Advances in tectonic genesis of Nadanhada terrane

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Abstract. The Nadanhada terrain is the most typical terrain in Northeast China. It is located on the West Bank of the Wusuli River in the east of Heilongjiang Province. The division of tectonic units in Nadanhada area includes five stages: geosynclinal fold zone, Mesozoic subduction zone around the Pacific Ocean, back-arc marginal sea, orogenic belt and terrain formed by the closure of forearc basin, and so on. During the Mesozoic, the northeastern China was affected by the Mongolia-Okhotsk Ocean closure and the subduction of the Paleo-Pacific Ocean, and a large-scale tectono-magmatic activity took place. At the same time, the Nadanhada terrane drifted from low latitudes and eventually grew on the eastern side of the Jiamusi massif. Therefore, the Nadanhada terrane was formed in an oceanic environment. During the Mesozoic, it was situated on the continental margin of East Asia and formed terrigenous turbidite at the trench. At the same time, it underwent continuous subduction and local accretion, and finally formed a complete sedimentary sequence including oceanic siliceous rocks and terrigenous melanges. The direction of the tectonic line of the Nadanhada terrane changes from north to south, from NNE to NNW, and then to NW, showing an arc structure protruding westward. The direction of the present tectonic line can not represent the direction of its formation. It is the direction after the transformation of Dunmi fault left-lateral strike-slip activity and Sikhot-Alin region whole rotation.

1. Regional situation

The Nadanhada terrane is the most typical terrane in Northeast China. It is located on the West Bank of the Wusuli River in the east of Heilongjiang Province. It is an important metallogenic area for precious and non-ferrous metals. The Nadanhada terrane is 160 km long and 60 km wide, showing an arc-shaped tectonic belt in NNE direction. The terrane is adjacent to Jiamusi block in the west, Xingkai block in the South and Bijin terrane in the east across the river in Russia. It is an important part of Sikhot-Alin accretionary complex belt.

The geographical coordinates of Nadanhada area are 133°00′E~134°13E, 46°10′N~47°15′. The area is rich in vegetation, poor visibility, serious residual slope and quaternary coverage, and the natural environment has created certain obstacles to geological survey. However, the area has convenient transportation, roads and lanes crisscross, continuous construction traces and abandoned quarries are exposed along the roadside, and the existence of silica rocks is found in the field geological survey.
2. Advances of Regional Tectonic

Based on plate theory, some people have tried to divide the tectonic units of Nadanhada area. So far, they have mainly experienced the following understandings:

(1) Ground fold zone: In the mid-20th century, the Sino-Soviet Geological Survey Project discovered Mesozoic radiolarian fossils in the Ussuri area, which suggested that the Nadanhada area was a Mesozoic geosynclinal fold zone; Li Wenkang recognized Carboniferous-Permian coral and dragonfly fossils in limestone blocks and classified the Nadanhada area as late Paleozoic geosyncline fold belt [4]; Huang Jiqing thinks that Nadanhada area is a Mesozoic geosyncline area on the Variscan fold basement.

(2) Circum-Pacific Mesozoic Subduction Zone: In 1982, Li Chunyu defined the Nadanhada area as Circum-Pacific Mesozoic Subduction Zone by using the theory of plate tectonics.

(3) Back-arc marginal sea: Yang Bingzhong considered that the Nadanhada area was a back-arc marginal sea from Late Triassic to Early Jurassic in 1982.

(4) Orogenic belts formed by the closure of pre-arc basins: Zhang Chuanheng and Zhang Shihong in 1999 considered that the Triassic-Jurassic siliceous rock-clastic rock series constituted the main body of the Nadanhada area, in which the sandstone framework grain composition was the same as that of the typical pre-arc basin. Therefore, the Nadanhada area was defined as formed by the closure of the pre-arc basin. Orogenic belt [8].

(5) Terrain: In 1986, Mizutani considered the Nadanhada area to be an exotic terrain based on paleomagnetic data and radiolarian fossils. Because of the abundant evidence, "terrain theory" has been accepted by more and more scholars.

3. Advances in Geogenesis

Northeast China, located in the eastern part of the Central Asian orogenic belt, encloses the convergence area of the Pacific, Siberian and North China plates, and is a superimposed orogenic belt formed by multiple interactions. This area is a unified landmass formed by collision and combination of several micro-blocks and Nadanhada terrane with exotic characteristics. During the Paleozoic, the Northeast China experienced the superimposition and transformation of the Paleo-Asian Ocean tectonic system. The Jiamusi, Xingkai, Xingan, Songnen and Erguna blocks collided to form a unified landmass, and then joined with the North China and Siberia plates [12]. During the Mesozoic, the northeastern region was affected by the Mongolia-Okhotsk Ocean closure and the subduction of the Paleo-Pacific Ocean, and a large-scale tectono-magmatic activity took place. At the same time, the Nadanhada terrane drifted from low latitude and eventually proliferated on the eastern side of the Jiamusi massif [13].

The Nadanhada terrain is located in Raohe County in the eastern part of Heilongjiang Province. It is adjacent to the Jiamusi massif in the west, Xingkai massif in the South and Bijin massif in the Sikhote Alin region in Russia in the east. The Bijin terrane in the East is similar to the Nadanhada terrane in terms of stratigraphic palaeontological assemblage, lithofacies and tectonic characteristics, and other adjacent blocks are quite different from it. Because of its geographical proximity and similar attributes, the Nadanhada terrane and the Bijin terrane are often collectively called the Nadanhada-Bijin terrane, which belong to the part of the Sikhot-Alin accretionary complex belt [14]. Current studies suggest that the Nadanhada terrane was formed in an oceanic environment and was located on the continental margin of East Asia during the Mesozoic, forming terrigenous turbidite at the trench, subducting continuously and accreting locally, and finally forming a complete sedimentary sequence including oceanic siliceous rocks and terrigenous melanges.
3.1. Horizontal structures are arc-shaped and the melanges and folds overlap each other

3.1.1. The direction of tectonic line of terrane is changing from north to south, from NNE to NNW, and then to NW, showing an arc structure protruding westward as a whole. The reason for the arc distribution of terrane structural lines is that in the early Cretaceous, the Izanagi plate obliquely subducted to the continental margin of East Asia, resulting in the Tan-Lu fault entering a strike-slip period, and the Dunmi fault (an important branch fault in the northern part of the Tan-Lu fault) in the southern part of the Nadanhada terrane took place a large-scale sinistral strike-slip activity [15], with a strong strike-slip effect. The direction of the structural line in different areas of the Nadanhada terrane has been affected to varying degrees: the southern part of the terrane is close to the Dunmi fault, and the strike-slip effect is the most obvious. The original NNE-trending structural line (the direction of the structural line before the structural reset, the same below) is dragged counterclockwise into the NW-trending; the middle part of the terrane is a little farther from the Dunmi fault, and is affected by the strike-slip effect. The influence of strike-slip is weakened, and the strike-slip only makes the NNE trending structural line rotate to NNW trending; the north of the terrane is far from the Dunmi fault, and the effect of strike-slip is very weak, and the NNE trending structural line formed during the process of accretion can be retained. Therefore, under the action of the above stress field, an arc-shaped structural line is formed.

The accretion process of Nadanhada terrane mainly occurred in the late Jurassic. Because the subduction direction of Izanagi plate obliquely intersects with the NE-trending continental margin of East Asia [16], the NW-trending principal compressive stress will be decomposed and the NE-trending tectonic line will be formed. However, the overall contour of terrestrial tectonic lines is NNE, which is obviously not consistent with the NE direction formed during accretion. Therefore, the author believes that the contour direction of the present tectonic line does not represent the direction of the tectonic line at the time of the formation of the accretionary complex, and the terrane has undergone important tectonic event transformation again after the accretion. Paleomagnetic data show that after the end of the Late Cretaceous, the anticlockwise rotation of the Sikhot-Alin region in Russia relative to the Eurasian continent occurred about (20.5° ± 17.7° ~41° ± 16°), and the Nadanhada terrane also occurred anticlockwise rotation. Based on this, the authors reconstructed the direction of the structural line of the Nadanhada terrane in the late Jurassic, and clockwise rotated the NNE to the overall contour (20.5°±17.7°~41±16°), and obtained the NE-trending structural line. The orientation of the structural line after the restoration coincides with that of the late Jurassic Nadanhada terrane.

To sum up, the direction of the present tectonic line does not represent the direction of the tectonic line at the time of the formation of the accretionary complex, and the terrane has undergone two major tectonic reforms after the end of accretion. At the beginning of early Cretaceous, the sinistral strike-slip movement of Dunmi fault in the south of the terrane resulted in the local anticlockwise rotation of the terrane, bending the terrane structural line into an arc; after the end of Late Cretaceous, the terrane rotated counterclockwise with the Sikhot-Alin area, and finally formed the present contour of the structural line[3].

Figure 1. Model Map of Structural Line Profile Formation of Nadanhada Terrane
a. When the Nadanhada terrane accretes to the continental margin of East Asia, NE-trending tectonic lines are formed. b. Strike-slip action changes the direction of tectonic lines in different areas of terrain to varying degrees, resulting in the curved structure lines. c. The Nadanhada terrane rotates counterclockwise with the Sikhot-Alin region, forming the present structural line direction.

3.1.2. In the southern part of the terrane, there are two sets of structural lines in NW and NE directions. Melanges, thrust faults and folds in different directions superimpose each other. In the OPHIOLITIC MELANGE belt in Dongshan, Hongzhou, East China, the NE-trending thrust faults cut NW-trending structural lines, and in the siliceous rock belt near 52km of the S 211 line, NE-trending folds superimposed on NW-trending folds. This indicates that the southern terrace experienced two different compressive activities in different directions, and the formation age of NE-trending tectonic line is later than NW-trending tectonic line.

The first stage of extrusion occurs in the process of terrestrial growth. In the Middle and Late Jurassic, the Izanagi plate subducted to N at high speed [17]. Because the subduction direction intersected obliquely with the continental margin of East Asia, the NW-trending compressive stress was decomposed, resulting in a NE-trending fault-fold zone. In the early Cretaceous, the southern part of the terrane was dragged by the left-lateral strike-slip of the Dunmi fault, and the tectonic line rotated counter-clockwise. In the Sikhot-Alin region, counter-clockwise rotation occurred as a whole, and the southern part of the terrain rotated counter-clockwise again. The tectonic line in the southern part of the terrane undergoes two counter-clockwise rotations, and eventually turns from NE to NW.

The second stage of extrusion occurs after the end of the proliferative process. Near the boundary between Nadanhada terrane and Xingkai massif, the NE-trending structures (ophiolitic melange, argillaceous melange, thrust nappe fault and fold axis) cut NW-trending structural lines. The NE-trending structure is nearly EW-trending after the clockwise rotation and reduction mentioned above, so it can be inferred that near SN-trending strong compression occurred between the Nadanhada terrane and the Xingkai terrane after the end of the accretion process. The Nadanhada terrane and Xingkai massif are two geological bodies with completely different tectonic attributes. Previous comparative studies have often focused on the differences between them, such as paleontological assemblages, lithofacies characteristics and tectonic evolution history. However, the understanding of the relationship between them is still unclear [18].

In the Middle and Late Jurassic, the Nadanhada terrane accretion and collage to the Jiamusi massif. At this time, there may be a residual oceanic basin between the Nadanhada terrane and the Xingkai massif, but there is no compression between the terrane and the Xingkai massif. At the turn of Jurassic and Cretaceous, the accretion of the Nadanhada terrane to the Jiamusi massif ended. In the middle of Early Cretaceous, the residual oceanic basin between the Xingkai block and the Nadanhada terrane was closed, and both of them were strongly compressed in the near SN direction. Therefore, near the contact zone between the Nadanhada terrane and the Xingkai terrane, EW-trending melanges, thrust nappe faults and superimposed folds were formed. Later, they were counterclockwise rotated and eventually transformed into today's NE. In the direction of the tectonic line. The paleomagnetic data of predecessors also support our interpretation. Sun Ge made paleomagnetic measurements of the Middle East Anzhen Formation in the complex belt, and found that the paleomagnetic poles and paleogeographic latitudes of the upper and lower Donganzhen Formation are obviously different [19]. The paleomagnetic poles of the lower subgroup rocks (upper part of the Upper Jurassic) are 208.5° E, 51.2° N, and the paleogeographic latitude is 43.5 degrees N. The paleomagnetic poles of the upper subgroup rocks (lower part of the Lower Cretaceous) are 175.0° E, 42.2° N, and the paleogeographic latitude is 61.0° N. The paleogeographic latitudes of the upper and lower subformations of the Donganzhen Formation are obviously different, reflecting the northward migration of the Nadanhada terrane during this period. By the middle of Early Cretaceous, the residual oceanic basin between the terrane and the Xingkai massif was completely closed, and the Nadanhada terrane was subjected to intense compression from south to North during this period.
3.2. Sectional genetic anatomy
The Nadanhada terrane is strongly deformed. The secondary folds are mainly tight-synclinal folds, which can not extend to the deep underground. They belong to the typical detachment folds. The folding will disappear at a certain depth, and there may be a large detachment surface between them and the underlying basement. Liu Guoxing and Liu Cai have made two-dimensional inversion of several magnetotelluric sounding profiles across Jiamusi and Nadanhada terranes, and obtained the electrical structure characteristics of these two areas: the lithosphere of Jiamusi block is a uniform and stable high resistivity area; the resistivity is near the boundary zone between Jiamusi block and Nadanhada terrane. The steeper electrical boundary at the gradient zone may represent the Yuejinshan fault; the shallow part of the Nadanhada terrane is a thin layer (about 2 km thick) with resistivity of 1-10 p/omega m, and the lower part is a structure between high resistivity blocks and low resistivity bands, which is completely different from the stable high resistivity characteristics of the Jiamusi terrane. The author considers that the low conductivity thin layer is the geophysical response of tectonic slices, and the bottom boundary represents the boundary between the overlying tectonic slices and the underlying original foundation, that is, the large detachment surface of the detachment fold mentioned above. Therefore, we infer that the original foundation of the Jiamusi block is below the detachment surface in the depth of the Nadanhada terrane. However, more direct geological evidence is needed to confirm this conjecture, which will benefit both high-precision seismic observation and deep geological drilling in the future.

A large number of NNE-striking faults in the Nadanhada terrane divide the accretive complex into a series of parallel structural slices, which are thrusting and overlapping in turn, forming a large complex imbricated fault zone vertically, and the Yuejinshan fault corresponds to its front zone. The thrust direction of the large thrust faults which constitute the boundary of tectonic schist points to the Jiamusi massif as a whole. The dip angle of the fault plane is large in the shallow part, local upright or even reversed. The dip angle gradually slows down in the deep part, and finally converges to the near-horizontal detachment surface at a certain depth with the detachment fold. The detachment surface is the most important geological boundary in the vertical structure of Nadanhada terrane, which divides the upper exotic complex and the lower original foundation, and restricts the whole process of terrane growth. The imbricated fault zone above the detachment surface, the original foundation under the detachment surface and the Benioff zone below the base constitute a "three-layer structure" vertically.

4. Conclusion
The direction of the tectonic line of the Nadanhada terrane changes from north to south, from NNE to NNW, and then to NW, showing an arc structure protruding westward. The direction of the present tectonic line can not represent the direction of its formation. It is the direction after the transformation of Dunmi fault left-lateral strike-slip activity and Sikhote-Alin region whole rotation.

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