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Paleostress of the Joseon and Pyeongan Supergroups in South Korea using the New Calcite Strain Gauge (NCSG)

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Limestone bodies under the tectonic environment have experienced various tectonic processes, and also changed the stress state. In this study, calcite twins found in limestones of the Joseon Supergroup and Pyeongan Supergroup in the northeastern part of the Ogcheon Belt, South Korea were measured, then the paleostress (i.e., the maximum shortening axis) was reconstructed using the new calcite strain gauge (NCSG) technique. The average twin thickness and average twin intensity increase as the total twin strain increases. We utilize the appearance of twins, the average twin thickness and average twin intensity, and the total twin strain to estimate that the observed calcite twins were produced at temperatures of < 200°C in the Joseon Supergroup and 170°C in the Pyeongan Supergroup. In the Joseon Supergroup, the dominant direction of the maximum shortening axis WNW-ESE to NW-SE; NE-SW shortening is also observed. The maximum shortening axes in the Pyeongan Supergroup are oriented NW-SE and NE-SW. The NE-SW direction of maximum shortening is associated with the occurrence of the Songrim orogeny of the Paleozoic to Early Jurassic, and the NW-SE direction of maximum shortening correlates to the Daebo orogeny of the Early Jurassic to Late Jurassic. It is thus concluded that the paleostress across the study area changed from NE-SW to NW-SE during the Mesozoic.

Key words : paleostress, Joseon and Pyeongan, Ogcheon Belt, new calcite strain gauge (NCSG), maximum shortening axis

Introduction

The Ogcheon Belt is the largest mobile belt in Korea and extended across central South Korea (Fig. 1). Establishing constrains on the paleostress of the Joseon Supergroup and Pyeongan Supergroup is important for clarifying the stress history and tectonic evolution of the Ogcheon belt and the surrounding area during the Mesozoic. In South Korea, Mesozoic tectonic movements are divided into three main phases: the Songrim disturbance, the Daebo orogeny, and the Bulguksa disturbance (Lee, 1988; Kim, 1996; Chough et al., 2000). The whole Korean peninsula was uplifted during the Late Triassic (the Songrim disturbance), which was then followed by the Daebo orogeny during the Early Jurassic to Early Cretaceous. The Daebo orogeny is recognized as the most intense orogenic movement in the geological evolution of Korea, as all pre-existing rocks and formations were deformed and locally metamorphosed. Extensive faulting, thrusting, and folding were particularly well

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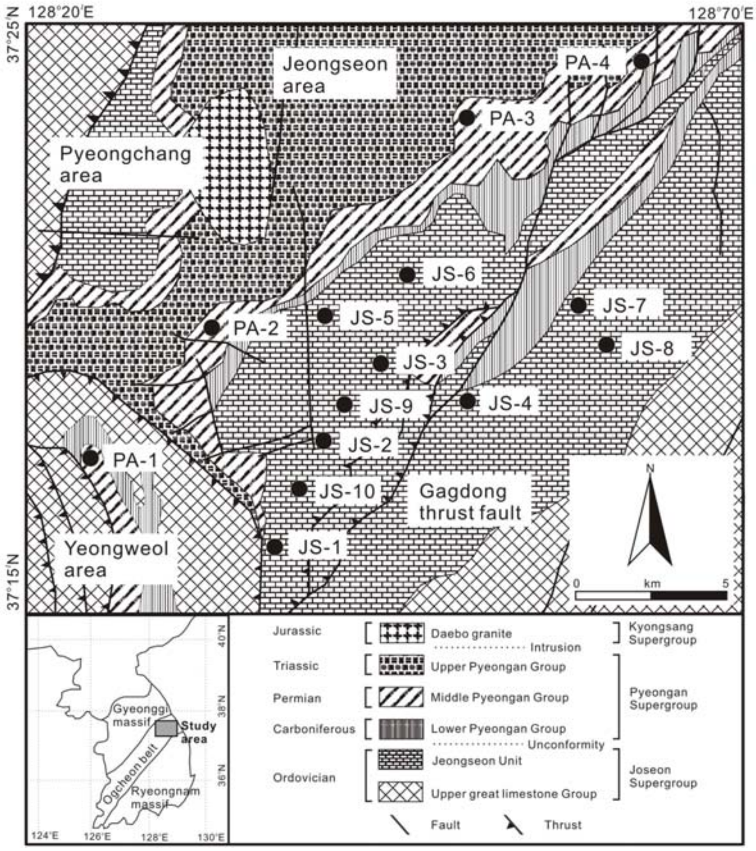


Fig. 1. Simplified geological map of study area and sampling locations along the formations of the Joseon and Pyengan Supergroups. South Korea bounded by Gyeonggi assif, Ogcheon belt, Ryeongnam massif and Gyeongsang basin.

developed in the Ogcheon Belt during this period, and these sturctures trended mainly NE-SW, consistent with the stress field during Sinian. Intensive volcanism and plutonism occurred during the Bulguksa disturbance of the Late Cretaceous. However, this deformation was minor, characterized by locally developed normal and strike-slip faults. These sinistral strike-slip faults trend mostly NE-SW, whereas the orientations of the normal faults vary from NW-SE to NE-SW. These igneous activities and deformations can be related to contemporaneous plate tectonic movements during the Late Cretaceous.

The fabrics of certain minerals in rocks contain information on the stress field of a given region. For example, dislocation intensity, subgrain size, and the size of dynamically recrystallized grain have been used to determine the magnitude of paleostress magnitudes (Twiss, 1977; Pfiffner, 1982). Such information plays an important role in clarifying the stress history of a given tectonic belt, which is of increasing interest in geotectonic studies (Rocher et al., 1996; González-Casado and García-Cuevas, 1999; Lacombe, 2001). Mechanical twinning is commonly observed in deformed calcite (Turner, 1953; Rowe and Rutter, 1990; Burkhard, 1993; Newman, 1994; Ferrill, 1998), and the orientations of calcite twin lamellae can be used to determine the direction of paleostress (i.e., the stress field at the time of deformation). 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 axis of maximum compressive stress 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 twins, and the width of grain perpendicular to the twin plane, the orientation of paleostress field can be estimated (Groshong, 1972, 1974; Groshong et al., 1984; Evans and Groshong, 1994).

Paleostress have previously been calculated for the northeastern Ogcheon Belt, South Korea, using the calcite strian gauge (CSG) computer program written by Q-BASIC to process calcite twin data (Jang and Kang, 1998; Kang et al., 2005a, 2005b; Kim et al., 2008). The main objectives of this paper are to reconstruct paleostress of the Joseon Supergroup and Pyeongan Supergroup in this region, and to estimate deformation temperature, thus providing constraints on the deformation history and tectonic evolution of the Ogcheon Belt during the Mesozoic. We measured the parameters of mechanical twinning within calcite grains across the region; i.e., *c*-axis orientation, twin set orientation, average thickness of both thin and thick twins, number of thin and thick twins, and grain width. The magnitudes and orientations of principal strain axes, total twin strain, average twin thickness and average twin intensity, and orientations of compression and tension axes were calculated using the new calcite strain gauge (NCSG) computer program, which was written by FORTRAN language and modified from the CSG computer program.

Calcite twin measurement and calculations

The principal strains and stresses refleted in calcite twinning were calculated using the CSG technique (Groshong, 1972, 1974; Evans and Groshong, 1994; Kang et al., 2005a; Jang et al., 2012), where the magnitudes and orientations of the principal strains were calculated using Groshong's CSG technique, and the relative magnitudes and orientations of the principal stresses were determined using Spang's (1972) numerical dynamic analysis. The NCSG technique calculates the average twin thickness, average twin intensity, negative expected value (NEV), total twin strain, and magnitudes and orientations of the principal strains and stresses for each rock sample, as well as the orientations of the compressive and tensile stress axes and the expected value of the tensorial shear strain for each twin set (Evans and Groshong, 1994). All of the expected value of tensorial shear strain should be positive (positive expected value, PEV) for a single homogeneous deformation, because twin gliding in calcite occurs only with a positive shear sense. A NEV of the tensorial shear strain implies that the calcite grain is not properly oriented to twin given the computed strain tensor (Groshong, 1974; Teufel, 1980). A small NEV $<40\%$ may occur for grains that have either rotated slightly or whose orientations were not accurately measured. However, a large NEV ($>40\%$) implies that strongly inhomogeneous or multiple deformation, which highlight a complex strain history, have occurred, making it difficult to distinguish a PEV from data with a NEV (Groshong et al., 1984). The total twin strain is the square root of the second invariant of the global strain tensor. The scatter of the twin data in the calculation was reduced by eliminating the 20% of the twin sets that gave the largest deviations between the calculated and expected values to improve the precision and accuracy of calculation following Groshong et al. (1984). The remaining deviation indicates the difference in magnitude between the measured and calculated tensorial shear strains.

Study area and samples

The study area lies between $37^{o}15'$ and $37^{o}25'$ north and $128^{o}20'$ and $128^{o}70'$ east (Fig. 1). The Joseon Supergroup and Pyeongan Supergroup are located along the northeastern section of the Ogcheon Belt. The Ogcheon Belt, which is about 70 km wide and 450 km long, and extends across central 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 Supergroup and Pyeongan Supergroup), and southwestern part, comprising crystalline schists and phyllites (Ogcheon Group).

The rocks in the study area are affected by polyphase deformation that formed structures such as folds, thrusts, and faults. General strikes and dips of these structures are $N30^{o}E$ and $52^{o}NW$, respectively. However, the strikes and dips of the structures distributed across the Yeongweol area along the western part of the Gagdong thrust fault are N30°W and 28°SW, respectively. The trends of the axial traces of folds related to faulting can be classified into NW-SE, NE-SW, and E-W orientations (Kim et al., 1992). In addition, folds and thrusts that formed in association with the Songrim disturbance, the Daebo orogeny, and the Late Cretaceous Bulgugsa 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.

Fourteen oriented limestone samples were collected from analysis: 10 from the Joseon Supergroup and 4 from the Pyeongan Supergroup (Fig. 1). The procedure for preparing the thin sections from the collected samples is described in detailed by Kang et al. (2005a).

Results

Deformation temperature

Twinned grains were found to be distributed throughout the calcite grain of the samples. The calcite grains for measuring twins were randomly selected from thin sections. Figure 2 shows microphotographs of twins from samples collected in the Joseon Supergroup (Fig. 2a,b) and Pyeongan (Fig. 2c,d) Supergroup. Most of the calcite grains investigated in the Joseon Supergroup and Pyeongan Supergroup possess one or two twin sets which were classified as either Type I straight thin twins (Fig. 2a,c) and Type II straight thick twins (Fig. 2b,d), implying deformation at relatively low temperatures of approximately under 200°C (Burkhard, 1993; Ferrill et al., 2004).

The NCSG results from the fourteen limestone samples are summarized in Table 1. One sample (JS-4) in the Joseon Supergroup and two samples (PA-1, PA-2) in the Pyeongan Supergroup show NEVs > 40%. The data were thus divided as either PEV and NEV. The twin strain, twin intensity and twin thickness were 0.83%-8.14%, 33.49-101.87 twins/mm, and 0.43-1.92 mm for the Joseon Supergroup, and 0.89%-9.36%, 32.27-64.35 twins/mm, and 0.37-1.47 mm for the Pyeongan Supergroup, respectively.

Twin thickness exhibits a dependence on deformation temperature and strain, allowing twin thickness and twin intensity to be used as indicators of deformation condi-

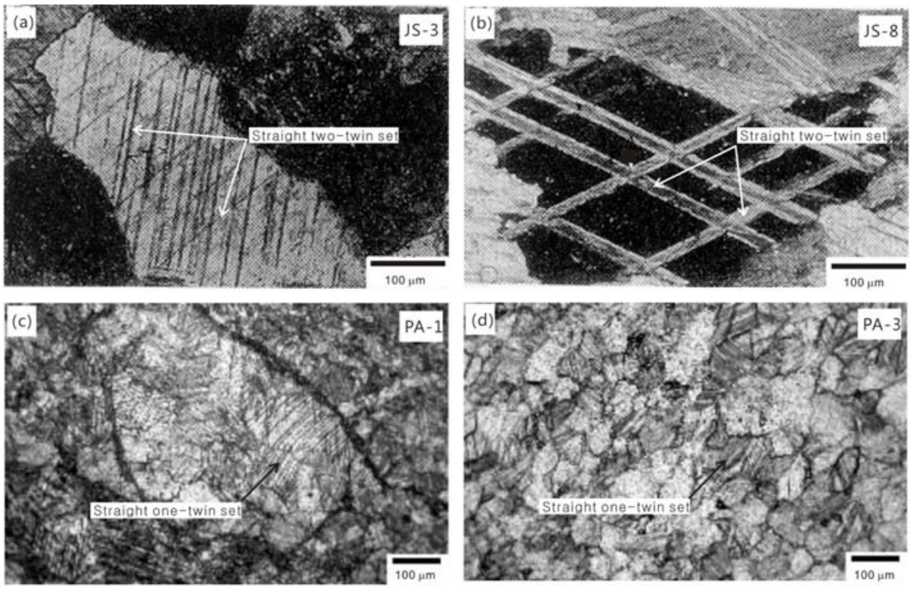


Fig. 2. Microphotographs of twins in calcite grains observed and measured from the Joseon (JS, a and b) and Pyeongan (PA, c and d) Supergroups (Kang et al., 2005b). The images were taken under cross polarized light.

Table 1. Results of the NCSG technique application to limestone in the Joseon and Pyeongan Supergroups, South Korea. N and n are the number of measured twins and twins analyzed after removing those with large NEV. NEV and PEV are negative and positive expected values of strain. t_{avg} is average twin thickness, and ρ_{avg} is average twin intensity. $\sqrt{J_2}$ is total twin strain by twinning (Jaeger & Cook, 1979). J_2 is calculated from the three principal strains, namely, $J_2 = -(e_2e_3 + e_3e_1 + e_1e_2)$. e_1, e_2 and e_3 are percent elongations and orientations of principal strain axes are given as trend/plunge of their axes.

Sample No.	N/n	NEV (%)	t_{avg} (μm)	ρ_{avg} (twins/mm)	$\sqrt{J_2}$ (%)	Strain and orientation of principal strain axes		
						e_1	e_2	e_3
JS-1	60/48	25	1.92	61.85	8.14	8.429 272°/49°	-0.614 9°/6°	-7.816 104°/41°
JS-2	57/46	15	0.56	90.17	3.21	2.410 329°/25°	1.235 203°/52°	-3.645 73°/27°
JS-3	50/40	20	1.47	57.69	6.03	6.023 181°/8°	0.021 347°/82°	-6.044 91°/2°
JS-4 NEV	64/52 52/21	41 19	0.43	35.53	0.83	0.860 234°/37°	-0.059 80°/50°	-0.801 334°/13°
JS-4 PEV	64/52 52/31	41 6	1.42	33.49	3.69	3.216 332°/20°	0.808 77°/35°	-4.024 218°/48°
JS-5	50/40	13	0.75	46.65	3.15	2.861 46°/19°	0.509 159°/49°	-3.369 302°/35°
JS-6	58/47	30	0.54	101.87	5.22	5.507 139°/73°	-0.624 33°/5°	-4.883 301°/16°
JS-7	65/52	33	1.08	48.30	5.34	4.877 176°/18°	0.834 77°/27°	-5.711 296°/57°
JS-8	53/43	33	0.87	40.73	1.88	1.941 160°/12°	-0.133 69°/5°	-1.808 319°/77°
JS-9	50/40	5	0.53	90.18	3.54	3.532 110°/31°	0.007 248°/51°	-3.539 6°/21°
JS-10	59/48	21	0.99	89.62	5.91	6.203 21°/2°	-0.631 116°/71°	-5.573 290°/19°
PA-1 NEV	51/41 41/18	43 17	0.47	37.88	1.60	1.836 323°/16°	-0.718 219°/40°	-1.118 70°/46°
PA-1 PEV	51/41 41/23	43 4	0.79	60.43	3.92	2.733 81°/34°	1.754 205°/40°	-4.487 326°/32°
PA-2 NEV	50/40 40/16	40 25	0.63	54.42	4.93	4.488 137°/54°	0.795 242°/11°	-5.283 340°/34°
PA-2 PEV	50/40 40/24	40 4	1.47	64.35	9.36	10.418 327°/45°	-2.730 216°/20°	-7.688 109°/38°
PA-3	50/40	10	0.37	32.27	0.89	0.921 81°/27°	-0.069 346°/11°	-0.852 236°/61°
PA-4	50/40	25	0.55	57.74	2.87	2.501 195°/20°	0.632 286°/4°	-3.134 27°/70°

tions in limestone (Ferrill, 1991; Ferrill et al., 2004). Figure 3 illustrates the relationship between calcite twin parameters, deformation temperature, and strain for both our 14 limestone samples (Table 1) and the results presented by Ferrill et al. (2004). According to Ferrill et al. (2004), three temperature-dependent deformation domain arise from the data: < 170°C, 170-200°C, and > 200°C (Fig. 3a to c) As shown in Fig. 3c, calcite develops thick twins and low twin intensities at higher temperature, whereas thin twins and high twin intensities develop at lower temperatures. Figure 3d shows that the product of twin thickness and twin intensity is directly proportional to the amount of shear strain, because twin thickness and twin intensity together determine the amount of twin

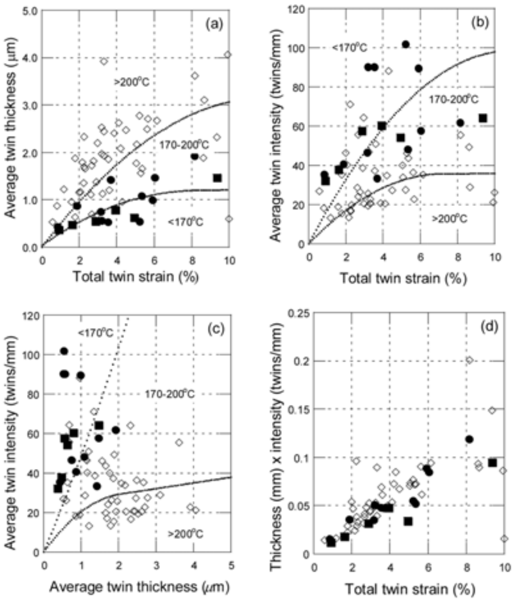


Fig. 3. Estimation of deformation temperature from total strain, average thickness and average intensity of twins. (a) Average twin thickness versus total twin strain, (b) average twin intensity versus total twin strain, (c) average twin intensity versus average twin thickness, and (d) product of average twin thickness and average twin intensity versus total twin strain. Plots include data from this study and Ferrill et al. (2004, Table 1). Closed circles and rectangles stand for results from the Joseon and Pyeongan Supergroups, respectively. Open diamonds stand for those from Ferrill et al. (2004).

strain, because twin thickness and twin intensity define te amount of shear strain, and the degree of the twin thick ess and twin intensity can accommodate a given shear strain (Groshong, 1972; Ferrill et al., 2004). The results of this study with those of Ferrill (1991) and Ferrill et al. (2004), it is estimated that calcite twins were produced at temperatures < 200°C in the Joseon Supergroup and < 170°C in the Pyeongan Supergroup. These results are in good agreement with the temperatures suggested by the appearance of Type I and Type II twins.

Paleostress

The NCSG computer program calculates the orientations of the principal strain axes (e_1: the maximum extension axis, e_2: the intermediate axis, e_3: of the maximum shortening axis) based on Groshong's (1972) technique as well as the orientations of compression and tension axes based on Turner's (1953) technique. The stress and strain axes are supposed to be the following relation: $\sigma_1 \leftrightarrow e_3$, $\sigma_2 \leftrightarrow e_2$ and $\sigma_3 \leftrightarrow e_1$. The magnitudes and orientations of the principal strain axes on the samples are presented in Table 1. The directions of the principal strain, compression, and tension axes obtained from calcite twins are plotted on a lower hemisphere equal-area Schmidt stereonet projection in Fig. 4. In sample JS-4 of the Joseon Supergroup and samples PA-1 and PA-2 of the Pyeongan Supergroup with a large NEV (> 40%), two events with different principal directions could have produced the observed calcite twins, whereas only one event is needed to account for the calcite twins in the other samples.

In the Joseon Supergroup, the dominant direction of the maximum shortening axes is WNW-ESE (JS-1, JS-5, JS-6, JS-7, JS-10) to NW-SE (JS-8, JS-4NEV). The trends of the maximum extension axes are primarily NW-SE (JS-2, JS-8, JS-4PEV, JS-6), and also show N-S (JS-3, JS-7) and NE-SW (JS-5, JS-4NEV) orientations. The maximum shortening axes show two contrasting plunges: a gentle to moderate plunge (JS-2, JS-3, JS-4NEV, JS-6, JS-9, JS-10) and a steep plunge (JS-1, JS-4PEV, JS-5, JS-7, JS-8). The maximum extension axes also show a gentle to moderate plunge (JS-2, JS-3, JS-4PEV, JS-5, JS-7, JS-8, JS-10) and a steep plunge (JS-1, JS-4NEV, JS-6, JS-9). Samples JS-1, JS-2, JS-4NEV, JS-4PEV, JS-5, JS-7, JS-9, and JS-10 have the same direction in the relationships between σ_3 and e_1 and σ_1 and e_3, suggesting a coaxial deformation. In contrast, the σ_3 and e_1 directions in sample JS-3, JS-6 and JS-8 are different, which suggests a non-coaxial deformation.

In the Pyeongan Supergroup, the maximum shortening axes are approximately NW-SE (PA-1PEV, PA-2NEV, PA-2PEV) and NE-SW (PA-1NEV, PA-3, PA-4). The maximum shortening axes inferred from calcite twins are inclined with a steep plunge, indicating that the stress field was influenced by normal faulting in an extensional tectonic environment. The maximum extension axes are oriented primarily NW-SE (PA-1NEV, PA-2NEV, PA-2PEV), with some axes also oriented ENE-WSW (PA-1PEV, PA-3). The maximum extension axes are inclined at both a moderate plunge (PA-1NEV, PA-3, PA-4) and a steep plunge (PA-1PEV, PA-2NEV, PA-2PEV). In all samples, the σ_1 and σ_3 directions have the same orientations as those of e_3 and e_1, which suggests a coaxial deformation.

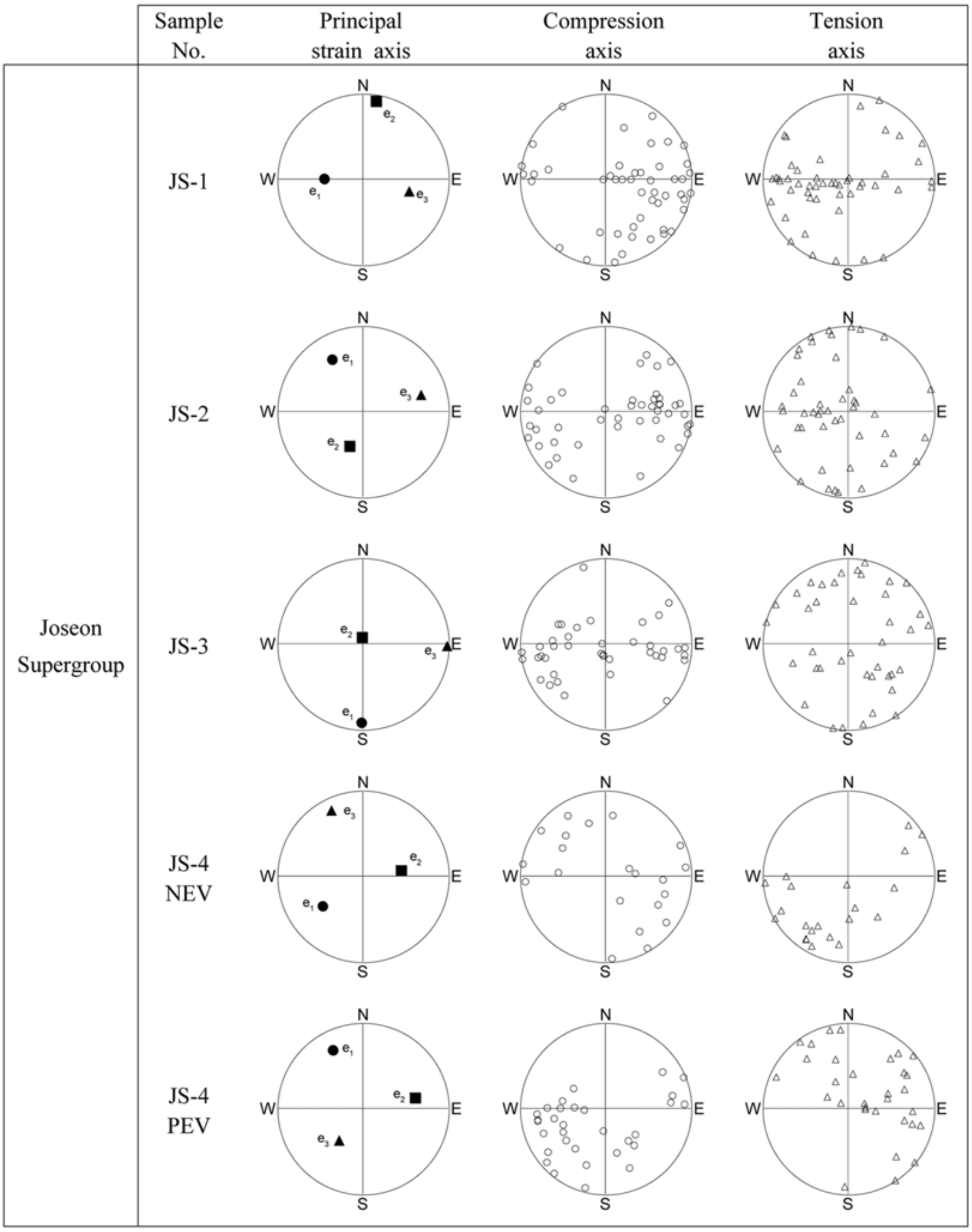
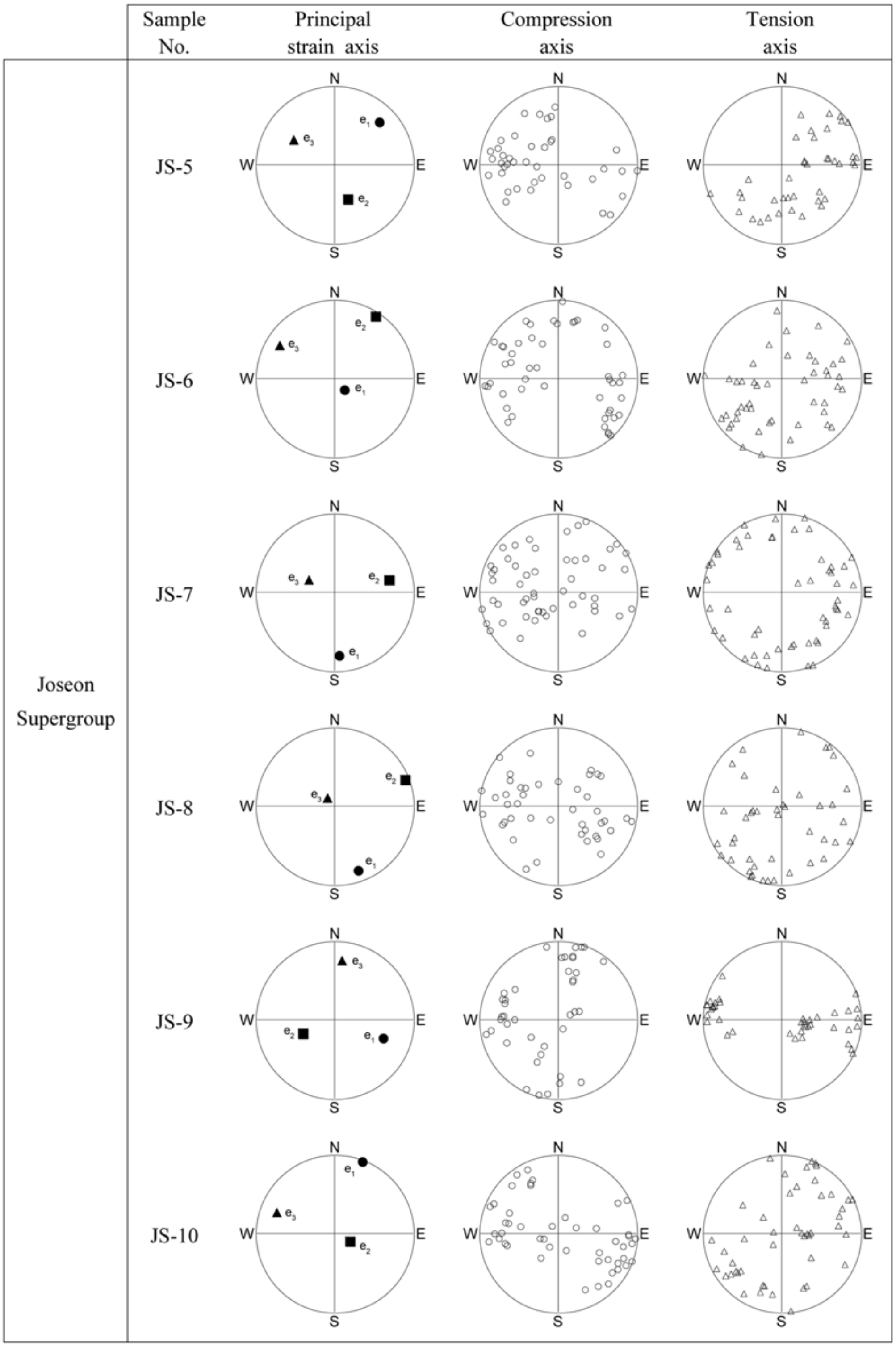


Fig. 4. Stereographic projection of the orientations of principal strains, compression and tension axes in the Joseon and Pyeongan Supergroups. Each closed open circle, rectangle and triangle represents the maximum (e_1: maximum shortening), intermediate (e_2) and minimum (e_3: maximum extension) principal strain axes. Each open circle and triangle stands for compression and tension axes.



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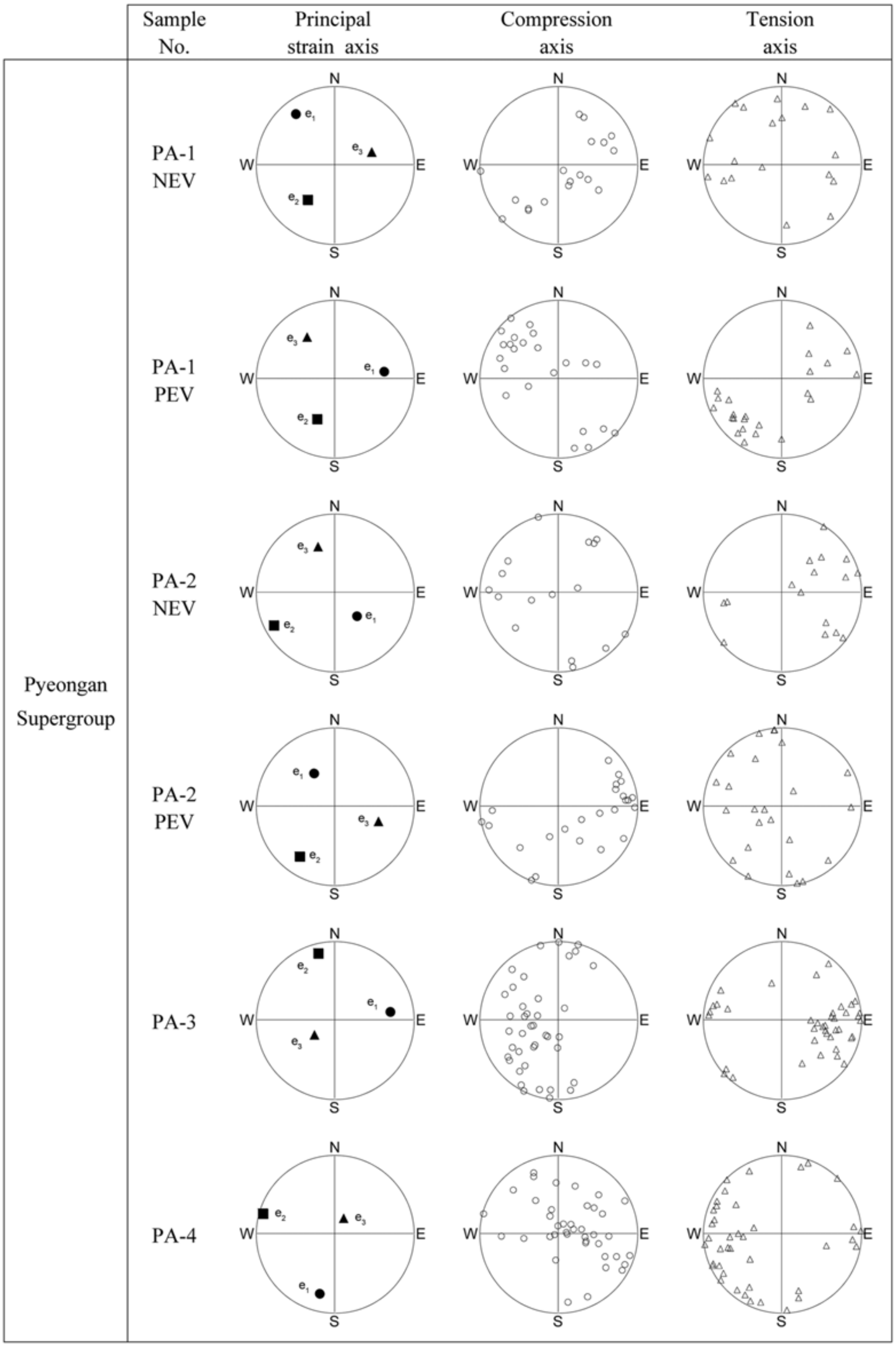

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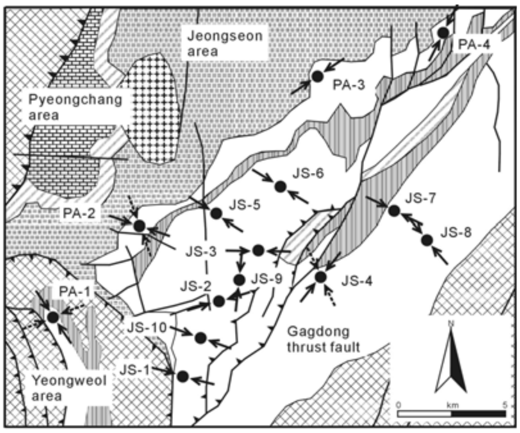

Fig. 5. Orientations of the maximum shortening axis (solid and dashed arrows) at each sampling location. The dashed arrows for the JS-4, PA-1, and PA-2 represent the direction of maximum shortening axis for a NEV. The geologic units and the precise location of the study area in South Korea are given in Fig. 1.

Discussion

South Korea has been affected by three tectonic events during the Mesozoic: the Songrim disturbance (225-190 Ma) during the Late Triassic period, the Daebo orogeny (180-130 Ma) from the Early Jurassic to Early Cretaceous period, and the Bulguksa disturbance (63-41 Ma) during the Late Cretaceous period (Lee, 1988; Kim et al, 1992; Kim, 1996; Chough et al., 2000). Kim et al. (1992) established the deformational sequence in Danyang, by using observed striations on fault planes within the thrust zone to analyze paleostress tensors. The rock in this area were folded and thrusted during polyphase deformation related to several tectonic events. Their study revealed that the direction of the maximum principal stress was oriented NE-SW during the late Triassic, then rotated WNW-ESE during the early Jurassic to early Cretaceous, and was finally aligned N-S during the late Cretaceous. The direction of the NE-SW trending maximum principal stress is in accordance with that inferred during the Songrim disturbance, and the directions of the NW-SE trending maximum principal stress corresponds to that inferred during the Daebo orogeny. Hwang (1994) investigated the geodynamic deformation history of the southeastern Korean peninsula since the Early Cretaceous period by reconstructing paleostress orientations using Angelier's (1989) method, based on brittle tectonic data collected from faults and joints. His research shows that the direction of the maximum principal stress since the Early Cretaceous period was oriented predominantly NE-SW and sometimes aligned E-W or WNW-ESE. Jang and Kang (1998) analyzed paleostress from calcite twins in the Jeongseon area and showed that the maximum shortening axes were oriented E-W during the Silurian and changed to NW-SE during the Late Triassic to Late Cretaceous. Kihm and Kim (2003) reported the structural evolution of the central Ogcheon Belt, where they suggested that the maximum compressive stress axis changed from NE-SW during the Early Triassic to NW-SE between the Late Triassic and Jurassic, and to N-S during the Cretaceous.

The direction of maximum shortening axis is expressed at each sampling location on a geological map in Fig. 5. The dashed arrows for the JS-4, PA-1, and PA-2 represent the direction of maximum shortening axis for a NEV. The dominant direction of the maximum shortening axis is WNW-ESE to NW-SE in the Joseon Supergroup, and NW-SE and NE-SW in the Pyeongan Supergroup. Comparing the results of this study with those obtained previously (Lee, 1988; Kim et al, 1992; Hwang, 1994; Kim, 1996; Jang and Kang, 1998; Chough et al., 2000; Kihm and Kim, 2003), we suggest that the NE-SW direction of maximum shortening is correlated with the Songrim orogeny of the Paleozoic to Early Jurassic, and the NW-SE direction of maximum shortening is correlated with the Daebo orogeny of the Early Jurassic to Late Jurassic. These data suggest that the paleostress (i.e., the maximum shortening axis) in the study area changes from a NE-SW to NW-SE during the Mesozoic.

Conclusions

We estimated deformation temperatures from calcite twins found in limestones of the Joseon Supergroup and Pyeonan Supergroup in the northeastern Ogcheon Belt, South Korea, and reconstructed the paleostress (i.e., the maxium shortening axis). The average twin thickness and average twin intensity increase as the total twin strain increases. Deformation temperature estimated to have been < 200°C in the Joseon Supergroup and < 170°C in the Pyeongan Supergroup. The direction of maximum shortening was primarily WNW-ESE to NW-SE in the Joseon Supergroup, and NE-SW shorteing is also observed. The direction of maximum shortening in the Pyeongan Supergroup is primarily NW-SE to NE-SW. These results, combined with existing data, suggest that the NE-SW direction of maximum shortening is associated with the occurrenc of the Songrim orogeny of the Paleozoic to Early Jurassic, and that the NW-SE direction of maximum shorteing is correlated with the Daebo orogeny of the Early Jurassic to Late Jurassic. Furthermore, it is inferred that the paleostress (i.e., the maximum shortening axis) across the northeastern Ogcheon Belt in South Korea shifted from NE-SW during the Paleozoic to Early Jurassic, to NW-SE during the Early Jurassic to Late Jurassic.

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