Sandstone petrography and areal comparison of the Lower Siwalik Group(Miocene), west-central Nepal

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Metamorphism and exhumation of high-grade metamorphic rocks that consists of the Higher Himalaya took place during Miocene time (Sakai, 2005). The Himalayan orogen is a result of ongoing collision between Indian and Asian continents. A number of studies carried out about this example of continental collision progressed from Paleogene to present time (Honda and Sakai, 1988; Najman, 2006). Metamorphism and uplift process is related to formation of the Himalayan orogeny. In this study, sandstone petrography is studied in the Lower Siwalik Group in four areas; Karnali River, Dang Valley, Surai Khola and Tinau Khola in west-central Nepal. The comparison with each petrographical result reveals the timing of exhumation of the high-grade metamorphic rocks in central Himalaya.

Siwalik Group is interpreted as a foreland basin deposit of Himalayan orogen from Miocene to Pliocene time, especially the deposition of the Lower Siwalik Group is contemporaneous to the exhumation of Higher Himalaya. Thus this study aims to clarify the historical change of the hinterland constitution using modal composition of sandstones, heavy mineral assemblage and chemistry of detrital garnet grains by EDS. Paleomagnetic stratigraphy is used to determine the depositional age in each area (Gautam and Fujiwara, 2000; Rosler et al., 1997; Gautam et al., 2012). Result of modal analysis of sandstone in each area shows the recycled orogenenic provenance, which indicates the Himalayan origin. Furthermore most quartz grains are classified into middle and upper rank metamorphic field in triangular diagram proposed by Basu et al. (1975), which is suggestive of middle and upper rank metamorphic rock source. Some sandstones, which were deposited in 13-8Ma, contain high-temperature minerals, such as kyanite, sillimanite, and staurolite. These minerals imply the exhumation of high-grade metamorphic rocks in hinterland, though definite timing of unroofing in these crystalline rocks is obscure due to scarcity of the minerals. Then the chemical composition of detrital garnet grains, which are included in all of sandstone samples, is used to chase the transition of hinterland. As a result, the chemical composition of detrital garnet grains had been changed in the Lower Siwalik deposited during 13~8Ma. Because this duration is likely to be close to an appearance of kyanite and staurolite, the compositional change of detrital garnets suggests the exhumation of Higher Himalaya in Late Miocene time. Timing of exhumation in each area are estimated as follows; 13.2~12Ma in Karnali River area, 13~10.9Ma in Dang Valley area and 10.9~9.5Ma in Srai Khola area. It is suggested that the unroofing in western area is probably prior to that in eastern area. This tendency indicates the unroofing of Higher Himalaya propagated from the west to the east. Previous works in Pakistan and north-western India showed that the unroofing of high-grade metamorphic rock progressed from the west toward the east in north-western margin of Indian sub-continent (Najman et al., 2003a,b; White et al., 2002).

Keywords: Himalayan orogen Siwalik Group

Origin and tectonic evolution of the accretionary complex in central and north-central Mongolia

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Introduction We aim to clarify the origin and tectonic evolution of accretionary complexes (ACs) in central and north-central Mongolia. **Geologic setting** **North-central Mongolia (NCM)** consists of the following three terranes: the **Haraa** and **Bayangol terranes** consisting of an AC and minor volcaniclastic cover rocks of Early Paleozoic times, and the **Khentei terrane** consisting of an AC and shallow-marine cover of Middle Paleozoic to Early Mesozoic times. The Khentei AC strikes NE and dips to N. The pelagic chert of the AC yields Late Silurian and Early-Late Devonian microfossils (Kurihara et al., 2009). The overlying Lower Carboniferous mudstone yields brachiopods, and the Middle-Upper Permian Urmegtei formation is a periglacial formation. **Central Mongolia (CM)** consists of the following two terranes: the **Zag terrane** consisting mainly of Early Paleozoic crystalline schists, and the **Khangai terrane** consisting of an AC and terrestrial cover. The terranes of CM and NCM are separated by a sinistral shear zone, whereas the boundary between the Zag and Khangai terranes trends NWN and dips N. A NWN-trending syncline runs in the middle of the Khangai terrane, where plant-bearing Carboniferous sediments with horizontal conglomerate occur with andesite pebbles. The Carboniferous sediments are thus terrestrial sediments. The Zag terrane collided with the terranes on the south in Permo-Triassic times (Jian et al., 2010). **Method** We extracted detrital zircons from 21 sandstone samples of the AC and terrestrial sediments: from the Khentei (8 samples), Haraa (5), Bayangol (2), Khangai (5), and Zag (1) terranes. We then measured their U-Pb ages with the LA-ICP-MS equipped in the Graduate School of Environmental Studies, Nagoya University. **Results** We recognized two types of detrital-zircon-age spectra. One was a multimodal pattern with small peaks at 420-650 Ma, 700-1000 Ma, 1600-2200 Ma, and 2300-2700 Ma and had 75 % or more Precambrian zircons. Three samples from the upper part of the AC in NCM and the Zag terrane showed this pattern. The other was a unimodal pattern with the youngest peaks (YP) between the Devonian and the Early Permian and has virtually no Precambrian zircons, indicative of an island-arc setting. The Khangai terrane and lower part of the AC in NCM, and the terrestrial sediments in CM showed this pattern (17 samples). **Discussion** We assumed, from the volcaniclastic nature of most of the sandstone samples, that the YP of the spectrum is the depositional age (DA) of each sample (YP of meta-samples is the upper limit of the DA because of the absence of volcaniclasts). The DA of the multimodal-type sandstone clustered at 526-426 Ma, whereas those of the unimodal-type sandstone clustered at 409-374 Ma (Early Devonian), 358-332 Ma (Early Carboniferous), and 304-259 Ma (Early Permian). Moreover, the DA clearly showed a downward-younging polarity in the **Khangai Terrane of CM** and **NCM**. Moreover, the older interval in the DA (374-348 Ma) and the hiatus of Paleozoic igneous activity in the Tuva-Mongol Massif (385-350 Ma) roughly coincide with each other. These facts indicate that the studied AC intermittently grew downwards in front of the Tuva-Mongol Massif. The Zag sample is similar with the Cambro-Silurian sediments in NCM and contained Pan-African (550-750 Ma) zircons, indicative of their derivation from Gondwana. In particular, the zircon-age spectrum of the Cambo-Ordovician sandstone of the Kufra Basin in the Saharan Metacraton has a close affinity with the multimodal-type of NCM. The YP of the terrestrial sediments (322 Ma) indicates that CM became land by early Carboniferous, and the later collision of the Zag and southern terranes produced the syncline of CM.

Keywords: U-Pb age, (detrital) zircon, LA-ICP-MS, Gondwana continent, Paleozoic

Detrital zircon U-Pb ages from Permian clastic units within the Kurosegawa belt

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U-Pb dating of detrital zircons was performed on Permian clastics from the Kurosegawa belt, distributed in Ino district, Kochi, Shikoku, to determine the sedimentary age. The Permian clastics of the Kurosegawa belt are subdivided into three geological units such as Middle Permian accretionary complex (Ino and Agekura units), and Late Permian accretionary complex (Singai and Tosayama units, and Late Permian shallow marine sediments (Ichinose Formation). In particular, the Middle Permian accretionary complex was subjected to pumpellyite to actinolite facies metamorphism during Late Triassic to Early Jurassic.

Keywords: zircon U-Pb age, Permian, Kurosegawa belt

Zircon U-Pb dating of igneous-rock clasts from the Monobegawa and Nankai groups in Shikoku, SW Japan

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INTRODUCTION

The Lower Cretaceous strata of the Chichibu Composite Belt in Shikoku, SW Japan, are divided, from bivalve fauna and lithofacies, into the Monobegawa and Nankai groups (MG and NG; Tashiro, 1985). Tashiro (1985) also suggested that the Nankai fauna indicates lower latitude than the Monobegawa fauna. Matsukawa and Eto (1987), on the other hand, suggested that the two groups were deposited in a same basin, where the Boreal–Tethyan mixed ammonite fauna inhabited. Matsukawa and Eto (1987) further discussed that some clasts in the Hauterivian Shobu Formation (Fm) of the NG were supplied from the pre-Cretaceous rocks of the Kurosegawa Tectonic Belt (KTB) on the south of the basin. To solve the confusion, we measured the zircon U-Pb age of igneous-rock clasts from the Hibihara Fm (1 clast) and Yunoki Fm (1; MG) in central Shikoku, and the Hoji Fm (1; MG) and the Shobu Fm (2; NG) in eastern Shikoku.

METHODS

We separated zircons from igneous-rock clasts and measured the U-Pb isotopic ratios of each grain on the LA-ICP-MS equipped in the Graduate School of Environmental Studies of Nagoya University. Data with the (206Pb/238U age)/(207Pb/235U age) between 0.9 and 1.1 were used for discussion.

RESULTS

Granite clast from the Albian Hibihara Fm : We obtained 14 concordant measurements ranging in age between 133 and 120 Ma and calculated the 206Pb/238U weighted mean age of 126.4 +/- 2.5 Ma.

Granite porphyry clast from the Aptian Yunoki Fm : We obtained 12 concordant measurements with the age clusters at 129-122 Ma (N=6), 137-135 Ma (N=2), 181-174 Ma (N=2), 269 Ma (N=1), and 2,334 Ma (N=1) and calculated the 206Pb/238U weighted mean age of 125.4 +/- 2.6 Ma from the youngest 6 grains.

Granite porphyry clast from the Aptian Hoji Fm : We obtained 13 concordant measurements ranging in age between 143 and 118 Ma and calculated the 206Pb/238U weighted mean age of 130.0 +/- 4.4 Ma.

Granite clast from the Hauterivian Shobu Fm : We obtained 34 concordant measurements with the age clusters at 173 Ma (N=1), 186-184 Ma (N=2), 218-193 Ma (N=27), and 232-224 Ma (N=4) and calculated the $^{206}Pb/^{238}U$ weighted mean age of 203.9 +/- 2.5 Ma from the 27 grains forming the largest age cluster.

Granite porphyry clast from the Shobu Fm : We obtained 11 concordant measurements scattering in age at 204-203 Ma (N=2), 241-228 Ma (N=3), 263 Ma (N=1), 287 Ma (N=1), 1,910-1,879 Ma (N=2), 2,090 Ma (N=1), and 2,263 Ma (N=1) and calculated the concordant age of 203.4 +/- 2.8 Ma from the youngest 2 grains.

DISCUSSION

The igneous-rock clasts from the MG are 130-125 Ma in age. Coeval igneous rocks occur in the Kitakami Belt of NE Japan, around the Bohai Bay, and along the South China coast (e.g., Kiminami and Imaoka, 2013; Li *et al.*, 2014; Tsuchiya *et al.*, 2015). Since the measured clasts are all cobble size, the provenance was probably near the eastern shelf margin of Asia. Moreover the Late Jurassic–Early Jurassic paleophytogeography (Kimura, 1987) indicates that the MG, having the Ryoseki-type flora, must have been deposited along the Zhejiang coast of South China or on the south.

The age of the igneous-rock clasts from the Shobu Fm (NG) is 204 Ma, which does not coincide with the age of the igneous rocks in the KTB (around 400 Ma: Hada *et al.*, 2000; Murata *et al.*, 2006). Further, the sandstone on top of the Shobu conglomerate has many detrital zircons of around 200 Ma, but no 400-Ma and Early Cretaceous zircons. Hence the 200-Ma clasts of the Shobu Fm, differing in age from the igneous rocks of the KTB, must not have been supplied from the south. Hence the Hauterivian of the MG and NG was probably deposited along different parts of the East Asian coast. A possible candidate of the hinterland of the Shobu Fm is Indochina, where Triassic igneous rocks are widely exposed but Early Cretaceous igneous rocks are rare.

Keywords: U-Pb age, LA-ICP-MS, Lower Cretaceous of the Chichibu Composite Belt, Southwest Japan, East Asia, igneous-rock clast

Back-arc opening and across-arc tectonics in Cenozoic Japan

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Multiple check on U-Pb nad Pb-Pb age spectra was conducted for detrital zircons in various Cretaceous sandstones in SW Japan. Their comparison revealed a long-distance (more than 200 km across the arc) transportation of a Cretaceous back-arc sedimentary package into the fore-arc domain during the early Cenozoic, almost coeval to the back-arc spreading of the Jpan Sea. The overall configuration of the Cretaceous subduction-related arc-trench system in Japan is preserved in the current distribution of the relevant orogenic components, i.e., the coeval set of accretionary complexes at trench (the Sanbosan and North Shimanto belts), high-P/T meta-ACs along the Wadati-Benioff zone (the Sanbagawa and Shimanto metamorphic belts), arc batholiths (Ryoke-Sanyo and San-in belts), and fore-arc basin strata (Ryoseki-Monobegawa and Izumi groups). We identified unique age spectra of detrital zircons in the Cretaceous sandstones in the Atogura area in the northern Kanto Mountains, and the Maana area in western Shikoku. These strata occur on the south of Median Tectonic Line of SW Japan as allochthonous klippen. The results of U-Pb dating by LA-ICPMS showed that these sandstones have common age spectra with 4 major age groups; i.e., 120-150 Ma (Early Cretaceous), 170-200 Ma (Jurassic), 250-300 Ma (Permian), and 1600-2200 Ma (Paleoproterozoic), with minor amounts of much older grains up to 2900 Ma (Archean). This age spectrum is quite unique, when compared with other coeval Cretaceous fore-arc and/or intra-arc sandstones in Japan. The Early Cretaceous grains were obviously derived from a proximal source to the depositional site, likely the Cretaceous volcanic arc of the Ryoke-Sanyo belt in SW Japan. The dominant grains of the Jurassic and Permian ages were likely derived from coeval plutonic belts in the provenance, whereas the Paleoproterozoic grains were probably derived from the continental blocks in East Asia with crusts of the corresponding ages, such as the North and South China blocks. Except for the Cretaceous arc source, the occurrence of Jurassic and Permian granitoids is extremely rare in the major parts of Japan, and the Paleoproterozoic crust is totally absent in Japan.

The analyzed sandsotnes from the Atogura and Maana klippens are remarkably different from other coeval fore-arc sandstones, whereas they clearly show similarity to those of the Tetori/Jinzu groups in the Hida belt. The Cretaceous sandstones of the Atogura/Maana klippen were primarily deposited with a close link to the Hida belt. The tectonic emplacement onto the present position immediately above the Cretaceous high-P/T meta-ACs occurred likely during the Paleogene-Neogene time, probably in relation with the Miocene rifting of the Japan Sea. This study provides the first evidence for the material transfer from the back-arc to fore-arc on the order of 200-300 km across the arc.

Keywords: SW Japan, Cretaceous, detrital zircon, U-Pb dating

SHRIMP zircon U-Pb ages of acidic tuff layers within the Ishikari and Kushiro coal basins, in Hokkaido, Japan

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SHRIMP zircon U-Pb ages were obtained for acidic tuff layers within the Ishikari and Kushiro coal basins, in Hokkaido, Japan to understand timings of the coal formations. The sample from the Ishikari coal basin was taken from an open pit of the Sanbi Coal Mine, Bibai city. It is collected from the thin layer of white tuff in the No. 4 coal bed of the mine. The coal bed and the acidic tuff layer is members of the Bibai Formation. The sample from the Kushiro coal basin was taken from underground of the Kushiro Coal Mine. The coal bed is present in the Harutori Formation of the Urahoro Group. Analytical results show that age of the acidic tuff within the coal bed in the Bibai Formation is 43.52 ±0.41 Ma. The age of the acidic tuff in the coal bed of the Harutori Formation in Kushiro basin is 39.54 ±0.56 Ma. Katagiri et al. (2015) obtained 39.87 ±0.35 Ma from an acidic tuff in the Urahoro Group. Our result is slightly younger than the result of Katagiri et al. (2015), however those ages are identical within the analytical uncertainty. Present results show that the deposition of the coal bed in the Ishikari basin is 4 million years older than that in the Kushiro basin.

Katagiri, T., Naruse, H. and Hirata, T. (2015) Facies and depositional age of the Urahoro Group: implication to the Paleogene tectonics of the Hokkaido Island. Program and abstracts annual meeting of the Sedimentological Society of Japan. 39.

Keywords: Ishikari Coal Basin, Kushiro Coal Basin, SHRIMP zircon U-Pb age

Injection direction of a clastic dike inferred from magnetic measurements: an example from the Osa dike in central Japan

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The Osa dike is a 50–70 cm thick sandstone dike in an early Miocene sedimentary succession (named the Morozaki Group) on the Chita Peninsula, central Japan. An earlier investigation suggested that the dike formed by upward sand injection. However, a later study found microfossils from the dike, whose age could be younger than the country rock, implying downward injection. The present study was conducted to solve this problem by means of magnetic measurements. Thermomagnetic results indicate magnetite is the main magnetic mineral. Hysteresis data fall into the pseudo-single-domain range. Analyses of alternating field and thermal stepwise demagnetization results revealed a north-northeasterly paleodeclination of normal polarity characteristic remanent magnetization. The age of this paleodirection of the Osa dike is possibly younger than that of the easterly paleodirection of the Morozaki Group that represents early to middle Miocene clockwise rotation of southwestern Japan. More importantly, anisotropy of magnetic susceptibility (AMS) measurements suggest imbrication of magnetic foliations that is consistent with downward flow within the dike. Therefore, downward injection is supported by both the paleomagnetic direction and the AMS result. We suggest that magnetic measurements can be a useful tool for determining the injection direction of clastic dikes.

Keywords: anisotropy of magnetic susceptibility, clastic dike, Morozaki Group, paleomagnetism, rock magnetism

Paleostress analysis using Hough-transform based inversion method from slip data of mesoscale faults in the Dewa Hills, Akita

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Paleostress analysis was conducted using Hough-transform based inversion method (HIM; Sato, 2006) from slip data of mesoscale faults in the Dewa Hills, Akita, where both pre- and post-lift deposits are widely exposed. The Dewa Hills has been uplifting under E-W compression stress field since late Neogene, and shows a regional variety in deformation intensity and structure. Low angle faults with reverse sense are dominant in the Iwaki coastal area, where an intense shortening occurred showing N-S trending folds and thrusts associated with the activity of the Kitayuri thrust fault. Orientations of σ_1 and σ_3 are detected in E-W and nearly vertical, respectively. In the Toyokawa area at the hinge of the anticlinorium and the northeast part of the Dewa hills without intense deformation, high angle normal faults mainly occur. Stress states of relatively strong σ_1s in vertical and σ_3s diffused widely in NW-SE are obtained from the stress analyses. These are different from the regional stress field, and infer that mesoscale faults in these areas provide signals of later stage of uplifting. Under a limited influence of the regional stress state, the effect of equalization of crustal topography would be apparent. Normal faulting probably occurred resulted from the gravitational spreading (e.g., Ikeda and Yamaji, 2008) towards the structural low away from the high.

Keywords: Hough-transform, paleostress analysis, mesoscale fault, Dewa hills

Redefinition of stratigraphy from Pliocene to Pleistocene of drill core from Sendai Bay.

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We investigated stratigraphy and geological structure around Sendai Bay by geological survey, which included acoustic profiling and 80m drilling on the sea, in order to estimate the activity of NNW-SSE strike faults developed under the inversion tectonics. (Torigoe and Hashimoto, 2007)
Torigoe and Hashimoto (2007) defined five seismic stratigraphic units along seismic profiles: Unit A (Holocene), Unit B (Pleistocene), Unit C (Pliocene), Unit D (Miocene) and Unit E (acoustic basement; Pre-Neogene). They also recognized four lithostratigraphic units in the borehole drilled at the sea bottom of Sendai Bay: Unit A (0-5.17m; soft silt), Unit B (5.17-26.90m; silt or sand), Unit C-1 (26.90-51.13m; siltstone or sandstone) and Unit C-2 (51.13-78.75m; hard tuffaceous siltstone or sandstone). The core was examined by biostratigraphic (diatom and pollen) and tephrochronologic analyses. The lower part of Unit C-1 was placed in the diatom zone NPD8 of Yanagisawa and Akiba (1998) based on the existence of both *Neodenticula kamtschatica* and *N. koizumii*. The upper part of Unit C-1 was assigned to the zone NPD9 based on the presence of both *N. koizumii* and *N. seminae,* and Unit B was inferred to belong to the zone NPD10. No distinct tephra beds were found.
As for the boundary of Unit B / Unit C, comparing seismic stratigraphic and core lithostratigraphic units, although we recognized several meters difference between them: about 35m in seismic profile to about 27m in core, both almost showed good correspondence, consequently we defined the boundary of Unit B / Unit C of core (about 27m depth) as the boundary of Pliocene / Pleistocene boundary. However, there were some uncertainties in our previous diatom biostratigraphy due to extremely rare occurrence of marker species along with a current revision of Pliocene / Pleistocene boundary. In this study, we reevaluated the diatom biostratigraphy of the offshore core through reconsidering reworking of diatoms from older sediments. Furthermore, we established the tephrochronology by detecting cryptotephra in the core on the basis of mineral composition, index of refraction and principal component analysis.
As a result, we can assign the top of Unit C-2 (55m depth) to the zone NPD8, and the upper Unit C-1 (33m depth) to upper part of the zone NPD9 (2.2Ma), respectively. Moreover, we have detected five age-diagnostic tephra beds: Ata-Th (240ka) and O-Ik (240-270ka) at horizon 11m depth, Kkt (330-340ka) at 16m depth, TE-5 (350ka) 17m depth and Hap-2 (2.3Ma) at 31m depth.
These results suggest that the upper Unit C-1 (26 to 36 m) would be Gelacian in age, because of the presence of Hap-2 tephra (2.3Ma) at 31m depth and the occurrence of diatoms indicative to zone NPD9 at ca. 33 m depth. We therefore redefine the upper Unit C-1 as Unit B-2. This revised chronology leads to change of Pliocene / Pleistocene boundary from 27m to 36m depth. This horizon corresponds to the most remarkable reflection with truncation of lower sequence in seismic profile. This new redefinition can solve the discrepancy between profile and core in our previous evaluation.
Reference
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Keywords: Sendai Bay, Pliocene, Pleistocene, diatom, tephra

