論文内容の要旨

論文題目　**Crustal extension and shortening in the back-arc region of Northeast Japan**
（東北日本背弧域における地殻伸張と地殻水平短縮）

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Background and Objectives. There are a wide variety of subduction-related orogens in the world. One extreme is the Marianas type orogens, which are characterized by back-arc spreading; the other extreme is the Andean type orogens, which are characterized by a fold-and-thrust belt on the back-arc side. The Northeast Japan arc has changed from a Mariana-type orogen in Miocene time to an Andean-type orogen since Pliocene time to the present. Therefore, detailed studies on the tectonic evolution of the Northeast Japan arc, with the use of exceptionally dense observational data on it, would place an important constraint in understanding subduction-related orogeny in general.

It has been widely accepted that fore-arc deformation is important in the evolution of subduction-related orogens, and therefore a lot of previous studies have focused on the forearc. However, recent studies on the Andean Orogen have revealed that large horizontal shortening in the back-arc region plays an important role in thickening the crust beneath, and hence uplifting isostatically, the Andean Mountains. Deformation styles in back-arc regions are divided into two types: the thick-skinned type and the thin-skinned type. The most significant difference between these two types is in the amount of shortening; thin-skinned type deformation can result in a large amount of horizontal shortening, whereas thick-skinned type deformation causes much less shortening.

In Northeast Japan, these two types of deformation have never been distinguished clearly. We revealed in this study that the study area is divided into two tectonic domains; (1) the thin-skinned domain, including the Uetsu–Northern Fossa Magna basin and its seaward extensions, and (2) the thick-skinned domain, including the Sado Ridge and its northeast extension. We then demonstrate a potential role of Miocene extension structures, which have been inherited to, and have been reactivated to produce contractive deformation in the present-day Northeast Japan arc.

Faults Distribution in the Study Area. We reprocessed multi-channel seismic reflection data and gravity data that were obtained by the Japan National Oil Corporation (JNOC). We also used the single-channel seismic profiles that were obtained by the Advanced Industrial Science and Technology (AIST). Based on the interpretation of these seismic profiles, first we mapped faults and fault-related deformation; the following results were obtained: The faults in the north-northeastward extension of the Sado Ridge are mainly west-dipping, active, reverse faults, some of which clearly show tectonic inversion. The normal and reverse faults in the north-northeastward extension of the Sado Ridge have small amounts of slip during both the rifting stage and the post-inversion stage; the syn-faulting sedimentary unit associated with each fault is about 2 km at maximum. In contrast, the reverse faults in the seaward extension of the Uetsu–Northern Fossa Magna basin have much more amounts of slip. In this rift basin, a thick pile of Miocene sediments have been deformed into fault-bend folds and fault-propagation folds with large horizontal shortening since Pliocene time.

In terms of the nature, amplitude and distribution of the faults, we divided the study area into two tectonic domains: (1) the *thin-skinned domain*, which includes the Uetsu–Northern Fossa Magna basin and its seaward extensions, and (2) the *thick-skinned domain*, which includes the Sado Ridge and its northeast extension. In the former, we found such tectonic features that are reasonably explained by the presence of a detachment fault, upon which upper crustal layer can deform independently from the lower part of the lithosphere. That is why we use the term “thin skinned”. On the other hand, there is no indication of intra-crustal decoupling in the latter domain, which therefore is termed “thick skinned”.

Crustal Extension and Shortening in the Back-Arc Region. Then we examined the amounts crustal extension and shortening along four transects (A~D from north to south). We found tectonic features characteristic to thin-skinned domain; they are fault-bend folds, rotated fault blocks, isolated fault blocks, rollover anticlines, and breakaways.

In transect A extending from Line-09 to the Yokote basin, there exists a deep (~10 km) and wide (~40 km) basin filled with a thick pile of Miocene and younger sediments. Post-inversion structures in this transect include fault-bend folds within the rift basin, the Kitayuri Thrust Zone at the rift flank, and the Sen’ya Fault in the east. We reconstructed a pre-inversion cross-section by restoring thrust slip on faults in this transect. The total amount of horizontal shortening along the whole length of this transect was estimated by comparing the restored and present-day cross-sections, and is found to be 14.3 km. The pre-inversion cross-section thus reconstructed shows characteristic features of an asymmetric rift, including a rollover anticline on the east and a breakaway at the west. Then, we reconstructed a pre-rift cross-section by restoring normal slip on the detachment fault. The amount of extension during the Miocene rifting is estimated by comparing the post-rift (pre-inversion) and pre-rift cross-sections, and is found to be as large as 39-43 km.

In transect B along Line-14 off Murakami, we identified a series of dramatically rotated (17-33°) basement blocks bounded by normal faults, forming a rotated domino structure. Sediments on top of each block dip progressively steeper with increasing depth. Such strong rotation is best explained by deformation due to normal slip on listric faults, which are likely to sole onto a detachment fault at depth. In this transect, compressional deformation since Pliocene time is hardly identified. Therefore, we made a direct reconstruction of pre-rift geologic section from the present-day geologic section, without considering post-inversion deformation. Then, the amount of extension in Miocene time is estimated to be 10.7-12.5 km.

In transect C from Sado via Mt. Kakuda to the Niitsu anticline, we identified a wide rift basin, within which two isolated fault blocks exist. These isolated blocks show dramatically-strong rotation and hence were interpreted to have separated from the hanging wall during Miocene rifting. We also revealed post-inversion deformation, including 2.4 km of vertical displacement on the East Boundary Fault of Mt. Kakuda, and 5.8 km of shortening across the Niitsu Anticline. Total amount of shortening since Pliocene time and extension in Miocene time are estimated to be 8.2 km and 56 km, respectively.

In transect D from the Itoigawa-Shizuoka Tectonic Line (ISTL) via the Sai-gawa Hills to the Nagano Basin, again we identified a wide rift basin. Post-inversion deformation is concentrated near the both margins of the rift: At its east margin is the Western Boundary Fault Zone of the Nagano Basin, which is interpreted to be a back thrust that was formed on top of the rollover anticline bulldozing rift-fill. At the west margin are the ISTL and two subparallel faults, which are interpreted to merge downdip onto the reactivated detachment fault. By restoring the post-inversion deformation, the shortening since Pliocene time is estimated to be 7.3 km. The pre-inversion cross-section thus reconstructed shows characteristic features of an asymmetric rift, including a rollover anticline on the east and a breakaway on the west. The Miocene extension in this transect is estimated to be 30.9 km.

Conclusions. We demonstrated that, in terms of the nature, amplitude and distribution of faults, the back-arc region of Northeast Japan is divided into two tectonic domain: the *thin-skinned domain* and the *thick-skinned domain*. In the thin-skinned domain, a deep (~10 km) and wide (30-60 km) asymmetric rift basins were formed in Early–Middle Miocene time due to slip on low-angle detachment faults, the existence of which is evidenced by rollover anticlines, breakaways, and dramatically rotated isolated fault blocks. These rift basins in the thin-skinned domain were filled with a thick pile of sediments, which have subsequently been deformed into fault-bend folds and fault-propagation folds since Pliocene time. Although these structures kinematically require large slip on the causative faults, significantly large vertical offset does not exist across the Uetsu–Northern Fossa Magna basin since Pliocene time. This suggests that the causative faults of fold-and-thrust structure merge onto a low-angle detachment fault at depth. Thus we interpret that, after ~10 Myr of tectonic quiescence, the low-angle detachment fault beneath the Early to Middle Miocene rift basin has reactivated in Pliocene time; since that time, reverse slip on the reactivated detachment fault have resulted in the fold-and-thrust structure within the rift-fill sediments. By comparing the present and restored cross-sections, a large amount of shortening (10-15 km) in Pliocene to Quaternary time and a large amount of extension (30-60 km) in Early to Middle Miocene time were estimated across the Uetsu–Northern Fossa Magna basin. The total amount of the Pliocene-Quaternary shortening is much smaller than that of Miocene extension. Therefore, the present-day crustal necking observed beneath the back-arc region was caused principally by large Miocene extension.

The strains rates since Pliocene time derived from the four transects of this study are $1.2\sim2.3\times10^{-8}$ yr^{-1}, which are one order of magnitude smaller than geodetic strain rates (on an order of 10^{-7} yr^{-1}). This suggests that the rapid strain accumulation in the last ~100 years is mostly elastic, and would be released in association with a large decoupling event on the subduction zone; only a fraction (~10%) of the geodetically observed strain would accumulate within the arc on a geologic time scale.

Comparisons both in structure and evolution between the Northeast Japan arc and the Andean orogen suggest that the Northeast Japan arc can be viewed as an incipient analogue of the Andean orogen. We speculate that the present-day westward underthrusting of the continental lithosphere beneath the Andean Cordillera is inherited from the Mesozoic rifting, which could have been asymmetric and associated with crustal-scale detachment. Because the early stage of the Andean evolution has been obscured by subsequent strong convergence, the present study would make a significant contribution to understanding the Andean-type orogeny in general.