Timing and implications for the late Mesozoic geodynamic settings of eastern North China Craton: Evidences from K–Ar dating age and sedimentary–structural characteristics records of Lingshan Island, Shandong Province

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The Lingshan Island in Shandong Province in the eastern North China Craton, well known for the Late Mesozoic multi-scale slide-slump structures is related to paleo-earthquake. Terrigenous clastic rocks, volcanic clastic rocks and volcanic lavas are extensively exposed in the Lingshan Island and its adjacent regions of the Shandong Province, which led to fierce debates on their ages, sedimentary characteristics and tectono-sedimentary evolution. In this contribution, we present the characteristics of the Late Mesozoic stratigraphy in the Lingshan Island. Whole-rock K–Ar dating of dyke at Beilaishi and rhyolites at Laohuzui of the Lingshan Island yielded ages of 159 Ma and 106–92 Ma which coincides with the Laiyang Period rifting and the Qingshan Period rifting in the Jiaolai Basin, respectively. On the basis of the analysis to the Late Mesozoic sedimentary environment of ‘flysch’ and ‘molasse’-like formations as well as tectonic stress fields reconstruction, four episodes of the tectono-sedimentary evolution were established in the Lingshan Island and its adjacent regions in the eastern North China Craton. They consist of two episodes of extensional events for the syn-rift, and two episodes of compression events for the inversion of the post-rift. The entire episodes can be summarized as follows: (1) the first syn-rift NW–SE extension in Laiyang Period can be identified by the ‘flysch’ formation (Unit 1) and by emplacement of the NE-trending dyke in the Laiyang Group. This syn-rift episode can be related to the NW–SE post-orogenic extension resulted from the gravity collapse of the thickened lithosphere along the Sulu Orogen. (2) The first post-rift NW–SE inversion, which was caused by the NW-directed subduction of Izanagi Plate, can be well documented by the ‘X’ type conjugate joints as well as slide slump folds in Unit 1. (3) The second syn-rift NW–SE extension in Qingshan Period is characterized by rhyolite rocks (Unit 2). This syn-rift episode can be considered to be associated with lithospheric delamination of the thickened lithosphere in the eastern North China Craton. And finally, (4) the second post-rift NW–SE inversion which resulted from the subduction of the Pacific Plate under the eastern North China Craton in the NW direction at the end of the Qingshan Period is recorded by ‘molasse’-like formation (Unit 3).

Keywords. Lingshan Island; eastern North China Craton; Late Mesozoic; tectono-sedimentary evolution; stress field; geodynamic.

1. Introduction

During the Late Mesozoic, extensional activities were widespread in the eastern North China Craton. Integrated researches in most of the extensional tectonics have shown that the extensional setting is characterized by intracontinental rifts, within-plate volcanic eruptions, rifted basins and metamorphic core complexes (Wan and Zhu 1989; Gilder *et al.* 1991; Fan and Menzies 1992; Griffin *et al.* 1992; Menzies *et al.* 1993; Zheng *et al.* 1998; Ratschbacher *et al.* 2000; Ren *et al.* 2002; Lin and Wang 2006; Hou *et al.* 2003, 2010b; Hou and Hari 2014). The Lingshan Island and its adjacent regions belong to the Late Mesozoic rift system in Shandong Province, and its tectono-sedimentary evolution is closely consistent with the changes of stress field and geodynamic setting in the eastern North China Craton (Li *et al.* 2015; Zhou *et al.* 2015). Researches in this area and its sedimentary strata can provide valuable information on extensional tectonic evolution of eastern North China Craton in the Late Mesozoic.

Many stratigraphic, structural and geochronological studies have been carried out in the Lingshan Island and its adjacent regions due to the occurrence of Late Mesozoic multi-scale slide-slump structures (Lu *et al.* 2011; Zhong 2012; Zhang *et al.* 2013; Shao *et al.* 2014; Wang *et al.* 2014; Li *et al.* 2015; Zhou *et al.* 2015). Based on the analysis of the sequence of the sedimentary rocks which are represented by the multi-scale slide-slump structures, Lu *et al.* (2011) considered that these depositions may be a set of distal turbidites and recognized it as a reflection of a remnant ocean basin between the North China Craton (NCC) and South China Craton (SCC) in the Late Mesozoic. However, the observed lamination and imbrication by Shao *et al.* (2014) led them to propose that the deposits represented a shallow-water deposition system. Further, the poorly constrained age data of these deposits may add more controversy to this entire episode. Based on the analysis of sporopollen in the sedimentary rocks of the Lingshan Island, Lu *et al.* (2011) considered that the age of the deposits could be Jurassic. Whereas, the zircon U–Pb age given by Wang *et al.* (2014) could be Early Cretaceous. Even though, Zhou *et al.* (2015) and Li *et al.* (2015) systematically summarized the Late Mesozoic tectono-magmatic activities and the evolution of regional tectonic stress field, detailed tectono-sedimentary evolutionary process and geodynamic background still remain unclear.

Lack of precise geochronological data of this sequence of deposit and deficiencies in the analysis of tectono-sedimentary data, causes the disputes and hampers the advancement of the study on the mechanism of regional tectonic evolution. In this paper, we present the whole-rock K–Ar dating of the dyke, which was emplaced in this deposit successions and presume that it could constrain the sedimental age for the multi-scale slide-slump structures. Based on the recovery of the sedimentary environment from the ‘flysch’ and ‘molasse’-like formation as well as the regional structural stress fields analysis, the tectono-sedimentary evolution is also established. These results are important as these reveal the geodynamic evolutionary process of the eastern North China Craton during the Late Mesozoic.

2. Geological setting

2.1 Tectonic setting

The pear-shaped Lingshan Island, located in the Shandong Province (120°10′00″E, 35°45′48″N), eastern North China Craton (NCC) is situated roughly in the middle segment of the Sulu Orogen (figure 1a). Zhou *et al.* (2015) considered this island and its adjacent regions as part of the ‘Late Mesozoic offshore rift basin’ (gray colour in figure 1b), which is surrounded by uplifted structural belts such as Jiaonan uplift in the southwest and Qianliya uplift in the southeast, as well as, Jiaolai Basin in the northwest in the Shandong Province (figure 1b).

This island strikes in a NNE orientation, which is consistent with the orientation of its structural lines (e.g., mountain ridge, groove cast and fault scarps, etc.; Li *et al.* 2015) (figure 1c). Influenced by the Late Mesozoic regional tectonics, Lingshan Island was shaped as a cuesta-type island and its strata dips to NW (Luan *et al.* 2010). In the outcrop, NNE-trending volcanic-sedimentary strata were cut by a series of NWW-trending tensional faults and NNW to NEE-trending conjugate joints. These structural features restore the stress fields data and are helpful in reconstructing the tectono-sedimentary evolution of the island in the Late Mesozoic.

2.2 Late Mesozoic stratigraphy

In previous studies, only two units have been formally recognized in the Lingshan Island.

Figure 1. (a) Location and tectonic setting of Shandong Province, China (modified after Zhao *et al.* 2005). (b) Geological map of the Late Mesozoic offshore rift basin and interpreted profile of seismic line A-B in the Shandong Province (modified after Li *et al.* 2015; Zhou *et al.* 2015). (c) Geographical map of the Lingshan Island showing sample and field observation locations.

Figure 2. Stratigraphic column and sample locations on Lingshan Island. (a) Unit 1: interlayer of sophistication grain sizes with low maturation of texture at Laohuzui. (b and c) Unit 1: Flysh formation at Laohuzui. (d) Unit 2: rhyolite at Laohuzui. (e) Unit 3: Molasse formation at Laohuzui. (f) Unit 4: vocaniclastic breccia near Xiuchuanchang. For details of these locations, see figure 5.

Stratigraphic correlation shows that the units may correspond to the Laiyang Group (K_{1l}) and the Qingshan Group (K_{1q}) in the Jiaolai Basin of the eastern North China Craton (e.g., [Fourth Geological and Mineral Resources Survey of Shandong 2003](#)). Based on the field observations in the Lingshan Island, at least 4 units (1–4) (figure 2) are demarcated. Lithological features and age data of each unit are described as follows (for sampling and field observation locations, see figures 1 and 2;

laboratory procedures about the K–Ar dating; see ‘Appendix’).

Unit 1, mentioned as ‘flysh’ formation ([Lu et al. 2011](#)), is characterized by grayish sandstones and dark mudstones of variable thickness interbedded at graded intervals (figure 1c; figure 2a, b). The lithology is generally fine grained and the strata are highly continuous as well. Soft syn-sedimentary deformation structures (e.g., groove casts, load casts, sand sphere structures) are well developed

Table 1. Results of whole-rock K–Ar isotope dating in the Lingshan Island.

Sample ID	Rock type	Locations	Unit	Analyzed specimen	K(%)	Rad. ⁴⁰ Ar (10 ⁻⁸ ccSTP/g)	K–Ar age (Ma)	Non-rad. ⁴⁰ Ar(%)
Y1	Diorite-porphyrityte	Beilaishi	Unit 1	Whole-rock	1.32	0.038	158.96 ± 3.83	12.48
L5	Rhyolite	Laohuzui	Unit 2	Whole-rock	2.59	0.049	105.9 ± 1.77	12.87
L3	Rhyolite	Laohuzui	Unit 2	Whole-rock	2.92	0.0477	91.81 ± 1.59	14.11
L2	Rhyolite	Laohuzui	Unit 2	Whole-rock	2.98	0.0488	91.97 ± 1.76	14.88

*Remark: $\lambda = 5.543 \times 10^{-10}$ /year, $^{40}\text{K}/\sum \text{K} = 1.167 \times 10^{-4}$.

*The laboratory procedures about the K–Ar dating, see Appendix.

which displays the direction of the strata slide-slump.

This unit is generally considered similar to the Laiyang Group (K_{1l}) in the Jiaolai basin (Fourth Geological and Mineral Resources Survey of Shandong 2003). However, there are discrepancies that exist among the researchers regarding the age of this unit. On the basis of the analysis of sporopollen, Lu *et al.* (2011) regarded it as Middle Jurassic to Early Cretaceous which is different from its U–Pb ages of 138–121 Ma (Wang *et al.* 2014). Interestingly, we found a NE-trending tensile shear diorite-porphyrityte dyke (Y1) emplaced in the bottom of this unit at Beilaishi (figure 1c). Whole-rock K–Ar dating of this dyke (Y1) yielded ages of 159.0 ± 3.8 Ma (figure 2, table 1), which are in good agreement with the estimated age of the ‘flysch’ formation by the analysis of sporopollen (Lu *et al.* 2011). Therefore, it can be assumed that the age of the Unit 1 could range from Late Jurassic (K–Ar dating yielded age of the emplaced dyke: $\sim 159 \pm 3.8$ Ma) to Early Cretaceous (U–Pb age: 138–121 Ma) and can be correlated to the Laiyang Group in the Jiaolai Basin.

Unit 2 ranges in thickness from 5 to 20 m and consists of gray to white rhyolite that is in unconformable contact with the underlying Unit 1 (figure 1c; figure 2c, d; table 1). Whole-rock K–Ar dating of the rhyolites (L2, L3, L5) near Laohuzui in the Lingshan Island yielded ages of $105.9 \pm 1.8 \sim 92.0 \pm 1.8$ Ma. Unit 2 can be correlated well with the Qingshan Group in the Jiaolai Basin, as shown in figure 2.

Unit 3 consists of tuffaceous conglomerate, sandstone and mudstone, interbedded at graded intervals. This unit reveals the rapid sedimentary depositional environment with variable grain sizes and low maturation. These rapid sedimentary characteristics could be ‘molasse’-like deposits. A slump body of this unit, typically near Xiuchuanchang

in the Lingshan Island was found (figure 1c; figure 2e).

Unit 4, uppermost unit, consists of thick volcanic-clastic breccia and volcanic lava (figures 1c, 2f).

3. Late Mesozoic sedimentary-structural characteristics

Soft-sedimentary characteristics generally reflect the direction of material movement and sedimentary environment, whereas the structural characteristics reveal the transitions of the regional stress fields. Study of the sedimentary-structural characteristics of Lingshan Island and its adjacent regions is important for prototype basin restorations and regional stress field evolution analysis.

3.1 Sedimentary characteristic analysis

There are four sets of sedimentary units in the Lingshan Island as mentioned above: Unit 1: ‘flysch’ formation; Unit 2: rhyolite rocks; Unit 3: ‘molasse’-like deposits; and Unit 4: volcanic lava cap (figures 1c and 2). Using the analysis on the tectonic background and genesis of volcanic formations, we can infer that Unit 2 and 4 were formed by volcanic activities on the rift tectonic background in the Late Mesozoic (Ren *et al.* 2002; Zhu *et al.* 2012). It is obvious that the sequence of these two units suggest a tectono-thermal regime in an extensional setting. Here, we choose Unit 1 (‘flysch’ formation) and Unit 3 (‘molasse’-like formation) for discussion in detail on its sedimentary facies and tectonic significances.

3.1.1 ‘Flysch’ formation and soft-sedimentary deformation structures in Unit 1

Soft-sedimentary deformation structures are well developed in 4–5 deformed layers of Unit 1 ‘flysch’

Figure 3. Characteristics of sediments and deformation structures in Unit 1 with slide slump folds related to paleo-earthquake (modified after Ge *et al.* 2015). (a) Recumbent fold in Laohuzui; (b) pebbled sandstone interlayer; and (c) convolute fold at Xiuchuanchang. With the progressive shearing in the direction of SE–NW, slide slump folds evolved from recumbent fold to convolute fold.

formation, such as slide-slump folds, convolution structures and boudinages (figures 2 and 3). By analyzing the distribution characteristics and formation episodes of sedimentary deformation structures in the slide slump folds, Wang *et al.* (2013) considered that most of those deformation structures were earthquake-induced structures triggered by losing stability of soft sediments in topography from SE to NW. With the progressive shearing in the direction of SE to NW, slide slump folds evolved from recumbent fold to convolute fold (figure 3), which can be inferred from the change in topography resulted by the NW–SE compression in this episode.

According to analysis of this ‘flysch’ deposit successions, Lu *et al.* (2011) considered the deposits to be a set of distal turbidites related to a remnant ocean basin between the North China Craton (NCC) and South China Craton (SCC) in Late Mesozoic. However, the observed lamination and imbrication by Zhong (2012) and Shao *et al.* (2014) lead them to propose that

the deposits represent a shallow-water depositional system.

It is important to note that a set of 6–10 m thick pebbled sandstone interlayer in unit 1 indicate rapid deposition as these exhibit variable grain sizes and low maturation (figures 2a, 3a, b). The pebbled sandstone interlayer together with imbricate structure (Shao *et al.* 2014) shows that Unit 1 is related to Laiyang Group in the Lingshan Island and are deposited in an inland, shallow-water environment, such as a delta, and not in a deep-water or submarine continental-slop environment.

3.1.2 ‘Molasse’-like formation in Unit 3

‘Molasse’-like formation is a sedimentary assemblage, which is characteristic of clastic sediments and rapid accumulation on the front of mountain mass and represents the late stage of the foreland basin sedimentation (Rigassi 1977; Sinclair 1997).

Figure 4. Characteristics sediments and deformation structures in Unit 3 near Xiuchuanchang in Lingshan Island.

Unit 3, which consists of 50 m-thick interbedded tuffaceous conglomerate, sandstone and mudstone can be considered as a ‘molasse’-like formation, which is having unconformable contact with underlying Unit 2 (Qingshan Group).

A slump body from Unit 3 near Xiuchuanchang in the Lingshan Island reflects the typically rapid accumulation (figures 1c, 2e, 4). Massive conglomerates contacting gravels of metamorphic rocks (such as quartzite and gneiss), volcanic rocks (such as rhyolite) and sedimentary rocks (such as mud gravel) characterize this slump body. The gravels are in the size of 1–15 cm and sub-angular to sub-rounded, with a poor sorting. Interstitial materials are gray feldspathic siltstone (figure 4). These textural characteristics suggest that conglomerates were formed by rapid accumulation in a proximal, intensely oxidized environment, including non-marine environment. Furthermore, the ‘molasse’-like formation could not be real molasse.

It could have been formed in post-rift episode as rapid accumulation instead of foreland basin.

The sedimentary facies changing from ‘flysch’ formation (Unit 1) to ‘molasse’-like formation (Unit 3) implicates that the Lingshan Island and its adjacent regions were developed from an unfilled basin to a filled/overfilled basin in the Late Mesozoic. The former fan delta environment became shallow water, forming a shallow river or lake-fan delta sedimentary system. Meanwhile, there should be two episodes of syn-rift shown by ‘flysch’ formation (Unit 1) and rhyolite rocks (Unit 2), then subsequently, the post-rift episode in an inversion stress field shown by ‘molasse’-like formation (Unit 3).

3.2 Structural characteristic analysis

The joints and dykes (emplaced joints) are major structures in the Lingshan Island. The tectonic

Table 2. Statistical information of Lingshan Island structural deformation elements.

Sample ID	Locations	Unit	Num.	Average occurrence	Rock type
'X' type conjugate joints					
Series 1	35°45'33"N, 120°09'24"E	Unit 1	166	275°∠64°	Flysch
Series 2	35°45'33"N, 120°09'24"E	Unit 1	166	30°∠81°	Flysch
Folds					
Fold A	35°45'33"N, 120°09'24"E	Unit 1	20	Limbs: 123°∠18°, 150°∠24°	Flysch
Fold B	35°45'33"N, 120°09'24"E	Unit 1	20	Limbs: 107°∠23°, 150°∠24°	Flysch
Dyke					
Y1	35°47'03"N, 120°10'31"E	Unit 1	4	Trending: 50°	Diorite-porphryrite
Y2	35°23'47"N, 119°33'33"E	K	Zhou <i>et al.</i> (2015)	Trending: 45°	Diorite
Y3	36°33'39"N, 120°57'11"E	K	Zhou <i>et al.</i> (2015)	Trending: 48°	Diorite
Y4	35°48'24"N, 121°09'10"E	K	Zhou <i>et al.</i> (2015)	Trending: 40°	Diorite

events could be reconstructed by the structural characteristic analysis of observed data, such as faults, folds, conjugate joints and dykes (Delvaux and Sperner 2003; Hou *et al.* 2005, 2006, 2010a; Ju *et al.* 2012).

In the field of the Lingshan Island, we measured data from folds (at Xiuchuanhang), dyke (at Beilaishi) and 'X' type conjugate joints (at Xiuchuanhang and Beilaishi), mainly in Unit 1 (Li *et al.* 2015) (table 2; figure 5). β analysis of the fold limbs can provide an average estimate of the trends of the axial plane and limbs, which further can indicate the orientations of the horizontal maximum principal compressive stress. Rose diagram and joint isodensity diagram using a rotational optimization method (Delvaux and Sperner 2003), to obtain the orientations of horizontal maximum principal compressive stress (σ_1) (figure 5) were applied.

According to the measurement and analysis above, we considered that the orientations of horizontal maximum principal compressive stress (σ_1) could be near NW–SE over the Late Mesozoic (figure 5). Two episodes of stress fields can be reconstructed by the structural analysis. The whole-rock K–Ar age of 159.0 ± 3.8 Ma yielded for the NE-trending dyke emplaced in the Laiyang Group at Beilaishi of Lingshan Island indicates that the early offshore rifting and coeval dykes were developed in the NW–SE extension regime in Laiyang Period (figure 5). A series of 'X' type conjugate joints in the Laiyang Group and Qingshan Group may suggest that there was a NW–SE compression after Laiyang Period rifting in the Lingshan Island (figure 5).

4. Late Mesozoic evolution and its tectonic implication

In conjunction with the previous analysis on the Late Mesozoic sedimentary environment of 'flysch' and 'molasse'-like formations as well as on the basis of the tectonic stress fields reconstruction, four episodes of the tectono-sedimentary evolution can be established in the Lingshan Island and its adjacent regions in the eastern North China Craton, which resulted from the two episodes of extension events for the syn-rift and two episodes of compression events for the late inversion of the post-rift (figure 6). Two sets of sedimentary sequences formed in these two tectonic extension events, include Unit 1 'flysch' formation, which was accumulated in the offshore rift in the Laiyang Period and Unit 2 rhyolite rocks, which was extruded in the rift in the Qingshan Period. These two extensional episodes (syn-rift episodes) correspond to the two episodes of rifting time of eastern North China Craton. Meanwhile, two tectonic compression episodes (post-rift episodes) could be observed in 'X' type conjugate joints and Unit 3 'molasse'-like formation corresponding to the inversion after each rifting.

The two episodes of rifting with NW–SE extension may be related to post-orogeny of Sulu Orogen and subduction of the Izanagi Plate in Late Mesozoic, respectively (Engelbreton *et al.* 1985; Maruyama *et al.* 1997; Ratschbacher *et al.* 2000; Cottrell and Tarduno 2003; Liu *et al.* 2004; Wan *et al.* 2005; Wu *et al.* 2005; Isozaki *et al.* 2010; Li *et al.* 2016). The details of these two rifting episodes can be summarized as follows.

Figure 5. Structural deformation stress analysis in the Lingshan Island NW-SE extension in the syn-rift episode; NW-SE compression in the post-rift episode.

(1) First syn-rift episode (extension): earlier Early Cretaceous (Laiyang Period)
To the east of Tan-Lu fault zone, the NE-trending Laiyang Group in the Jiaolai basin, emplacement of NE-trending dyke and deposition of Unit 1 ('flysch' formation interbedded with conglomerates) in the Lingshan Island

and its adjacent regions indicate NW-SE extension and rift characteristics.
Considering that the Late Mesozoic rift basins (Jiaolai Basin and Lingshan Island Graben) were developed close to the Sulu Orogen, which is characterized as Late Mesozoic extension indicated by the ductile shear zone

Figure 6. Late Mesozoic tectono-sedimentary evolution and dynamics of eastern NCC.

(Zhang *et al.* 1997), it can be concluded that there was NW–SE post-orogenic extension by the gravity collapse of the thickened lithosphere along the Sulu Orogen (Zhang *et al.* 2008). The syn-rift NE-trending structures in Shandong Province (e.g., the Late Mesozoic offshore rift basin, dykes and sedimentary depocenters of Laiyang Group) (Zhu *et al.* 2012; Zhou *et al.* 2015) could be related to the post-orogenic event.

(2) First post-rift episode (inversion): at the end of earlier Early Cretaceous (at end of Laiyang Period)

At the end of later Early Cretaceous (Laiyang Period), the driving mechanism for eastern North China Craton was still in the transmission of the NS-directed collision between the NCC and SCC to the NW-directed subduction of Izanagi Plate (figures 6 and 7). The

NW–SE compression lead to the tilted topography of Lingshan Island from SE to NW, and it was well documented in the ‘X’ type conjugate joints as well as slide slump folds in Unit 1. These evidences suggest that the Lingshan Island and its adjacent regions turned into the post-rift episode in an inversion stress field at the end of Laiyang Period.

(3) Second syn-rift episode (extension): later Early Cretaceous (Qingshan Period)

Widespread volcanism occurred all along the NE-trending Tan-Lu fault zone with the intrusion of mafic to ultramafic into the rift basins indicating strong crustal extensional environment. These NW–SE extensional events might have occurred between 120 and 91 Ma, which can be evidenced from the available K–Ar and Ar–Ar dating of the volcanic rocks (table 1; Yan *et al.* 2003; Zhang *et al.* 2003; Zhou *et al.*

Figure 7. A sketch map showing dynamic motion evolution in eastern NCC from Early Mesozoic. (a) Early Mesozoic Sulu Orogeny: NW–SE collision along Sulu Orogen between the NCC and SCC; (b) early Late Mesozoic NW–SE post-orogenic extension: NE-trending rifts (Lingshan Island and Jiaolai rifts) related to NW-directed subduction of Izanaqi Plate at a rate of 20.7 cm/y (Maruyama *et al.* 1997); and (c) later Late Mesozoic NW–SE compression: inversion after rifting related to NW-directed subduction of Pacific Plate at a rate of 13.1 cm/y (Maruyama *et al.* 1997).

2015). The geodynamic of this episode was considered to be associated with lithospheric delamination of the thickened lithosphere in the eastern North China Craton (figure 6) (Zhang *et al.* 2003, 2008). At this time, Jiaolai basin and Late Mesozoic offshore rift basin in Shandong Province turned into rifting background, lots of rhyolite rocks (Unit 2) and dykes (Liu *et al.* 2004) had resulted from the NW–SE extension.

- (4) Second post-rift episode (inversion): at the end of the later Early Cretaceous (at end of Qingshan Period)

By the end of the later Early Cretaceous (Qingshan Period), the Izanaqi Plate moved northward to the northeast edge of East Asia due to the motion direction changing from NW to ~N (Engelbreton *et al.* 1985; Cottrell and Tarduno 2003; Maruyama *et al.* 1997; Isozaki *et al.* 2010). Meanwhile, the Pacific plate subducted under the eastern North China Craton in NW direction (figures 6, 7). With the uplifting and erosion, a set of massive conglomerate (Unit 3) were developed in the Jiaolai Basin as well as the Late Mesozoic offshore rift basin (i.e., Lingshan Island and its adjacent regions) in the Shandong Province. This indicates that Lingshan Island experienced post-rift process at the end of Qingshan episode.

In the eastern North China Craton (including Lingshan Island and its adjacent regions), the pulse-type evolutionary processes of the tectonic

stress fields and sedimentary systems might have resulted from the alternated effects of the post-orogenic extension in Sulu Orogen and the subduction motions of Izanaqi Plate and Pacific Plate (figures 6 and 7).

5. Conclusions

Whole-rock K–Ar dating of dyke at Beilaishi and rhyolites at Laohuzui yielded ages of 159.0 ± 3.8 Ma and $105.9 \pm 1.8 \sim 92.0 \pm 1.8$ Ma, which coincides with the Laiyang Period rifting and the Qingshan Period rifting in the Jiaolai Basin.

Analyses from the sedimentary–structural characteristics of Lingshan Island and its adjacent regions suggest that the eastern North China Craton underwent alternate extension and inversion during the Late Mesozoic. The Late Mesozoic extension of Lingshan Island and its adjacent regions in eastern North China Craton experienced two episodes of syn-rift NW–SE extensions in Laiyang and Qingshan Periods, which was followed by a post-rift NW–SE inversion at the end of each syn-rift extensions. The entire episodes can be summarized as follows:

- 1) The first syn-rift NW–SE extension in Laiyang Period can be identified by the ‘flysch’ formation (Unit 1) and by emplacement of the NE-trending dyke in the Laiyang Group. This syn-rift episode can be related to the NW–SE post-orogenic extension resulted from the gravity collapse of the thickened lithosphere along the Sulu Orogen.

- 2) The first post-rift NW–SE inversion, which was caused by the NW-directed subduction of Izu Plate, can be well documented by the ‘X’ type conjugate joints as well as the slide slump folds in Unit 1.
- 3) The second syn-rift NW–SE extension in Qingshan Period is characterized by rhyolite rocks (Unit 2). This syn-rift episode can be considered to be associated with lithospheric delamination of the thickened lithosphere in the eastern North China Craton.
- 4) The second post-rift NW–SE inversion that resulted from the subduction of the Pacific Plate under the eastern North China Craton in NW direction at the end of Qingshan Period is recorded by ‘molasse’-like formation (Unit 3).

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Appendix

A1. Sample preparation and analytical procedure for K–Ar

Four ‘fresh’ hornblende and biotite-bearing samples suitable for K–Ar dating were taken from surface outcrop at four sites in Lingshan Island. Sample locations are shown in figure 2. Dated specimens include diorite-porphyrity dyke and rhyolite whole rocks. These rocks were crushed with a rotary mill and sieved, and the 60–80 mesh size fraction was retained for pre-processing. The sieved fraction was washed ultrasonically in distilled water to exclude powder residue, and then dried in an oven (50°C).

Potassium was analyzed by flame photometry using a 2000 ppm Cs buffer (Nagao and Itaya 1988; Itaya 1991). The multiple runs of geochemical standards reference samples ZBH-25 and TC-18 showed that accuracy and reproducibility were with 2%. Argon was analyzed by isotope dilution at Key Laboratory of Orogenic Belts and Crustal Evolution (Peking University) using a 15 cm radius sector type mass spectrometer with

a single collector system (VSS-RGA-10). Mass discrimination was atmospheric argon several times each day. Physical constants used in the calculation of K–Ar ages are $\lambda = 5.543 \times 10^{-10} \text{yr}^{-1}$, $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$ (Steiger and Jäger 1977).

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