeongseon area using the methods of detailed field work and scanline survey. By the result of joint analysis, the preferred orientations (dip direction/dip) of three major joint sets are 206°/82°, 218°/23°, 126°/82°. Hwang (1994) investigated the geodynamic deformation history in the southeastern part of the Korean peninsula since the early Cretaceous period by reconstructing paleostress orientations using Angelier's method (1989) applied to collected brittle tectonic data from faults and joints. His research shows that the maximum principal direction in the area since the early Cretaceous period was predominantly oriented NE-SW and sometimes aligned E-W or NWW-SEE.

South Korea has been affected by three tectonic events in the Mesozoic era, that is, the Songrim disturbance (225 Ma — 190 Ma) in the late Triassic period, the Daebo orogeny (180 Ma — 130 Ma) in the early Jurassic to early Cretaceous period, and the Bulguksa disturbance (63 Ma — 41 Ma) in the late Cretaceous period (Nakazawa et al., 1982; Lee, 1988; Kim et al, 1992; Kim, 1996; Chough et al., 2000). Lee (1988) reported that the Songrim disturbance is equivalent to the Akiyoshi orogeny, the Daebo orogeny is equivalent to the mid-stage of the Sakawa orogeny, and the Bulguksa disturbance is equivalent to the last stage of the Sakawa orogeny in the Japanese Islands. Hara (1982) analyzed, in detail, the mutual relationship in metamorphism and tectonism between the Hida belt during the Triassic to Jurassic period and the Sangun belt during the late Permian to Jurassic period. According to Hara's analysis (1982), many of the metamorphic rocks in the Hida belt appear to give radiometric ages between 250 Ma — 160 Ma, forming an age clusters around 230 Ma — 180 Ma. Furthermore, granitic rocks in the Hida belt, which are formed in large exposures appear to give only an age cluster around 180 Ma. The data for radiometric ages of metamorphic and granitic rocks clearly indicates that the last main event of plutono-metamorphism in the Hida belt occurred 250 Ma — 160 Ma ago, that is, at the Triassic to Jurassic period. Metamorphic rocks in the Sangun belt give radiometic ages between 270 Ma — 160 Ma, forming an age clusters around 250 Ma — 170 Ma. The age cluster around 250 Ma clearly corresponds to the first uplifting stage during the latest Permian to earliest Triassic period, and the age cluster around 170 Ma corresponds to the second uplifting stage during the Jurassic period of the Sangun metamorphic rocks. From Shimazaki et al's model (1981), Hara (1982) reported that the structural direction in the Hida belt appears to be parallel to one (Sinian direction: NE-SW) of the pre-Cretaceous basement complex in the Korean peninsula. Thus, we can assume that the Songrim disturbance and Daebo orogeny were associated with the metamorphism and tectonism between the Hida belt and the Sangun belt.

Comparing the results of paleostress measurement from calcite twins in this study with those obtained by other studies, it strongly suggests that the direction of maximum principal paleostress in the Joseon and Pyeongan Supergroups had changed from NE-SW during the Songrim disturbance period (late Triassic) to NW-SE during the Daebo orogeny period (early Jurassic to early Cretaceous) in the Mesozoic era. Considering the results of the maximum principal paleostress, the tectonic events related with the Songrim disturbance and Daebo orogeny might have affected this study area. It is also considered that the tectonic movements in the study area might be deeply related with metamorphism and tectonism seen in the Hida belt during the Triassic to Jurassic period and the Sangun belt during the late Permian to Jurassic period in Japan. To discuss the stress history and tectonic evolution in the study area and its surrounding area, however, more data from a wider area are needed.

7. Conclusions

The CSG technique was carried out to clarify paleostress in the Joseon and Pyeongan Supergroups distributed in the northeastern part of the Ogcheon belt of South Korea and to infer the tectonic evolution of paleostress fields. One or two twin sets composed of thin or thick straight lines were observed and can be classified as types I and II suggesting deformation at relatively low temperatures. The twin strain, average twin density and width, which are used as indicators of deformation conditions in natural low-temperature deformation of limestone range from 0.83 to 9.83%, 33.5 to 113.4 twins/mm, and 0.28 to 2.03μm in the Joseon Supergroup, and 0.89 to 9.36%, 32.3 to 64.4 twins/mm, and 0.37 to 1.47μm in the Pyeongan Supergroup, respectively. Combining the results of this study and other studies with respect to twin width versus twin strain, twin density versus twin strain, and twin density versus twin width for each sample, it is estimated that calcite twins were formed at temperatures of 170-200°C in the Joseon Supergroup, and under lower temperatures than 170°C in the Pyeongan Supergroup.

Analyses of calcite twins from five samples in the Joseon Supergroup and two samples in the Pyeongan Supergroup suggest the influence of two different stress fields, in other samples, only one stress field is inferred. These results suggest the Joseon and Pyeongan Supergroups were affected by two or more separate tectonic events during the Mesozoic era. Appearances of fault in the study area show thrust faulting (compression tectonic events), normal faulting (extension tectonic events), and strike-slip faulting together. The directions of the maximum principal paleostress in the Joseon Supergroup are oriented NW-SE, NE-SW, E-W, and NW-SE, N-S, NE-SW in the Pyeongan Supergroup. The most dominant directions of maximum principal paleostress are oriented NE-SW and NW-SE, and N-S and E-W directions are also shown. These directions of maximum principal paleostress are accordance with the direction of many fault and thrust sets developed in the study area. Combining the results of paleostress measurement from calcite twins in this study with those obtained by other studies, it strongly suggests that the direction of maximum principal paleostress in the Joseon and Pyeongan Supergroups had changed from NE-SW during the Songrim disturbance period (late Triassic) to NW-SE during the Daebo orogeny period (early Jurassic to early Cretaceous) in the Mesozoic era. Considering the results of the maximum principal paleostress, the tectonic events related with the Songrim disturbance and Daebo orogeny might have affected this study area. It is also considered that the tectonic movements in the study area might be deeply related with metamorphism and tectonism seen in the Hida belt during the Triassic to Jurassic period and the Sangun belt during the late Permian to Jurassic period in Japan.

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