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Geologic evolution of the Neimonides: A Working Hypothesis

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ABSTRACT

The late Precambrian and Paleozoic rocks of Inner Mongolia constitute an orogenic system, which is called Neimonides, an anglicized Chinese abbreviation for "the mountains of Inner Mongolia". We present a working hypothesis that this mountain range has been formed by ocean-continent and continent-continent interactions, leading to continental collision during the Permian period. Our plate-tectonic model suggests that mountain ranges of the collision-type consist of three elements, or tectono-stratigraphic facies, namely: (1) the sedimentary "thin-skin" and its basement of the underthrust continental plate (the Allegheny/Helvetic Facies), (2) the mobilized sedimentary and basement rocks of the underthrust continental plate and a melange of rocks derived from a largely consumed ocean plate (the Franciscan/Penninic Facies), and (3) the sedimentary cover and basement of the overthrust continental plate (the Andean/Austroalpine Facies).

Using this model, the corresponding underthrust, mobilized, and overthrust facies of the Neimonides are: (1) The Daqingshan Unit (underthrust Huabei basement and cover), (2) The Sonid Unit (mobilized underthrust basement and cover and ophiolitic melanges), and (3) The Uliastai (overthrust Siberian margin rocks of the Andean facies). An intra-oceanic micro-continent (Sonidzuoqi) may have been present, however, between Mongolia and North China during Paleozoic time, and its paleogeography is reminiscent of the Briançonnais Swell of the Tethyan Realm. We suggest that this micro-continent was accreted onto North China during a mid-Paleozoic continental collision, before the final suturing eliminating the Paleotethys between North China and Mongolia.

ZUSAMMENFASSUNG

Die spätpräkambrischen und paläozoischen Gesteine der Inneren Mongolei bilden ein orogenes Gebirgssystem, welches Neimoniden genannt wird. Dieser Name ist die chinesische Kurzform für «Die Berge der Inneren Mongolei» in englischer Schreibweise. Wir unterbreiten eine Arbeitshypothese für die Entstehung dieser Gebirgskette als Folge von Wechselwirkungen Kontinent-Ozean und Kontinent-Kontinent nach der Kontinentalkollision während des Perm. Unser plattentektonisches Modell eines Kollisionsgebirges bedingt drei Elemente oder tektonostratigraphische Fazien: (1) die Deckfalten der Sedimenthaut (thin-skin) und ihr Grundgebirge der unterschobenen Kontinentalplatte (Allegheny/Helvetische Fazies), (2) die mobilisierten (metamorphen, deformierten) Sedimente und Altkristallinschuppen der unterschobenen Kontinentalplatte mitsamt einer Mélange von Gesteinen aus einer grösstenteils verschluckten Ozeankruste (Franziscan/Penninische Fazies) und (3) die Sedimentbedeckung und das Grundgebirge der überschobenen Kontinentalplatte (Anden/Ostalpine Fazies).

Dieses Modell auf die Neimoniden angewandt bedeutet: (1) die Daqingshan Einheit (unterschobenes Huabei Kristallin und Sedimentüberdeckung), (2) die Sonid Einheit (mobilisiertes unterschobenes Grundgebirge und Sedimente, und Ophiolithmélanges) und (3) die Uliastai Einheit (überschobene Gesteine des Sibirischen Kontinentalrandes des Typus Andenfazies). Möglicherweise existierte im Paläozoikum ein interozeanischer Mikrokontinent zwischen der Mongolei und Nordchina, dessen paläogeographische Stellung uns an die Briançonnais-Schwelle des Tethysraumes erinnert. Wir vermuten, dass dieser Mikrokontinent bei einer mittelpaläozoischen Kontinentkollision an Nordchina angeschweisst wurde, also vor der endgültigen Schliessung der Paläotethys zwischen China und der Mongolei.

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Introduction

Nei Mongol is the Chinese expression for Inner Mongolia. We suggest *Neimon* (instead of *Nei Meng* by Pingying spelling) as an abbreviation for Inner Mongolia, and the term *Neimonides* is proposed to designate the tectonic edifice formed by orogenesis in Inner Mongolia.

In compiling the Geologic Map of Asia, Li (1982) noted the presence of ophiolites and melanges in the vicinity of Hegenshan. He recognized thus a suture zone and proposed the existence of a Phanerozoic orogenic belt formed by the collision between the Siberian Craton and the Sino-Korea Block. His interpretation has been supported by the work of Chinese and American scientists working in the area (Tang et al. 1986; Coleman et al. 1987; Liou et al. 1988; Müller et al. 1990). This orogenic belt originated from continental collision is the Neimonides in our terminology (Fig. 1). Detailed mapping has shown, however, that the distribution of ophiolites is not restricted to a single trend. The question has been raised if there have been more than one Paleozoic ocean.

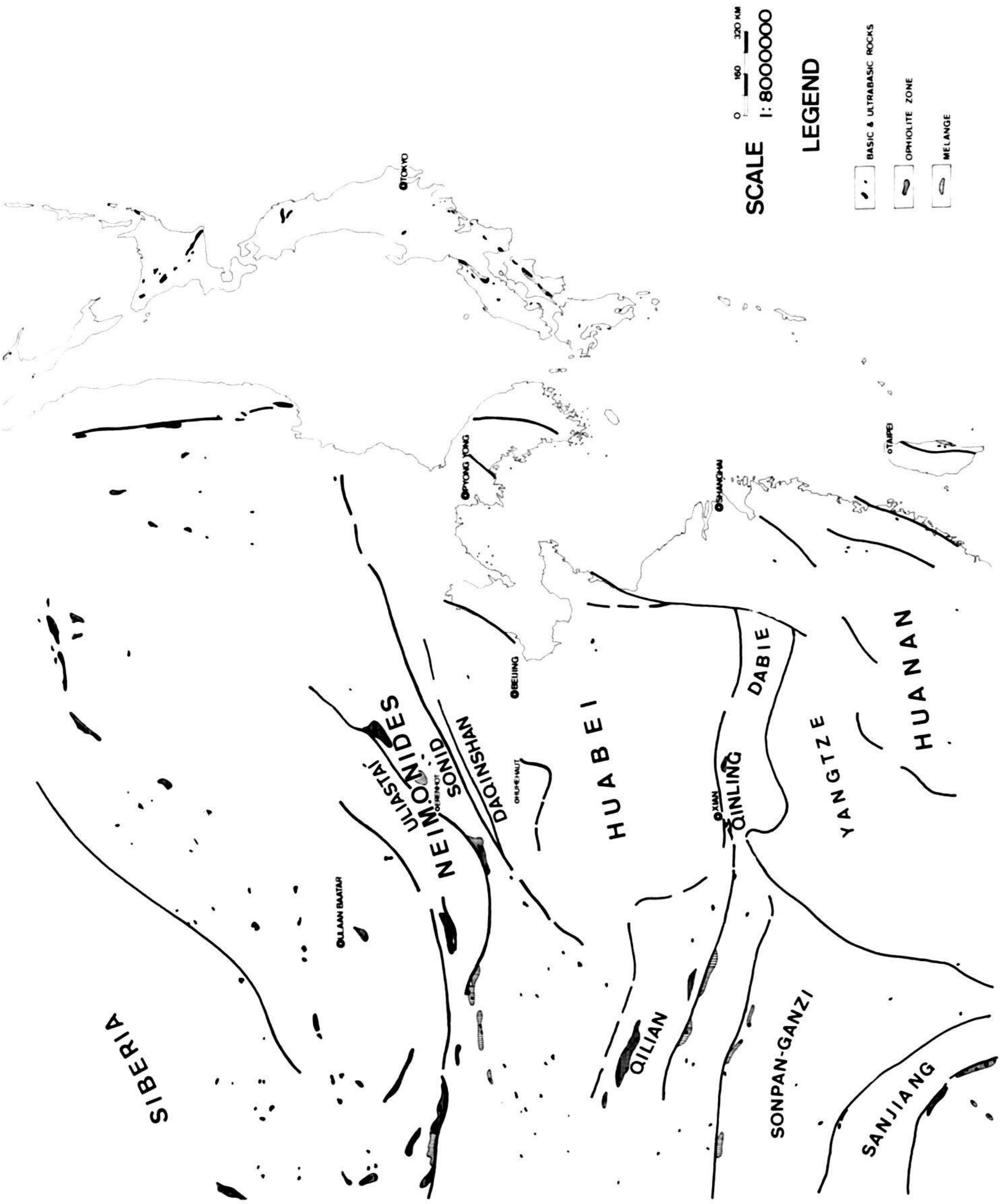
This article presents a working hypothesis to interprete the geology of the Neimonides on the basis of a model for collision-type of mountains. The hypothesis has manifold implications and those predictions could be verified or falsified by future research. A tectonic map of eastern and central Inner Mongolia, between 110° E and 119° E is presented (Plate 1). The basic information is derived from the Geologic Map of Inner Mongolia on a 1:1,000,000 scale, and from the explanatory text (Anonymous 1981). Tectonic classification and interpretation of the Neimonide units are based upon field observations during an 1988 expedition to Inner Mongolia.

The geographical names are either spelled in Pingying or they have been Anglicized, according to the Geographical Atlas of Chinese Provinces published in 1977, directly from Mongolian pronounciation.

Tectonostratigraphic facies

Mountains formed by plate collision consist of three elements, namely the overriding continental block, the underthrust continental block, and the remnants of an intervening ocean lithosphere which are now squeezed into the suture zone. Swiss Alps are a tectonic edifice formed by such collision (Hsü 1989). The overriding block in a collision consists of continental basement and a former active-margin sedimentary sequence, and those overthrust rocks are, as a rule, little metamorphosed as exemplified by the Austroalpine nappes of the Alps. The underthrust block can be divided into two parts: The continental basement on the outer margin and a part of its cover have been displaced to great depth where they are metamorphosed and mobilized; such rocks, together with a melange of ocean rocks, constitute, for example, the Penninic

Fig. 1. Tectonic Map of North China (After Li 1982). The map shows the position of the Neimonides between Huabei (North China) and Siberia cratons. We postulate the three major tectonic units of the Neimonides are the Daqingshan, Sonid, and Uliastai Belts, which are equivalent to the Helvetic, Penninic, and Austroalpine elements of the Swiss Alps. Two zones of ophiolite melanges have been recognized, marking the suture of collision of the three blocks.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DAQINSHAN
HUABEI
QINLING
DABIE
YANGTZE
HUANAN
QILIAN
SONPAN-GANZI
SANJIANG

units of the Alps. The main part of the sedimentary cover on an underthrust margin is, however, detached and pushed forward by the movement of the overriding block. The non-disrupted sequence is deformed to form decollement folds or strip-sheets in foreland thrust belts; the Helvetic nappes are an expression of this cover-deformation.

The tectonic units Helvetic, Penninic and Austroalpine are not only distinguished by their different styles of deformation; they are recognized also because their sedimentary sequences are characterized by different plate-tectonic settings of deposition: The Helvetic are largely passive-margin, the Austroalpine largely active-margin, and the Penninic largely oceanic sediments. The relation between the nature of a sedimentary sequence and the characteristic style of its deformation is not a coincidence, similar patterns of tectonics and sedimentation have been observed again and again in different mountain ranges. Those patterns owe their origin to plate-interactions: The Helvetic thin-skin deformation is, for example, typical deformation of passive margin sediments of an underthrust plate, the Penninic ophiolitic melanges are manifestations of ocean-lithosphere subduction, and the Austroalpine rocks are little metamorphosed because the overriding block has been pushed up to form the higher stories of a tectonic edifice.

While working on the tectonics of China, the concept of a tectono-stratigraphic facies, or in short, tectonic facies, has evolved (Hsü 1981, 1989). Each facies is identified by its stratigraphy and by its style of deformation. Using the Swiss Alps as a model, three major tectonic facies are (Fig. 2):

1. Helvetic Facies, s.l.

The largely unmetamorphosed tectonic units derived from the deformation of the underthrust plate are characterized by the structures displaced by this facies. Two subfacies can be recognized (Fig. 2):

(1 A) *Massif Subfacies:* The autochthonous and parauchthonous massifs are underlain by basement rocks on the continental margin of the underthrust plate; they have been little or only mildly metamorphosed during the Alpine deformation.

(1 B) *Cover-Thrust (Helvetic s.s.) Subfacies:* The Helvetic nappes of the Swiss Alps consist mainly of detached sedimentary cover which has been deposited above continental crust on the passive margin of the underthrust plate. They are characterized by decollement deformation and the sedimentary rocks are little metamorphosed, having been stripped off from underthrust basement and piled up on foreland.

2. Penninic Facies

The largely metamorphic rocks in the Alps, between the little metamorphosed rocks of both colliding plates, include both the outer margin of the underthrust plate, and the remnants of largely consumed ocean lithosphere. The following subfacies have been recognized in the Alpine region (Fig. 2):

(II A1) *Core-Nappe Subfacies:* The basement on the outer margin of the underthrust plate has been displaced along gently dipping crustal faults to great depth and thus subjected to mobilized-basement deformation and metamorphism. Those mobilized-basement rocks constitute the core nappes of the Penninic Realm.

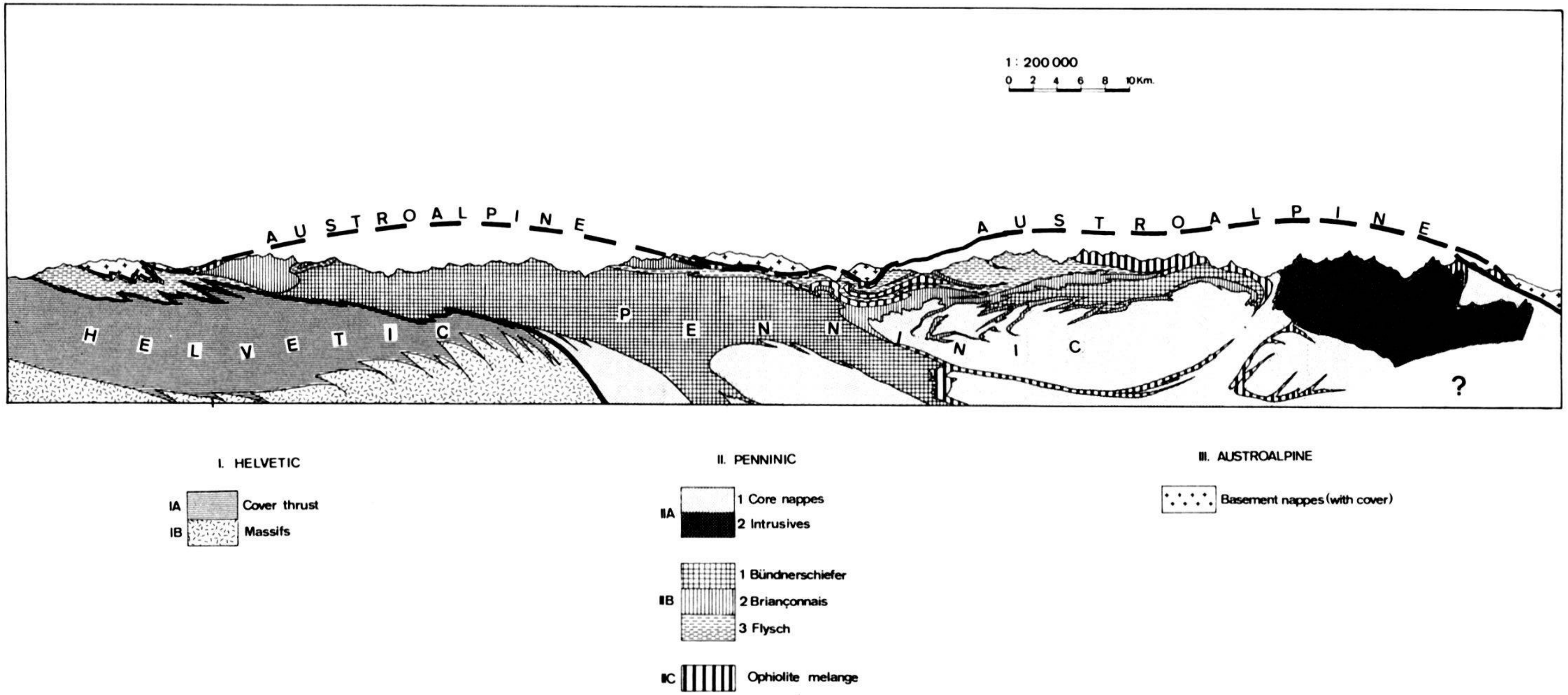

Fig. 2. Tectonic Facies as exemplified by the Alpine Geology. The three major elements of the Alps are the Helvetic, Penninic and the Austroalpine units. Autochthonous massifs (IA) and cover thrusts (1B) are present in the Helvetic. The Penninic units include core nappes (IIA1), intrusives (IIA2), Bündnerschiefer (IIB1), Briançonnais (IIB2), Flysch (IIB3) and ophiolite melange (IIC). The Austroalpine units (not differentiated in this figure) include rigid basement, mobilized basement and cover thrusts. This cross-section by Staub (1958) has been redrawn to illustrate the tectonic facies and subfacies recognized on the basis of classifying Alpine tectonic units.

(II A2) *Intrusive Subfacies:* The underthrust basement may have been displaced to such a depth that the crust is subjected to temperature and pressure conditions of partial melting. The Bergell granite shows evidence of intrusion into overlying Penninic rocks.

(II B1) *Bündnerschiefer (schistes lustrés) Subfacies:* The deep-sea sediments, mainly hemipelagic, were the sedimentary cover of the basement of core nappes. They have been metamorphosed during the Alpine deformation, and are now present as "septa" between various core nappes.

(II B2) *Briançonnais Subfacies:* The sedimentary cover of the basement on islands within the Tethys Ocean is characterized by shallow-water deposition. The cover is stripped off and displaced to form cover thrusts within the Penninic terrane. Those can, however, be distinguished from the sedimentary strata of the Helvetic cover thrusts by their characteristic sedimentary facies, which has been named Briançonnais/Subbriançonnais in the Alps; their degree of metamorphism varies according to their history of burial under tectonic burden.

(II B3) *Penninic Flysch Subfacies:* Turbidites are a dominant component of the deep-sea deposits of the Tethys Ocean after compressive deformation started. The Alpine Flysch consists of interbedded turbidites and hemipelagic sediments of Cretaceous and early Tertiary age. The Flysch nappes are commonly rootless, and the Flysch is rarely metamorphosed, having been stripped off from the underthrust basement and piled up onto the Helvetic nappes.

(II C) *Ophiolite Melange Subfacies:* The ophiolite melanges formed during the Eo-Alpine subduction consist of the remnants of ocean sediments, ocean crust and mantle. The melanges have since been sandwiched between two plates to form the suture of colliding continents. Their degree of metamorphism varies according to history of burial under tectonic burden; the melanges of eastern Swiss Alps are little metamorphosed, but those of the western Alps have been subjected to amphibolite-facies metamorphism after continental collision.

3. Austroalpine Facies

The overriding plate is displaced for long distance along gently dipping or nearly horizontal surface. The bulk of the displaced rocks is thus not deeply buried except in the root zone. This tectonic facies can be subdivided into three subfacies.

(III A1) *Rigid-basement (Silvretta) Subfacies:* This subfacies includes the basement and its sedimentary cover which are relatively unmetamorphosed. The rigid-basement nappes are thrust over lower-elements of the Alpine edifice, and the thrusts are manifested mylonitization in thin zones of ductile shear.

(III A2) *Mobilized-basement (Sesia) Subfacies:* The high-temperature and high-pressure metamorphic rocks of the Sesia-Lancia Zone (including eclogites and granulites) represent the continental crust of the Austroalpine margin which was brought down to great depth during the Eo-Alpine stage of ocean-lithosphere subduction. Those rocks were brought back up when the sense of movement at the ocean-continental boundary was reversed after continental collision, when the Austroalpine nappes were overthrust above the Helvetic unit.

(III B) *Cover-thrust (Northern Calcareous Alps) Subfacies:* The sedimentary cover of Austroalpine nappes can also be stripped off along a decollement horizon and deformed as cover thrusts under the shearing stress induced by the motion of overriding Upper Austroalpine nappes. The sedimentary cover of the Lower Austroalpine Err-Julier nappe has been deformed in this fashion. The North Calcareous Alps are also decollement structures of sedimentary cover stripped off from its underlying basement. Like other sedimentary rocks deformed by thin-skinned deformation, the rocks of the Austroalpine cover thrusts are also largely unmetamorphosed.

This classification of tectonic facies has a necessary shortcoming, owing to the fact that not all mountain ranges are mirror images of the Swiss Alps. Not all thin-skin structures, for example, form large recumbent folds like those of the Helvetic Realm. The docollement structures of the Rocky Mountains are characterized by low-angle overthrusts, and those of the Appalachians are the tight anticlines and synclines of the Allegheny "Valley and Ridge Province". A more comprehensive name for the thin-skinned deformation of former passive-margin of underthrust plate should perhaps be *Allenghenyl/Helvetic Facies;* we shall, however, use the shorter expression Helvetic for the sake of convenience.

The active-margin sequence of the Austroalpine nappes has little intercalation of volcanic rocks or of volcanogenic sediments. This sequence is thus significantly different from those on active-margin sediments of the Circum-Pacific regions. The Central Andean Mesozoic and Cenozoic sequence of Chile consists, for example, of very thick volcanic rocks and detrital sediments. The sediments are largely continental and are deposited in basins behind a magmatic arc, and they are intruded by batholitic granites of various ages. Volcanic/sedimentary sequences of the Andean type are not uncommon in collision-type of mountains, such as the Paleozoic volcanics of the Northern Appalachians. A more appropriate name for the rocks and structures in the overriding plate of a collision-type of orogen is perhaps *Andean/Austroalpine Facies,* the former refers to their stratigraphical and the latter to their tectonic settings. For sake of brevity, we shall use the term Austroalpine Facies in this article; the Neimonide active-margin sediments are typically Andean, but their tectonics are Austroalpine.

Finally, the proportion of tectonic melanges to mobilized basement and cover in collision zones differs greatly from place to place. In Circum-Pacific Mountains where plate collision played a minor role, such as the California Coast Ranges, ophiolite melanges constitute the dominant unit. In collision-type of mountains such as Northern Appalachians, ophiolitic relics are rare or absent. Perhaps a more comprehensive name for the facies in the collision zone should be called Franciscan/Penninic; the former refers to the style of deformation prior to continental collision and suturing, and the latter to post-collisional tectonics. Again, for the sake of brevity, we shall use the term Penninic Facies in this article.

Neimonides as collision-type of orogen

The Neimonides consist mainly of Precambrian and Paleozoic rocks, and they are intruded by large batholithic intrusions. The mountains have been worn down by erosion, and they form the basement under the Mesozoic/Cenozoic basins of Inner Mongolia. The Neimonides are now buried under thick volcanic rocks and lake beds of

Mesozoic and Cenozoic age. The outcrops of the Neimonide rocks constitute less than 1/3 of the mapped area (Plate 1). Even in the outcropping areas, the rocks are largely covered by steppe vegetation, and the relief is so reduced that our field vehicles could roam about without difficulty on broad expanses of grassland. Few outcrops are found at roadcuts, and in many places we have to depend upon man-made trenches for a modest perspective into the vertical dimension. Under such conditions, even the attitude of the layering cannot be easily determined, and the geometry of large structures cannot be directly observed, certainly not on a scale as we are used to in the Swiss Alps.

Faced with poor exposures and incomplete data, comparative tectonics is a most effective tool. Mountains of the collision-type are formed by plate-interactions, and their two stages of deformation are manifestation of an earlier stage of ocean-continent and a later stage of continent-continent interaction (Hsü 1989). The tectonic-stratigraphic units of the Neimonides have resulted from those deformations.

In examining the rocks of Inner Mongolia, a broad subdivision of the Neimonides can be recognized on the basis of the postulate that they have been deformed in a fashion analogous to the Alpine tectonic facies. The Neimonides units are (I) the Daqingshan unit (thin-skin cover and autochthonous basement), (II) Sonid unit (melanges, flysch, and mobilized basement and cover, intrusives), and (III) Uliastai Unit (Andean volcanic/sedimentary cover, intrusives); they are tectonically equivalent to the Helvetic, Penninic, and the Austroalpine nappes respectively.

1. The Daqingshan Unit

The rocks of the Daqingshan Unit crop out mainly south of the Bailingmiao-Huade-Chifeng trend (Plate 1). The two subdivisions are:

(I A) *Huabei Cover:* The Daqinghan Mountains west of Hohhot are underlain by Paleozoic shallow marine carbonate and siliciclastic strata, known locally as the Qingshuihe Group (Fig. 3). The lower part of the sequence is continuous from Proterozoic to Ordovician, and is thus similar to the sedimentary cover of the Sino-Korean Block. The lateral stratal continuity of those rocks has not been severely disrupted. The lower Qingshuihe lie unconformably above the Huabei basement and is overlain unconformably by shallow marine Permo-Carboniferous strata (Fig. 3).

(I B) *Huabei Basement:* The basement of the Sino-Korean Block consists of Archaean and Lower Proterozoic rocks. The Archaean and Lower Proterozoic rocks include pyroxene-granulite, biotite-bearing sillimanite-garnet gneiss, plagioclase amphibolite, and hornblende gneiss, as well as marble and quartzite (Yang et al. 1986). Their crystallization ages range up to 2.6 billion years. The granulite and amphibolite facies rocks have been veined by pegmatites which are dated 2.1 to 1.8 billion years. Similar Precambrian basement rocks are widespread in North China.

The Huabei-cover strata of Daqingshan form decollement folds in the foreland deformed belt of the Neimonides. The Huabei Basement underlie the early Paleozoic passive-margin sequence (Fig. 4). Upper Paleozoic and lower Mesozoic strata overlie the lower Paleozoic rocks unconformably. Those shallow marine and continental sediments were deposited after continental collision; they are foreland basin deposits, and they should not be considered a part of the Huabei passive-margin sequence.

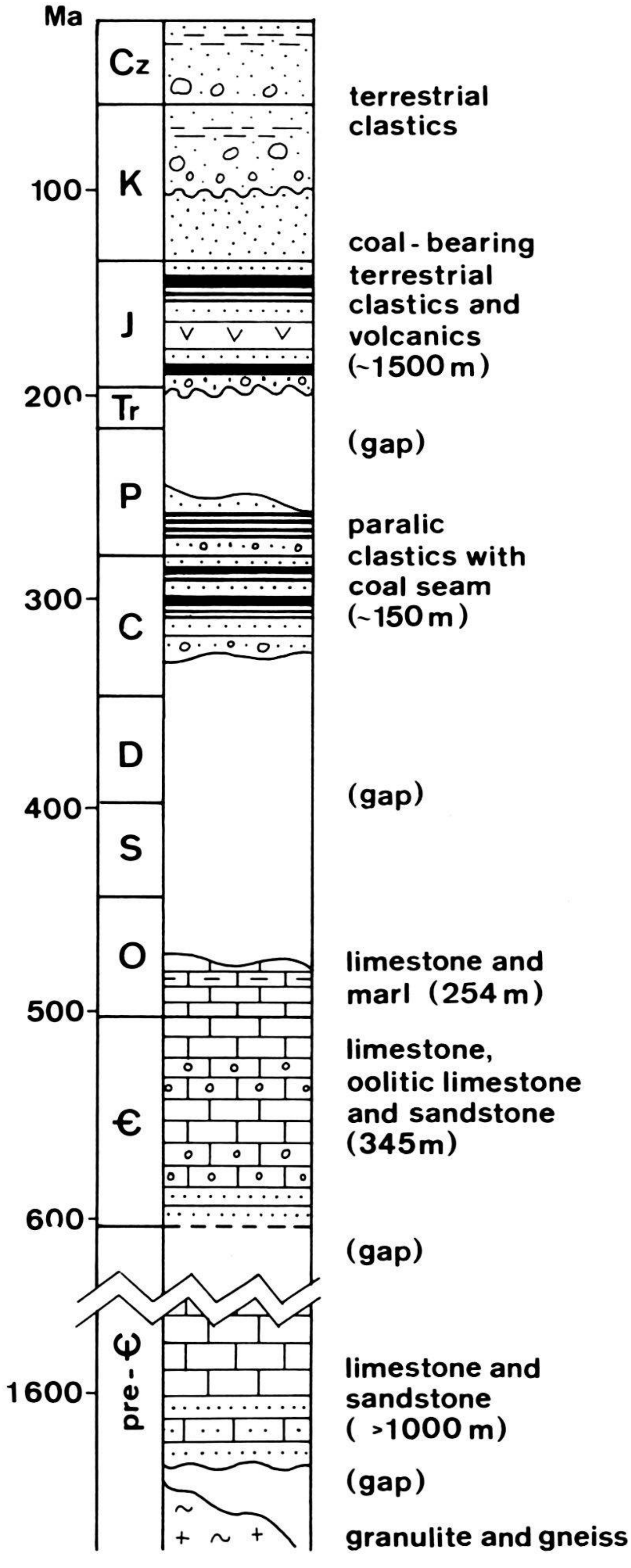

Fig. 3. Generalized stratigraphic section of southern Inner Mongolia. The Daqingshan Unit was a passive-margin sequence of the Sino-Korean Craton, and it ranges from middle Proterozoic to Ordovician in age and consists mainly of shallow marine deposits. Those strata were deposited on the northern passive margin of the Sino-Korean block. The upper Paleozoic shallow marine and the Mesozoic/Cenozoic strata were deposited after continental collisions.

The deformed Huabei cover occupies a position in the tectonic edifice of the Neimonides equivalent to the cover-thrust subfacies of the Helvetics, even though we have seen none of the spectacular recumbent folds in the Neimonides as those of the High Limestone Alps. Our interpretation that the Huabei cover may constitute decollement structures, or strip sheets, has yet to be verified by detailed field mapping. The existing information suggests that the foreland thrust belt extends southward from the Daqingshan trend in Inner Mongolia to northern Hebei Province. The Middle and Upper Proterozoic sequence north of Beijing, for example, is commonly considered the sedimentary cover of the Archaen basement and the thickness exceeds 10 km. Is it possible that the great thickness is a result of tectonic repetition? One of us (W.Q.) postulated that this sequence is overthrust above the basement because the quartzite directly above the basement is mylonitic.

The hypothesis postulating a Huabei deformed margin in Inner Mongolia explains the folding of the Paleozoic strata in the vicinity of Beijing as thin-skinned deformation comparable to the Jura tectonics. The presence of thrust faults in the Paleozoic terrane of Hebei and Liaoning provinces has been verified by drilling.

2. The Sonid Unit

The rocks of this belt are widely distributed in the mapped area. They crop out in a WNW-ESE trend from Sonidyouqi, Erenhot, Sonidzuoqi, Xilinhot, to Uliastai. The following subunits have been recognized.

(II A1) *Sonidzuoqi metamorphics:* Scattered outcrops of metamorphic rocks of amphiolite facies are present in the vicinity of Sonidzuoqi and Xilinhot, and they have been mapped as "Variscanian" quartz syenite ($\gamma\ \delta_4$) on the geologic map of the autochthonous region. We examined those rocks south of Sonidzuoqi and found them a part of a metamorphic basement-complex consisting of quartz-feldspar gneisses and plagioclase amphibolites. The same basement complex is exposed southwest of Xilinhot, mapped as Upper Proterozoic (Ptal) on the 1:200,000 geologic map, which consists of mica and chlorite schists, quartzites and marble. We propose the term *Sonidzuoqi metamorphics* to designate those metamorphic rocks and consider them the mobilized basement during the Paleozoic deformation of the Neimonides. The lower Paleozoic sedimentary cover of Sonidzuoqi basement consists mainly of metamorphic rocks of the greenschist facies; they are correlative to those of the Bainaimiao mining district, and are shown on our map as Bainaimiao Metamorphics (Plate 1).

(II A2) *"Variscanian Granites":* The coarse-grained plutonic rocks in the Sonid Zone have been labelled gamma-4 or "Variscanian granites", because radiometric dating of those intrusive has yielded radiometric dates ranging from 250 to 350 Ma (ANONYMOUS 1981, p. 108–122). Older granites are labelled gamma-3 ("Caledonian") and younger gamma-5 (Mesozoic).

We examined the "Variscanian granites" in the Bainaimiao Mine district and found them to be largely gneissic quartz diorite. Those have been dated 350 Ma (HAN, personal communication 1988), and they are intrusive into mica schists and greenschists, which also occur as xenolithic inclusions in the plutonic body. The granites are overlain by late Paleozoic shallow marine deposits.

(II B1) *Bayanobo Group,* sensu lato.

Meta-sediments are widely distributed on the northern slopes of Daqingshan Mountains. These include slates, phyllites, meta-graywackes and marbles. Those largely unfossiliferous rocks were considered Proterozoic until Cambrian and Ordovician fossils were found in some of the rocks during the 1960s (Anonymous 1981, p. 11).

Marbles and calc-silicate rocks yielding Silurian fossils were mapped as the Xibiehe Formation, and they are widespread in the Bayanobo and Bainaimiao mining districts. The marble occurs mainly as lenticular blocks in a matrix of calc-silicate rocks, giving evidence of very large shearing strain induced by deformation.

We propose to extend the term Bayanobo Group, *sensu lato,* to include all the upper Proterozoic and lower Paleozoic (including Xibiehe) shallow marine strata of the Sonid Unit. Those rocks, mainly carbonate, constitute only one mappable unit (Fig. 4). Situated more northerly of the Huabei Cover of the Daqingshan unit, on the outer margin where the sedimentation was more continuous, the youngest passive-margin sequence laid down before foreland-folding is Silurian, which is incidentally absent on top of the North China Platform.

(II B2) *Bainaimiao Metamorphics:*

Metamorphic rocks of greenschist facies are tectonically mixed with Silurian rocks at the Bainaimiao district, and both are overlain unconformably by unmetamorphosed late Paleozoic shallow marine strata. The mica schist and chlorite schist were once considered Ordovician, because radiometric dating gives metamorphic ages of about 450 Ma (Han, personal communication 1988).

The bulk of the schists examined by us in the Bainaimiao mining district are pelitic rocks, although meta-volcanic rocks are also present. They were apparently deposited as hemipelagic sediments on the outer margin of the Huabei continent (Fig. 4), and they were metamorphosed during the Neimonide deformation. The Beinaimiao greenschists belong to a tectonic facies equivalent to the *Bündnerschiefer* or the *schistes lustrés* of the Penninic Alps. Those rocks form mainly the matrix of the Ondorsum Melange and are mapped as such in our tectonic map (Plate 1).

(II B3) *Hunggermiao Flysch:*

Carboniferous and Lower Permian sediments of flysch facies are present in the Sonid Belt and on or near the southern margin of the Uliastai Belt. Those are characterized by interbedded turbidites and hemipelagic shales. Fossils are rare. An ammonite *Daubichites hunggermiaoensis* (Chu) of Early Permian age has been found near Abagqi, and the *Daubichites-Tumaroceras* faunas of the flysch are typical boreal type (Liang 1981).

The flysch strata are evenly bedded. Where they have been subjected to intensive shearing, the turbidite beds are broken up so that they constitute a broken formation, or a wildflysch. The flysch sandstones occur as exotic blocks, and the shaly material serves as matrix for the melange.

The Permo-Carboniferous flysch deposits were deposited in a foredeep on an active margin south of the Siberian/Mongolian continent (Fig. 4).

(II B4) *Volcanogenic Upper Paleozoic:*

Thick carboniferous to Permian shallow marine strata are also present in the Sonid Belt and they are associated with volcanic rocks (Li 1983).

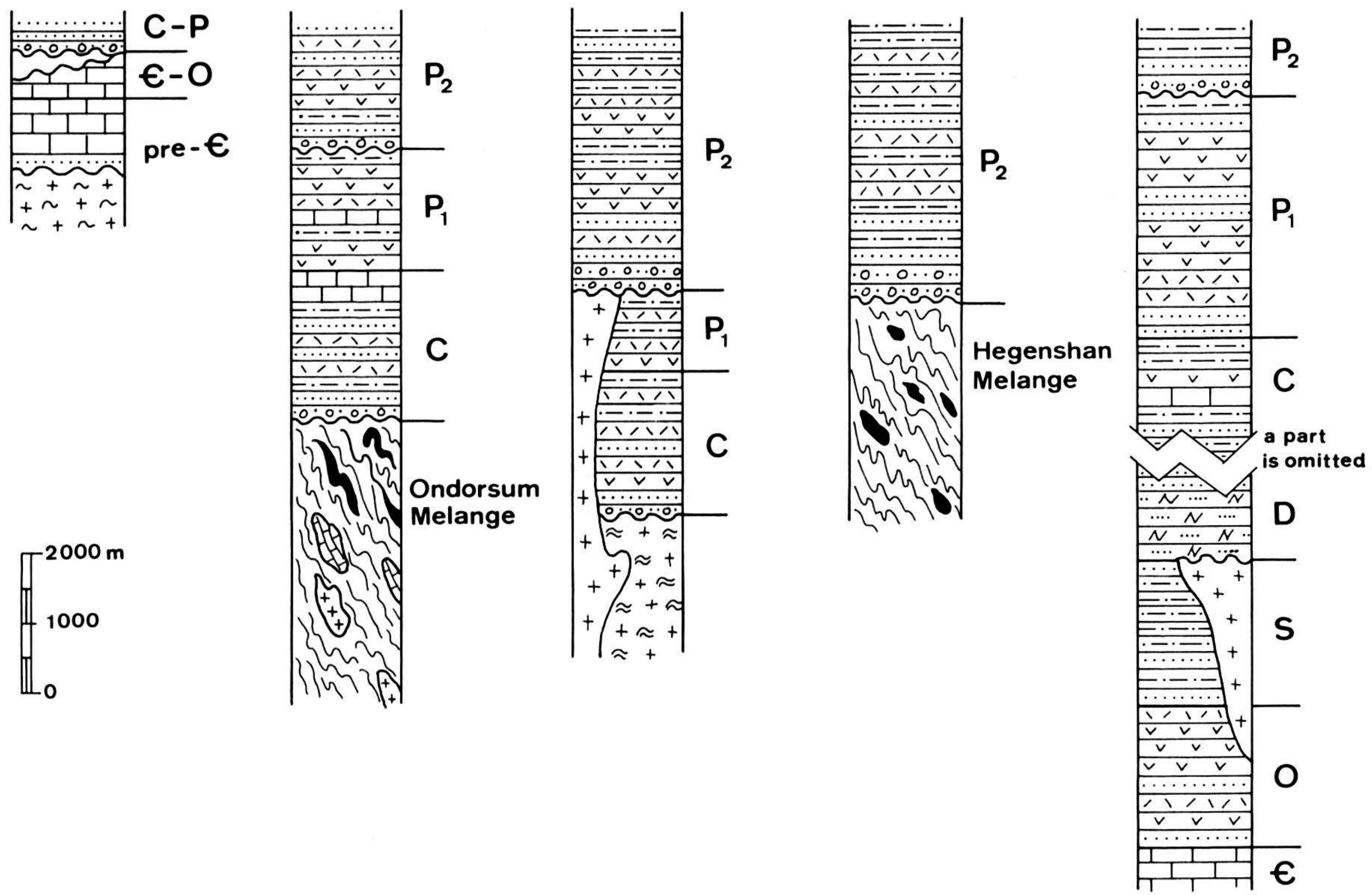

Fig. 4. Neimonides Sequences and their Paleogeographical Position. The sedimentary sequences of the Daqingshan and Uliastai Units are not disrupted, and the lower Paleozoic of those units were the sedimentary cover on the southern passive and northern active margin of the Ondorsum Ocean respectively. The upper Paleozoic sediments of the Uliastai Unit were deposited on the northern active margin of the Hegenshan Ocean, whereas the volcanogenic upper Paleozoic rocks of the Daqinshanghan and Sonid Units were deposited near a passive or a transform margin after the Mid-Paleozoic collision of the Sonid and Daqingshan Blocks. The sedimentary sequences of the melanges have been disrupted and they are reconstructed on the basis of principles of melange stratigraphy. The Ondorsum Melange consists mainly of Proterozoic and lower Paleozoic rocks, whereas the rocks in the Hegenshan Melange are mainly upper Paleozoic.

The middle and upper Carboniferous rocks are mainly shallow marine limestones and siliciclastics; they overlie unconformably Silurian marbles and the melange. The faunas include fusulinids, brachiopods and corals. The cold-water coral *(Tachilasma-Cyathocarinia)* fauna shows an affinity to the Siberian Carboniferous. The marine strata grade laterally to terrestrial siliciclastic strata southeast of the Bainaimiao district; *Calamites* sp. and other plant fossils have been found in siltstone beds there. Volcanic flows and tuffs of Carboniferous age are present in the western part of Inner Mongolia.

The lower Lower Permian (Sanmianjing, Hugete) Formations seem to unconformably overlie Silurian rocks or suture melange in the Bainaimiao district, but their contact relation with older rocks is not clear in the Sonidyouqi district. Those strata, thousands of meters thick and richly fossiliferous, consist of conglomerate, sandstone, siltstone, and fusulinid limestones. Andesitic tuffs and flows are intercalated. The early Early Permian faunas of southern Neimon show Tethyan affinity, in contrast to the coeval cold-water faunas in rocks of the Uliastai Belt of northern Neimonides.

The upper Lower Permian formation of the Sonid Zone consists of conglomerates, sandstones, and limestones. Those strata, several thousand meters thick, have been correlated with coeval Permian strata of the Uliastai Zone and both have been designated Jisu Formation. The *Richthofenia-Leptodus-Enteletes* faunas of Jisu are everywhere similar and they are considered typically warm-water.

The Upper Permian rocks of the Sonid zone are thick continental deposits interbedded with volcanics; those include arkosic sandstone, conglomeratic sandstone, siltstone, welded tuff, tuffaceous shale, andesite, andesite porphyry, etc. Plant fossils are common.

The Permo-Carboniferous shallow marine sediments of the Sonid Zone were probably deposited on the southern shore of the Tethys (Fig. 4), but their sedimentary association is not that of a typical passive-margin sequence. The upper Lower and Upper Permian shallow marine and terrestrial deposits show certain similarity to the Molasse of the Alpine foreland basin, but the Inner Mongolia sediments are interbedded with volcanic rocks. A more adequate tectonic-facies equivalent of the upper Paleozoic volcanogenic series of the Sonid Belt is the Jurassic volcanic and terrestrial clastic wedge laid down in the foreland basin of coastal Zhejiang and Fujiang of China.

An alternative interpretation is that this volcanoclastic sequence, or at least a part of the sequence, was the active margin deposits, laid down on the northern shore of the late Paleozoic Tethyan ocean, and is thus correlative to the volcanoclastic Baogeli sequence of the Uliastai Belt to be discussed later. The Sonid Upper Paleozoic could thus have been overthrust onto Ondorsum and Hegenshan Melanges, and occur now as Uliastai Klippes in the Sonid Belt. The change from their cold-water boreal faunas in the Carboniferous to their warm-water Tethyan faunas in the Permian would, according to this interpretation, be evidence for the southward displacement of the Siberia/Outer Mongolia Plate during the late Paleozoic prior to its collision with North China during middle Permian.

(II C1) *Ondorsum Melange:*

A heterogeneous assemblage of igneous and sedimentary rocks, subjected to various degrees of metamorphism, has been considered a stratigraphic unit and called Ondorsum Group. We examined those rocks at their type locality and found that they constitute an ophiolite melange. We propose the name Ondorsum Melange as a substitute.

Exotic blocks of ophiolites in the melange range in size from a few centimeters to several dozens of meters in size. A large, and only partially disintegrated slab of ophiolite suite is exposed in the Ulan Creek east of Zurhe. The ophiolite sequence consists of basalts (including pillow basalt), gabbros, peridotites, and serpentinites. Also present are exotic slabs of glaucophane schist which has yielded a 440 Ma radiometric age (Han, personal communication 1988). The ophiolite blocks, embedded in a pervasively sheared chlorite schist matrix, have been subjected to retrogressive metamorphism under greenschist facies conditions; chloritization and albitization are common. The radiometric dates of the schists range from 400 to 600 Ma (Hu et al. 1987).

Slabs of radiolarian chert and ferruginous chert, ranging from late Proterozoic to Silurian in age are intercalated in the melange. They were the sedimentary cover of oceanic lithosphere. Rare occurrences of marble and of granite in the melange are, on the other hand, exotic elements.

The Ondorsum Melange is overlain unconformably by Carboniferous strata.

(II C2) *Hegenshan Melange:* Ophiolite melanges also cropped out north of Xilinhot, but those are apparently upper Paleozoic. The ultramafic body in the Hegen Mountains is one of the largest such bodies in Inner Mongolia. Drilling has shown that the ophiolite occurs as a giant exotic slab in a melange which has been thrust above Jurassic red beds (Fig. 5).

Other rocks of the ophiolite suite, such as pillow lavas and gabbros, are also exposed in Hegenshan (Cao et al. 1986, 1987). Dating by K/Ar method has yielded 285-430 Ma ages.

Sedimentary strata such as radiolarian cherts, breccias and limestones are present as exotic blocks in the melange. The radiolarian faunas are characterized by *Entactinia* spp. and *Tetrentactinia* spp. The coral faunas described from the limestone exotics include *Thomnopora beliakovi, Favosites* spp., etc. The paleontological ages of the exotic sedimentary rocks range from Late Devonian to Early Permian in age (Liu 1983; Cao et al. 1986, 1987).

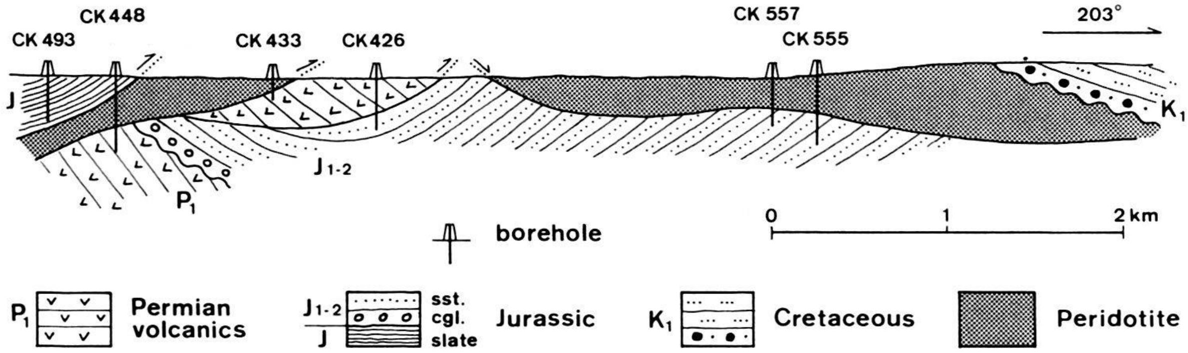

Fig. 5. Tectonic Superposition of Ophiolite above Jurassic. Drilling has verified the allochthonous nature of peridotite slabs in the Hegenshan area. The Hegenshan melange has been overthrust above the foreland basin Jurassic sediments. Regional compression was changed to extension during Late Jurassic or Early Cretaceous when Eren Basin was formed by rifting; the Neimonides are overlain unconformably by Lower Cretaceous red beds.

The Permian breccias consist mainly of chert pebbles and ophiolite fragments and they are deposited unconformably above ophiolite slab. At a gold-copper mine explored by the Geological Team 109, the breccias are found interbedded with turbidite and chert beds, indicating that some of the ophiolite melanges had been uplifted to form coast ranges when the breccias were deposited on deep-sea bottom.

In conclusion, we believe that Sonid Unit, except for its volcanogenic upper Paleozoic, is equivalent to the Penninic Alps. The Sonidzuoqi metamorphics (II A1, Plate 1) and the "Variscanian granites" (II A2, Plate 1) are the mobilized basement at the outer margin of the Huabei continent. They have been underthrust to such depth as to have been subjected to amphibolite-facies metamorphism and partial melting, like the Penninic core nappes (II A1, Fig. 2) and the Bergell intrusives (II A2, Fig. 2). The Bayanobo Group of dominantly shallow marine carbonates formed the sedimentary sequence on the outer margin of the Huabei continent. The Bainaimiao Metamorphics are metamorphosed hemipelagic sediments of the Neimon Ocean. The metamorphosed sedimentary rocks occur either as septa between core nappes or as blocks or matrix of ophiolite melanges. The Bayanobo *sensu lato* constitute a tectonic facies equivalent to the Triassic limestone and quartzite of the Penninic Alps, and the Bainaimiao are equivalent to the Bündnerschiefer of the Penninic Alps.

Two ophiolite melange units have been recognized in the Sonid Belt. The Ondursum Melange has mainly exotic blocks of lower Paleozoic rocks, whereas the Hegenshan Melange has upper Paleozoic exotics. The age of metamorphism is also older in the former. These melanges apparently mark the sutures of two separate acts of continental collision.

3. Uliastai Unit

The rocks of the Uliastai Unit crop out mainly in an ENE-WSW trending belt north of 44° N in Inner Mongolia. Three subdivisions have been recognized:

(III A) *"Variscanian Granites":* The "Variscanian Granites" of the Uliastai Belt are very coarse grained, and are distinguished by their pink feldspar phenocrysts. The "granites" are probably intrusive into the lower Paleozoic rocks.

(III B) *Northern Neimon Group:*

The upper Proterozoic and Lower Paleozoic strata of northeastern Inner Mongolia consist mainly of terrigenous clastics, intercalated limestones and tuffs and flows of acidic to intermediate composition (Anonymous 1981, p. 44–53). The sequence east of Erenhot (Fig. 6) in the northeast of Inner Mongolia is very similar to that west of Erenhot (Fig. 7), and both consist mainly of active-margin deposits.

Northern Neimon Group of Northeastern Inner Mongolia

The Cambrian strata cropped out in the Horqin-youyiqianqi in the northeast are thick-bedded limestone and intercalated fine siltstone, about 100 m thick. They are dated by a sponge fauna (Anonymous 1981, p. 45).

The Ordovician rocks of the Uliastai district have been called Hanwula formation (Anonymous 1981, p. 48), named after its type locality at Hanwula, about 100 km

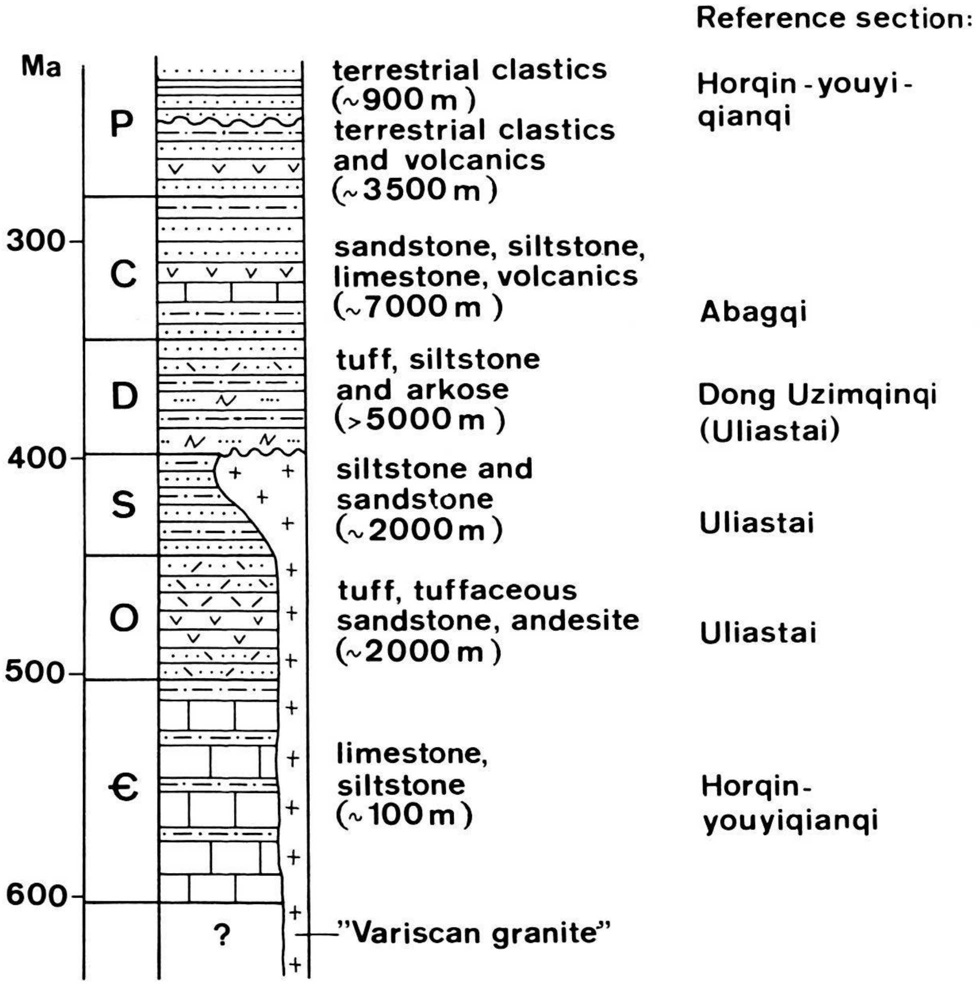

Fig. 6. Stratigraphical Column of the Paleozoic in Northeastern Neimon. The northern continental margin was a passive margin before it was changed into an active margin during the Ordovician when volcanic activities first became active. Granitic ("Variscanian") intrusions of the area are mainly pre-Devonian, emplaced near an Andean-type of margin.

northeast of the town of Uliastai. This Ordovician formation consists mainly of tuff, tuffaceous slate, sandstone, and andesites, ranging up to 2,000 m thick. Brachiopod *(Hesperothis* spp.) and trilobite faunas have been described.

The Silurian formations consist mainly of sandstones and slates in the Uliastai area, but include thick trachyte and trachytic tuff beds in the Horqin-youyiqianqi district. The Silurian is dated by brachiopods *Tuvaella gigantea* and *T. rackovskii* (Su 1981).

The Devonian formations of the northeast are several thousand meters thick, and they are well exposed north of Uliastai (Anonymous 1981, p. 53–37). The basal Devonian arkose overlies a granite basement. The Lower Devonian consists mainly of fine-grained sandstone and calcareous siltstone, which contain a coral-brachiopod-sponge fauna. The Middle Devonian of the Uliastai area include tuff beds, feldspathic sandstone, siliceous siltstone, and is also characterized by a coral-brachiopod fauna. The

Upper Devonian is an interbedded sequence of marine and continental siliciclastics, dated by fossil corals and plants. The Devonian has a coral-brachiopod fauna in marine deposits and plant species *Barssassia sibiria* in terrigenous clastics (Li & Cai 1979). All the faunas and floras have close affinities to those of Siberia.

The Carboniferous rocks of the Uliastai Belt are interbedded volcanic rocks and terrigenous clastics, with thin intercalations of shallow marine limestone beds (Anonymous 1981, p. 57–63). The marine faunas are typically coral-brachipod assemblages. The floras include *Calamites* spp., *Neoggerathiopsis* spp., *Angaropteridium cardioptroides*, etc.; all are typically Siberian forms.

The Lower Permian are volcanic and terrestrial formations several thousand meters thick (Anonymous 1981, p. 63–67). They consist of sandstones, siltstones,

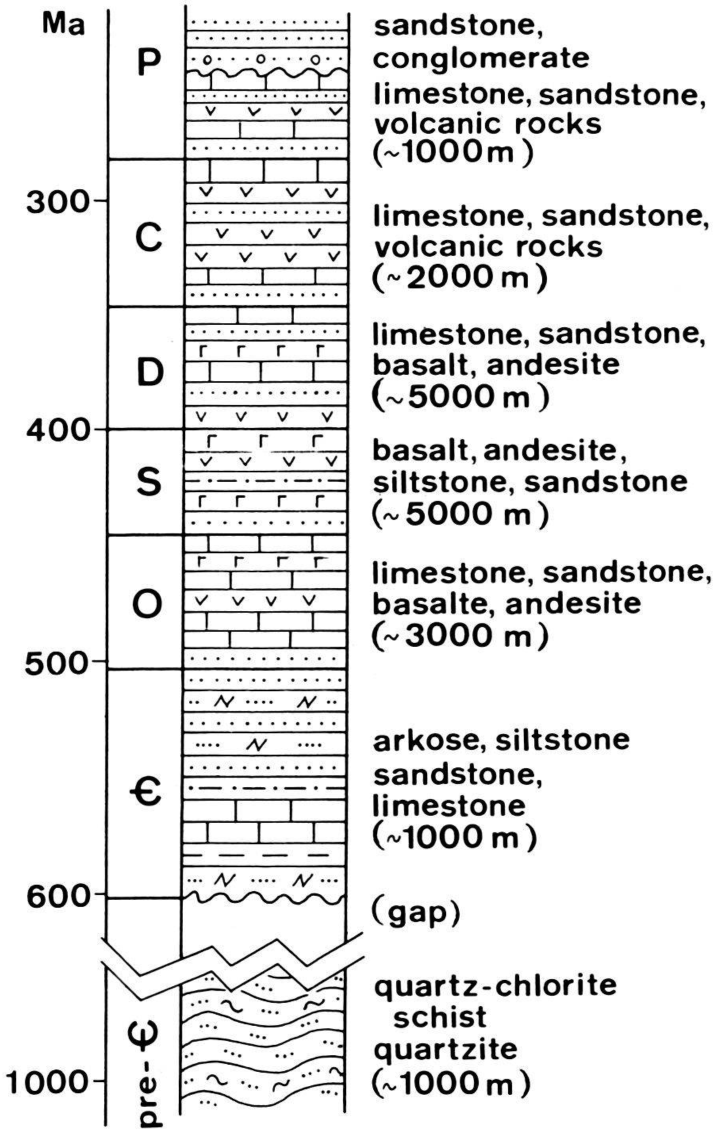

Fig. 7. Stratigraphical Column of the Paleozoic in Northwestern Neimon. This part of the northern continental margin has undergone a similar geologic evolution as that farther to the east.

conglomerates, andesite flows, tuffs, tuff breccias, etc. The early Early Permian fauna consists of *Neospirifer* sp., *Streptorhynchus* sp., *Liosotella* sp., *Rotiphyllum* sp., *Bradyphyllum* sp. etc. and is a typical cold-water assemblage. The middle Early Permian, including *Spiriferella* sp., *Kochioproductus* sp., *Yakovlevia* sp., *Tachylasma* sp., *Calophyllum* sp. is also a cold-water fauna, but is mixed with some warm-water elements. The late Early Permian is warm-water fauna of *Richthofenia* sp., *Leptodus* sp., *Enteletes* sp., *Waagenophyllum* sp., *Wentzelella* sp.

Northern Neimon Group of Northwestern Inner Mongolia

Upper Proterozoic and lower Paleozoic formations are also well exposed in the Ejinqi district in northwestern Inner Mongolia (Fig. 7). The upper Proterozoic consists of quartz sandstone, siltstone, quartz-chlorite schist, sericite-chlorite schist, quartz sericite schist, limestone, and tuff beds. Fossil spores *Leiosphaeridaceae* spp. have been found in this 1,000–2,000 m thick sequence.

The Cambrian formations of the northwest consist of arkosic sandstone, siltstone, slates, limestone, siliceous dolomite, dolomitic limestone etc., a few hundred meters thick. Those sediments are dated by brachiopods (*Lingula* sp.), trilobites and gastropods, and they are overlain disconformably by Ordovician strata.

The Ordovician sequence of Ejinqi consists of siliceous slates, siltstones, quartz sandstone, argillaceous limestone, with numerous interbeds of tuffs and andesites in the upper Middle and Upper Ordovician. The strata are dated by trilobites, brachiopods, and corals (Anonymous 1981, p. 46–49).

The Silurian, thousands of meters in thickness, includes mainly basalt, andesite, and siliciclastic sediments, with marble intercalations. Graptolite faunas occur in slates and corals in limestones.

The Devonian formations are also thousands of meters thick. Those shallow marine or continental deposits are interbedded with trachyte, andesite, basalt and other intermediate and basic volcanic rocks. The Lower Devonian limestones are characterized by a coral-brachiopod fauna. The Middle and Upper Devonian siliciclastic and carbonates are also richly fossiliferous, having yielded corals, brachiopods, trilobites and plant fossils.

The Carboniferous sequence consists also of interbedded shallow marine siliciclastic, carbonate and volcanic rocks. These strata, thousands of meter thick, are dated by their coral, brachiopod and fusulinid faunas (Anonymous 1981, p. 57–63).

The Lower Permian strata are similar shallow siliciclastic, carbonate and volcanic rocks, and they are dated by their coral, brachiopod and fusulinid faunas. The Upper Permian consists of sandstone, conglomerate, gray slate and tuffaceous sandstone; they overlie the older strata disconformably, and grade upward into the Triassic red beds.

In conclusion, the upper Proterozoic and Cambrian of the Uliastai Unit were the platform cover or a passive-margin sequence, but the younger formations were active margin deposits of the Siberian/Mongolian Block. The "Variscan granites" are not basement, but batholiths intruded into this active margin. The first appearance of significant volcanic rocks during the Ordovician indicates that this passive-margin was converted then into an active margin. The geology of the post-Ordovician Paleozoic margin of the Siberian/Mongolian Plate is thus very similar to that of the Mesozoic/ Cenozoic geology of the Central Andes.

The Uliastai granites are thrust southward in a manner comparable to the rigid-basement (Silvretta) nappes of the Alps, whereas the sedimentary strata may have been thrust southward as strip sheets, somewhat in the fashion of the Northern Calcareous Alps. An exact analogue for the Uliastai Unit can, however, not be found in the Alps, because volcanic and intrusive rocks are practically absent in the Austroalpine sequences. A more appropriate analogue is probably the magmatic-arc complex of Maine and Maritime Provinces of Canada, which collided with North America during middle Paleozoic.

Reconstruction of the Neimonide stratigraphy

Normal-Stratigraphy Sequences

The sedimentary strata of the Daqingshan and Uliastai Units, like those in the Helvetic and Austroalpine Alps, may be folded and/or faulted, but their stratal continuity has not been severely disrupted. The stratigraphical principles, such as law of superposition, of lateral stratal continuity, and of paleontological dating, are easily applicable. Those strata constitute *normal-stratigraphy sequences.*

The passive-margin sequence overlying the Huabei basement in the Daqingshan Belt ranges from Proterozoic to Ordovician in age, and consist of shallow-water siliciclastics and limestones deposited on a passive margin; they are characterized by trilobite, brachiopod, and cephalopod faunas (Fig. 4).

The Paleozoic cover of the Siberian/Mongolian basement of the Uliastai Belt is also a non-disrupted sequence. The lower strata range from Proterozoic to Cambrian in age, and consist mainly of shallow-water carbonates deposited on a passive margin. The middle and upper Paleozoic strata are distinguished by their association with thick interbedded volcanic formations; this non-disrupted sequence seems to be the sedimentary cover of an active-margin (Fig. 4).

The Permo-Carboniferous formations of the Daqingshan and Sonid Belts seem to overlie unconformably older formations. Those sequences are not much disrupted. They were deposited on the southern shore of the Neimon Ocean (Fig. 4). The upper Paleozoic volcanogenic sequence of the Sonid Unit could be compared to the Jurassic volcanic formations of coastal Zhejiang and Fujian in South China, where the volcanic rocks owe their origin from the partial melting of the Yangzi basement which was thrust under the Huanan block. The volcanoclastic series was deposited on the far side of a deep-sea trough which marked an active plate-margin. Using this analogy, the volcanogenic upper Paleozoic deposits on the southern margin of the Neimon Ocean originated after a mid-Paleozoic continental collision: The partial melting of the Huabei basement, which had been thrust under the Sonidzuoqi basement along a north-dipping crustal fault, gave rise to batholitic intrusions and volcanic activities in the Sonid Belt during late Paleozoic (Fig. 8).

An alternative hypothesis suggests that the Upper Paleozoic volcanogenic strata of the Sonid Belt are correlative to those of the Uliastai rocks of the same age; the former are present as klippes, or erosional remnants of a giant Uliastai Nappe which has been overthrust above the ophiolitic melanges of the Sonid Belt.

Melanges

The sedimentary strata of the Sonid Belt, like those of the Pennine Alps, occur mainly as broken formations, and/or exotic slabs in melanges. The common practices of Smithian stratigraphy are not directly applicable to interprete the stratigraphy of the strata of the *melange-stratigraphy province.*

The methodology of deciphering stratigraphical succession of various exotic blocks in a melange has been described by Hsü (1968) in his paper on *Principles of Melanges.* Where the layering is not the original sedimentary stratification, the law of superposition is not applicable. As exotic blocks of vastly different ages may be tectonically mixed, the discovery of a fossil in any block does not give a date to the whole assemblage of exotics in the melange. We can, therefore, not depend upon contact relation to decipher stratigraphical sequence. The individual rock types have to be dated on the basis of their fossils or by event stratigraphy. Those which constitute a consanguinous suite could then be put together to reconstruct a stratigraphic succession. Hsü & Ohrbom (1969) suggested that a stratigraphic sequence reconstructed on the basis of clasts in sedimentary or tectonic breccias be called a phantom-stratigraphic unit, because the clasts are only a phantom or ghost of their former self.

Ondorsum Ocean Sequence

The Ondorsum Melange is distinguished by the following association of slabs derived from an oceanic realm:

(A) Ophiolite. Slabs detached from ocean crust sequence are well exposed on the banks of Ulan Creek near Ondorsum in the Sonidyouqi district. The sequence, now fragmented and disrupted, consists of green schist and blue schist (metamorphosed palagonite tuff?), pillow breccia and pillow lava, basalt and diabase, gabbros (now chloritized and albitized), and ultramafic rocks (now serpentinized). The basalts of the ophiolite suite have a chemistry typical of middle-ocean ridge type, although volcanic rocks with island-arc affinity have been recognized in the Bainaimiao district. (Li 1987; Hu 1988). The gabbro yielded K/Ar dates ranging from 525–630 Ma (Hu 1988). The basalt of Beilaomiao has Rb/Sr date of 430 Ma, and the blue-schist metamorphism has been dated to be about 440 Ma.

(B) Ferrugenious jasper and banded chert. The chert overlies pillow basalt in the Ulan Creek section, and the siliceous sediments were apparently deposited on ocean crust. The rare faunas in the cherts include *Pylosphaera* spp. (Proterozoic algae), *Acrotretidae* spp. (Cambrio-Ordovician brachiopods), and *Panderodus* spp. (Siluro-Orovician conodonts) (See Shao 1986; Li 1987).

(C) Sandstone, volcanoclastic sandstone, siltstone, slate, and argillaceous limestone, yielding Ordovician graptolites, brachiopod and trilobite faunas, are present as slabs in the melange in the Sonidzuoqi district (Anonymous 1981, p. 46–49).

Excluding other melange slabs and blocks which have been derived from Huabei passive margin, or from the volcanogenic upper Paleozoic, the Ondorsum rocks constitute the basement and sedimentary cover of an ocean (Fig. 4). We suggest the name Ondorsum Ocean to designate this late Precambrian/early Paleozoic Neimon Ocean. The ophiolite formed the ocean crust, the cherts are the pelagic sediments, and the siliciclastics are turbidites and hemipelagic sediments of the Ondorsum Ocean.

Hegenshan Ocean Sequence

The Hegenshan melange is also distinguished by a consanguious association of oceanic rocks, they are:

(A) Ophiolites. Large slabs of serpentine and other ultramafic rocks are present in the area between Xilinhot and Uliastai. Ocean basalt with a chemistry typical of the middle-ocean ridge type has also been reported (CAO et al. 1986, 1987). Dating of the ultramafics by K/Ar method yielded dates ranging from 285–430 Ma. The allochthonous nature of the ophiolites in the Hegenshan area has been verified by drilling. Boreholes have penetrated serpentinite slabs and encountered Jurassic sandstone below the melange (Fig. 5). Gold and copper deposits are found in fracture zones of the ophiolite.

(B) Radiolarian chert. Blocks of interbedded chert and turbidite are overthrust by the large ultramafic slab south of Uliastic. The radiolarian fauna in a chert is characterized by the late Devonian assemblage *Tetrentactinia-Entactinia* (CAO et al. 1986; HU 1988).

(C) Breccia, graded sandstone, and slate. A conglomerate bed overlies the peridotite slab at the gold-copper mine south of Uliastic. The pebbles and cobbles are subangular and are up to 3 or 4 cm long. The ophiolite fragments make up about 90% of the bulk, also present are a few black chert pebbles. The breccia is reported early Permian in age (HAN, personal communication 1988). However, the turbidite strata interbedded with chert are probably Devonian.

Excluding other exotic slabs which may have been derived from the Uliastic or from other parts of the Sonid Belt, the Hegenshan rocks constitute the basement and sedimentary cover of a late Paleozoic Neimon Ocean (Fig. 4), which is designated the Hegenshan Ocean. The ophiolite formed the ocean crust, the chert were the pelagic sediments, and the graded beds the deep-sea turbidites.

Plate Tectonic evolution of the Neimonides

Our analysis of the stratigraphical data confirms the current idea that the Neimonides formed as a result of continental collision. The rocks of the Daqingshan Belt formed the northern passive margin of the Huabei or Sino-Korean Block and those of the Uliastai Belt the southern active margin of the Siberian-Mongolian Block. The tectonic vergence was directed southward: The Uliastai rocks formed the overriding block and the Huabei passive margin was underthrust during their collision.

The simplest model is to assume one Neimon ocean and a late Paleozoic date of suturing. We have to invoke, however, a more complicated two-ocean model (Fig. 8) for the following reasons:

(1) The two melanges of the Sonid Belt are sufficiently distinct in age. The basement and sediments of the Ondorsum Ocean range from late Proterozoic to Ordovician or Silurian in age. Those of the Hegenshan Ocean are mainly upper Paleozoic.

(2) The age of deformation of the Ondorsum Melange is early Paleozoic, as suggested by the radiometric dating of the schists. The Eo-Neimon deformation may have been mainly subduction, but a collision should have taken place during the mid-Paleozoic, because the youngest sediments on the Huabei passive margin is Silurian, and

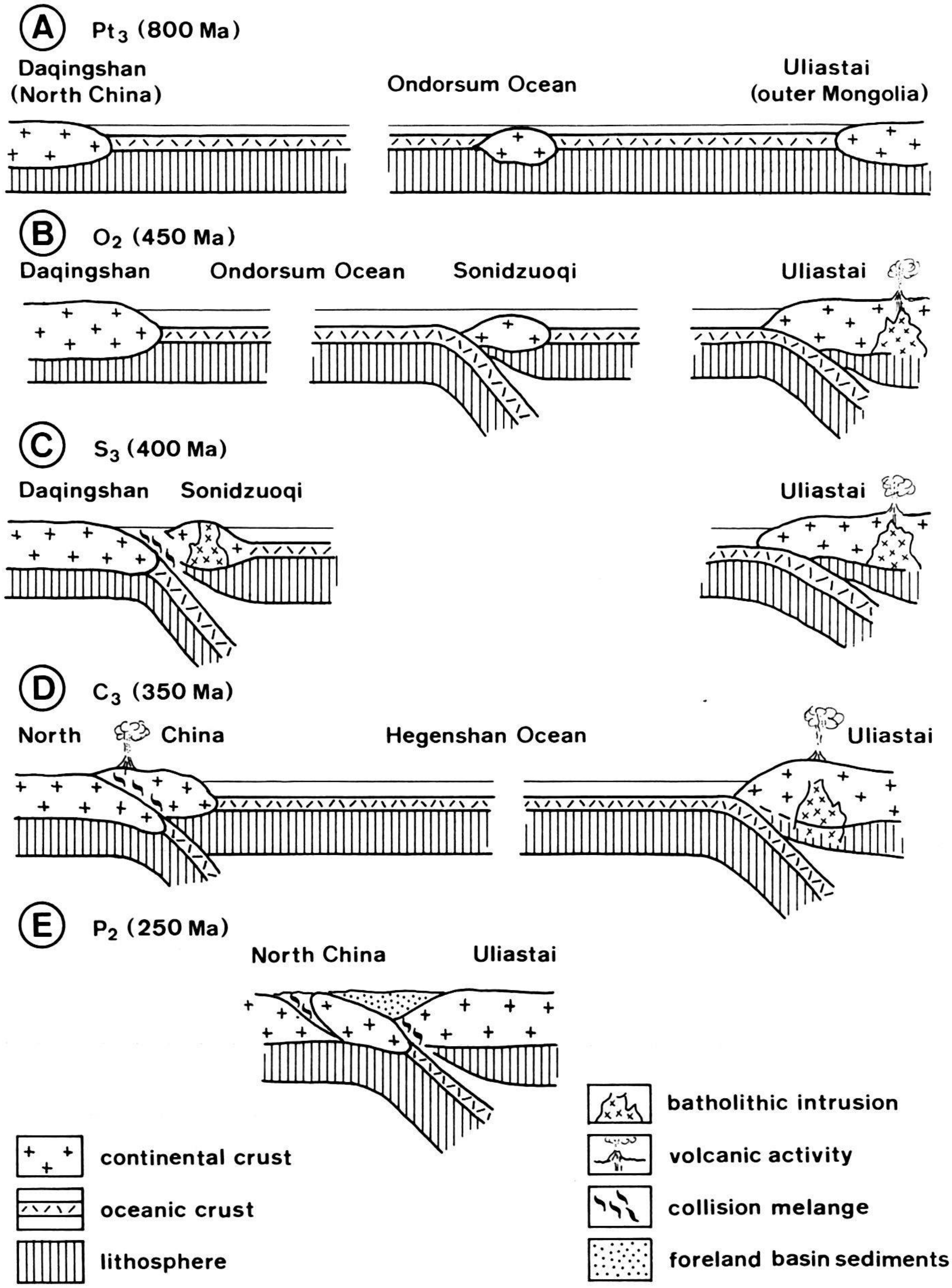

Fig. 8. Plate-Tectonic Evolution of the Neimonides. A. Late Proterozoic (800 Ma): Ondorsum Ocean between North China and Outer Mongolia. B. Late Ordovician (450 Ma): North-dipping Benioff Zone beneath the Uliastai active margin. The Sonidzuoqi metamorphic was either the basement of a western extension of the Uliastai active margin, or that of a mid-oceanic swell (like the Briançonnais of Tethys) underlain by continental crust. The latter hypothesis is represented by this figure. C. Late Silurian (400 Ma): Collision of the Sonid and North China Blocks. D. Late Carboniferous (350 Ma): Consumption of the Hegenshan Ocean. E. Late Permian (250 Ma): Collision of Uliastai (Outer Mongolia) and Sonid/Huabei Blocks, forming a foreland basin above the suture zone.

because upper Paleozoic strata overlie unconformably the Ondorsum Melange in the Sonid Belt. An early Paleozoic Neimon Ocean was apparently eliminated by a continent-continent or arc-continent collision prior to the final Permian suturing.

In the scenario of a three-block and two-collision model, we could assume the presence of a microcontinent or an island arc in the middle of the Neimon ocean. The role of the middle block in the tectonic evolution of the Neimonides would be somewhat analogous to the role of the "Briançonnais Swell" in the Tethyan model, and the Sonidzuoqi metamorphics could be the basement of this mid-oceanic swell.

According to this scenario, the continental blocks existed during the early Paleozoic: The Mongolia (which was then not yet welded onto the Siberian Craton, the North China, and the Sonidzuoqi Blocks, and they are separated by two oceans: the Hegenshan to the North and the Ondorsum to the south of the mid-oceanic swell (Fig. 8a). The Ondorsum Ocean floor was consumed down a north-dipping subduction, until the Sonidzuoqi Swell and the Huabei margin collided during late Silurian or early Devonian (Fig. 8c). The Ondorsum Melange was first deformed in the subduction zone as accretional prisms. Part of the oceanic rocks reached depth exceeding 50 km where they were converted into blue schists. The melange was subsequently squeezed between the colliding blocks and overthrust as suture melange and dragged upward by the overriding Sonidzuoqi Block.

The Bainaimiao metamorphics and the "Variscan granites", thrust under the melange and the Sonidzuoqi Block were the mobilized cover and basement of the Huabei margin (Fig. 8c). The Bayanobo and Daqingshan sequences were detached from their basement and overthrust southward onto the Huabei continent, and they formed decollement folds or strip sheets, although some of the Bayanobo rocks may have been fragmented and tectonically mixed in the Ondorsum Melange. The deformed Precambrian and lower Paleozoic rocks of the melange and on the deformed passive margin in the Sonid and Daqingshan Units were partly eroded before Carboniferous and these deformed rocks were overlain unconformably by upper Paleozoic shallow-water strata (Fig. 8d).

The Sonidzuoqi and the Siberian/Mongolian Blocks were separated by the Hegenshan Ocean (Fig. 8d). Although the rocks in the Hegenshan Melange are mainly upper Paleozoic, the existence of an early Paleozoic ocean south of Outer Mongolia can be surmised: Ordovician and younger Paleozoic strata of the Uliastai Unit were the deposits on the northern active margin of this ocean, where the ocean floor was subducted in the fashion of the present Central Andean margin of the East Pacific.

The Hegenshan Ocean was gradually consumed along a north-dipping Benioff Zone. Granitic batholiths were intruded into older rocks of the active margin. Volcanogenic siliciclastics became the dominant sediments in the shallow marine realm (Fig. 8d). The active margin was under-plated by accretional prisms, and oceanic rocks in subduction melange were uplifted and exposed in a coast range. Their debris were eventually dumped into a deep-sea trench on that margin to form the breccias and turbidites (Fig. 8d) which are now present as exotic slabs in the Hegenshan Melange.

The northern margin of the Hegenshan Ocean was active with andesitic volcanism. The southern margin was probably not an active plate-margin, because there is no evidence for a south-dipping Benioff Zone in the Neimonides. The late Paleozoic thermal activities in the Sonid belt, as we have indicated, was related to the post-collisional underthrusting of the Huabei margin under the Sonidzuoqi Block (Fig. 8d). The tectonic set-up is thus comparable to the late Mesozoic igneous activities in Fujian and Zhejiang provinces, where the batholitic intrusions and volcanic activities were related to the underthrusting of the Banxi Ocean and Yangzi Continent beneath the Huanan Block. An alternative postulate suggests that the volcanogenic rocks are allochthonous in the Sonid Belt.

The collision of the Siberian/Mongolian and the Sonidzuoqi/Huabei Block took place sometime before Late Permian, when the deep ocean between the two blocks was eliminated (Fig. 8e). The compression did not stop, however. The rocks of the Uliastai Belt were thrust steadily southward during the early Mesozoic, pushing the Hegenshan Melange forward till the melange was tectonically superposed above Jurassic continental sediments, which had been laid down in a post-collision foreland-basin (Fig. 5). The evolution of the Neimonides was completed during Late Jurassic or earliest Cretaceous, when regional compression was changed to extension and when the Eren Basin was formed by rifting.

Paleozoic paleogeography of the Neimonides

Our postulate of a Sonidzuoqi Swell, underlain by continental crust in the midst of the Neimon Ocean, finds an analog in the paleogeographic reconstruction of a Briançonnais Swell in the Alpine Tethys. The latter is identified by the sedimentary cover, namely, the Briançonnais/Subbriançonnais sequence, of the swell, and by the Valais Schist (North Penninic schistes lustrés) between the Briançonnais and the Helvetic margin. What is equivalent of the Valais Schist in the Neimonides? Where is the sedimentary cover of the Sonidzuoqi Swell?

The first question is not difficult to answer. The hemipelagic sediments between Sonid and North China must have been largely converted into the matrix of the Ondorsum Melange. The Bailaimiao metamorphics are, at least in part, an equivalent to the Valais Schist, and this Neimonide schist is early Paleozoic in age.

We have no answer to the second question. The Briançonnais cover in the Alps was stripped off to form decollement folds (Klippe Nappe) when this swell (Briançonnais) was thrust under the overriding block (Austroalpine). If this model is applicable, we should find a sedimentary sequence, mainly shallow marine and ranging from Proterozoic to late Paleozoic in age, as the cover of the Sonidzuoqi Swell. Furthermore this sequence should form a zone of decollement folds between the Uliastai and Sonidzuoqi basements. We have not been able to find such a passive-margin sequence similar to the Briançonnais, nor a belt of cover thrusts similar to the Klippe Nappe. Either we have overlooked the existence of Briançonnais-equivalent in the Sonid Unit, or the Alpine model is not applicable.

One way out of the dilemma is to suggest that the Sonidzuoqi basement is a sliver of continental crust which had been ripped off from Outer Mongolia to form an island arc prior to its collision with North China (Fig. 9). According to this scenario, seafloor-spreading of the Neimonides began during Proterozoic, resulting in the growth of the Ondorsum Ocean until late Cambrian or early Ordovician. At that time, the northern margin of this ocean was changed from a passive to an active margin, and the Ondorsum was subducted along a north-dipping Benioff Zone under Mongolia

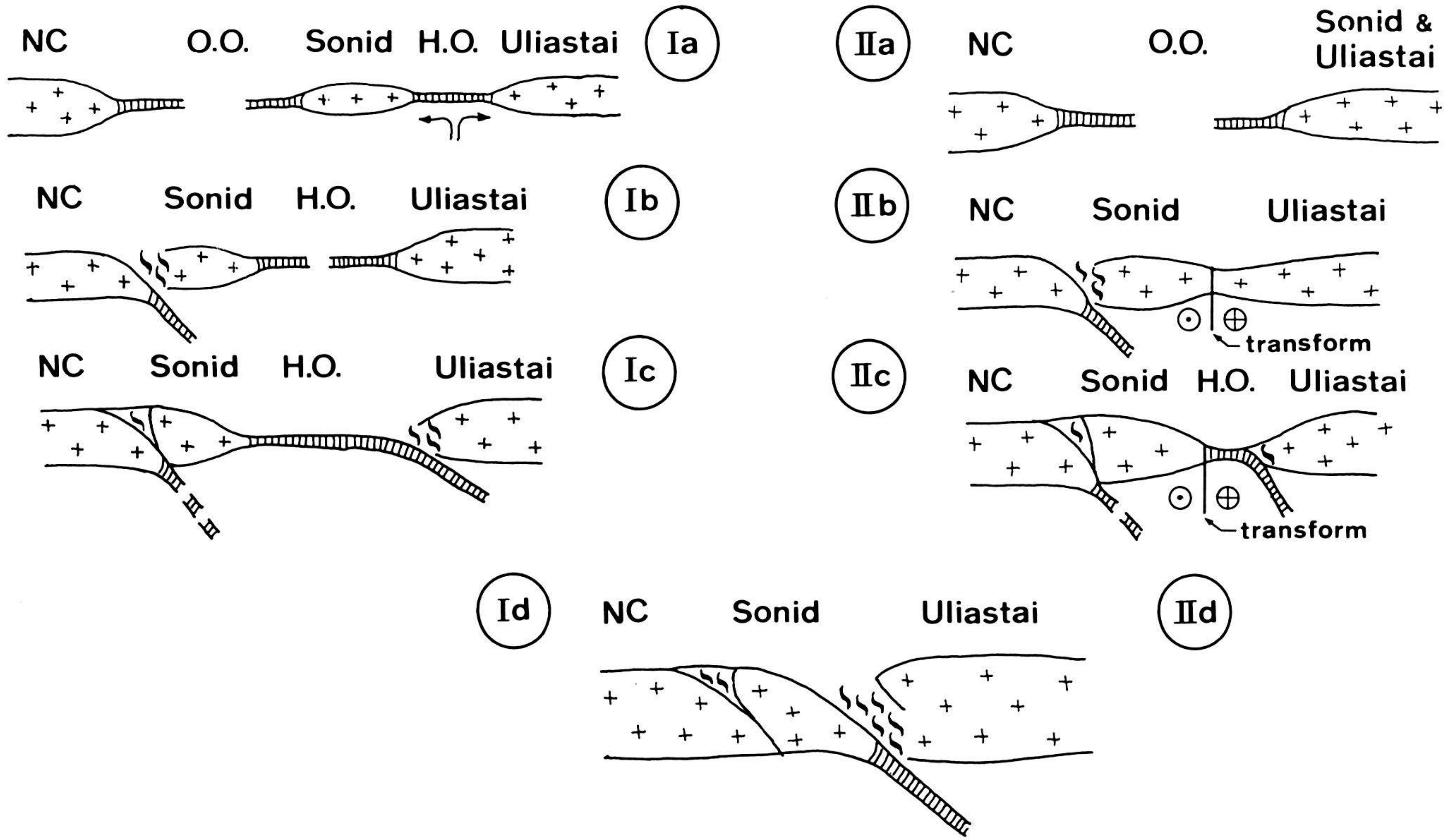

Fig. 9. Two alternative models of the role of Sonid Unit in the evolution of the Neimonides. I) The Sonidzuoqi metamorphic was originally basement on the Outer Mongolian continental margin, but this slice of continental crust was ripped apart from the continent to form a south-facing island arc (Ia). This arc collided with North China in Late Silurian or Devonian time (Ib). The Hegenshan Ocean was a back-arc basin, consumed by a north-dipping Benioff Zone under the Outer Mongolia active margin (Ic). North China and Mongolia collide in late Permian (Id). II) The Sonidzuoqi metamorphic was the basement on the Outer Mongolian continental margin and a western extension of the Uliastai margin (IIa). This western segment of the Mongolian margin collided with North China during mid-Paleozoic (IIb), but not the eastern Uliastai segment. The Sonidzuoqi, accreted to North China, moved by sinistral faults to their present longitudinal position, and the Hegenshan Ocean was a narrow ocean north of a transform margin (IIc). North China and Mongolia collided in Late Permian.

(Fig. 9-Ia). A sliver of continental lithosphere was ripped apart from the latter to constitute an early Paleozoic Sonidzuoqi island-arc. While the subduction of the Ondorsum Ocean continued, the Hegenshan Ocean opened behind the arc (Fig. 9-Ib). The Sonidzuoqi Arc collided with North China sometime during mid-Paleozoic, but the growth of the Hegenshan Ocean during the late Paleozoic (Fig. 9-Ic). Meanwhile, a new north-dipping Benioff Zone was formed under the Mongolian margin. The total consumption of the Hegenshan Ocean by the process of "back-arc basin collapse" led to the Permian collision of Siberia/Mongolia with North China (Fig. 9-Id).

The postulate that the Hegenshan Ocean had originated as an early Paleozoic back-arc basin fails to account for the absence of lower Paleozoic rocks in the Hegenshan Melange. This fact led us to favor a late Paleozoic origin of the Hegenshan Ocean: An alternative to the island-arc hypothesis is to assume strike-slip faulting after a mid-Paleozoic collision. According to this scenario, inspired by a suggestion by Celal Sengör, the Sonidzuoqi basement was originally the western extension of the Uliastai margin (Fig. 9-IIa). This western segment of the Mongolia margin collided with the North China during mid-Paleozoic when the Ondorsum Ocean was consumed (Fig. 9-IIb). The Sonidzuoqi/North China continent was subsequently displaced sinistrally with respect to Mongolia. The Hegenshan Ocean lay to the north of this left-lateral strike-slip fault (Fig. 9-IIc). This inter-continental ocean was consumed, along a north-dipping subduction zone, during late Paleozoic, resulting in the collision of Siberia/Mongolia and Sonidzuoqi/North China (Fig. 9-IId). Such a postulate explains the absence of a passive-margin sequence on Sonidzuoqi Swell: There is no such sequence, because the margin was not a passive margin, but a transform margin. As a matter of fact, the coarse breccias found as exotic slabs in the Hegenshan Melange may have been sediments deposited on such a transform margin.

Implications of the model of the Neimonide evolution

The purpose of writing this article is not to present final solution to a very difficult problem, but to present a working hypothesis and to suggest further studies so that our understanding of the Neimonide evolution could be advanced when those predictions are verified or falsified. The hypothesis predicts continental displacement, trace-element geochemistry of granites, and style of rock deformation, and those predictions could be tested by future studies in paleontology, paleomagnetism, isotope-geochemistry and structural geology.

Continent Displacement

Rate of plate-displacement, as judged from Mesozoic and Cenozoic data, should have been of the order of centimeters per year. The magnitude of the continent displacements should thus be of the order of thousands of kilometers during hundreds of million years. Such large displacements should have been indicated by habitat changes of faunas and floras.

The early Paleozoic positions of the North China and the Mongolia Blocks must have been sufficiently distant that the faunas on the opposite sides of the ocean belong to two distinct provinces. The postulate that the two blocks collided first during mid-Paleozoic and were later again separated could be verified or falsified by paleontological and paleomagnetic investigations.

We do know that the Carboniferous faunas of the Uliastai sediments have Arctic affinities and are thus distinctly different from the coeval Tethyan faunas of the Sonid Unit. The mixing of warm-water elements in the early Permian faunas of the Uliastai sediments indicate a significant southward shift of the position of Siberia/Mongolia. With the elimination of the Hegenshan Ocean in Late Permian, the faunas of both the Uliastai and the Sonid Units belong to the warm-water Tethyan type. The paleontological interpretation of the southward movement of the Uliastai rocks could be further verified by paleomagnetic studies.

The presence of Siberian cold-water fauna in the Carboniferous sediments of the Sonid Unit suggests that the Upper Paleozoic volcanogenic sequence occurs as Uliastai klippes in the Sonid Belt. The postulate could be verified by paleomagnetic studies.

Geochemistry of Granites

In our model, the "Variscan granites" of the Sonid Unit belong to the collision-type (Pitcher 1983), and the upper Paleozoic volcanic rocks of Sonid have been derived from partial melting of continental crust. In contrast, the igneous rocks of the Uliastai Unit should belong to the Andean type. These two entirely different igneous-rock types are characterized by their distinct trace-element chemistry. Studies of Sr isotopes and of Nd model ages could verify the postulated sources for igneous rocks of different origins.

The alternative hypotheses of the origin of the volcanogenic rocks in the Sonid Belt could also be tested by geochemical studies. If the Sonid volcanics are correlatives of the Uliastai, the trace-element chemistry of the two should be similar. Otherwise, the chemistry of the Sonid volcanics should manifest affinity to the "Variscan granites" of the Sonid Belt.

Structural Geology

The postulate that Daqingshan, Sonid and Uliastai units are facies equivalent to the Allegheny/Helvetic, Franicscan/Penninic, and Andean/Austroalpine is an interpretation based upon comparative tectonics. Detailed field mapping and structural geology analysis should verify or falsify the style of deformation postulated for the various units.

In conclusion, we have presented this working hypothesis as a first-order approximation of the tectonic evolution of Inner Mongolia. As we learned from our experience in working on the geology of South China, a tectonic model serves as a unifying theory to order geophysical, geochemical, petrological, paleontological, stratigraphical, structural and sedimentological observations. We expect considerable modifications of this very preliminary proposal. On the other hand, the principal postulate that the Neimonides constitute a south-vergent collision-type of orogen is not likely to be falsified.

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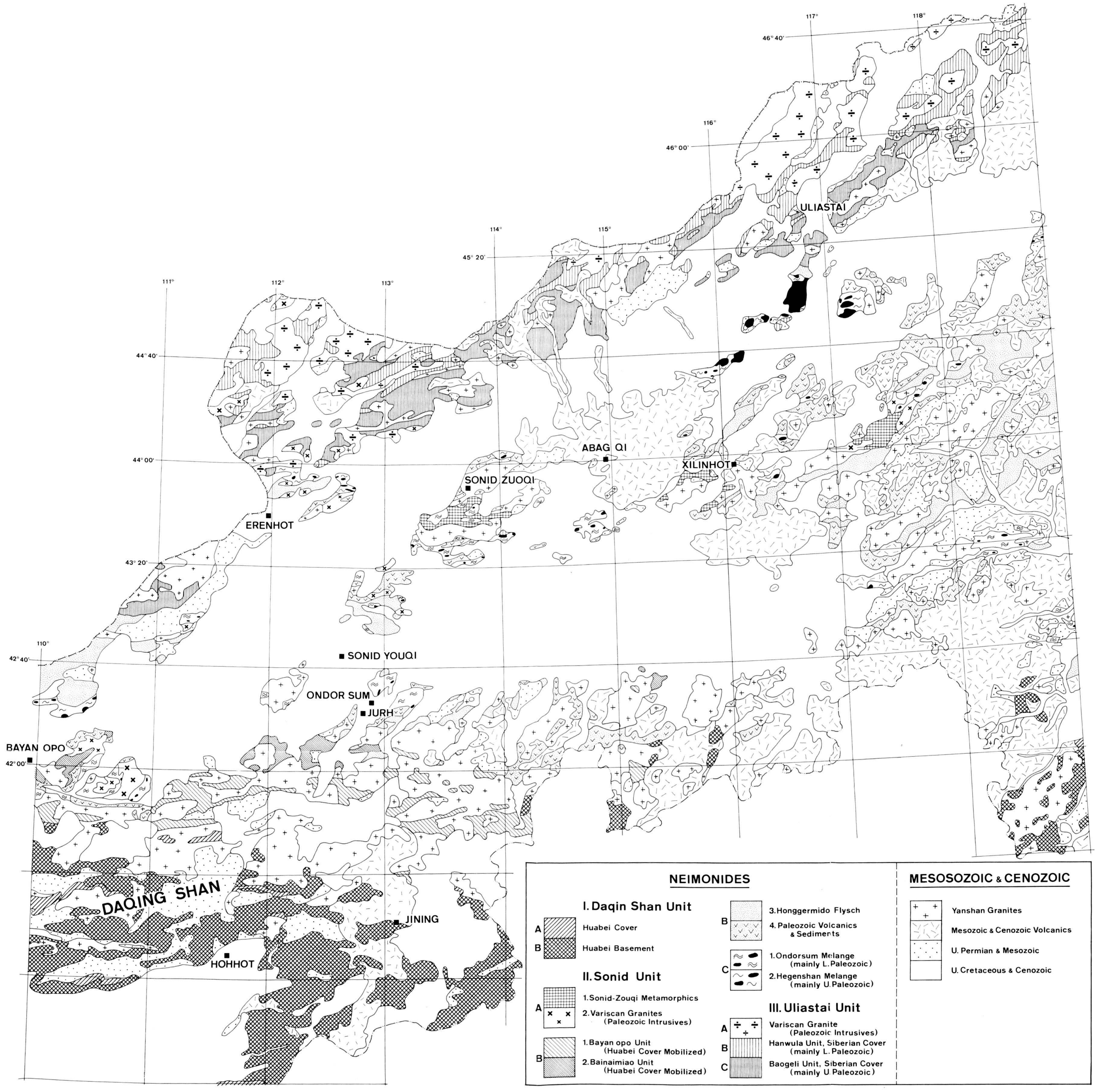
Plate 1

Tectonic Map of Inner Mongolia between 110° E and 119° E. The Neimonides tectonic units corresponding to the Alpine Helvetic, Penninic, and Austroalpine are the Daqingshan (I), Sonid (II), and Uliastai (III). They have been divided into subunits and their distribution is shown by this map. These units are tectonic facies, recognized on the basis of the sedimentological and tectonical significance of the various stratigraphic units which have been mapped by the Bureau of Geology of the Autonomous Region of Inner Mongolia.


117°
118°
46° 40'
116°
46° 00'
ULIASTAI
114°
115°
45° 20'
111°
112°
113°
44° 40'
ABAG QI
44° 00'
XILINHOT
SONID ZUOQI
ERENHOT
43° 20'
110°
42° 40'
SONID YOUQI
ONDOR SUM
JURH
BAYAN OPO
42° 00'
DAQING SHAN
JINING
HOHHOT
NEIMONIDES
I. Daqin Shan Unit
A Huabei Cover
B Huabei Basement
II. Sonid Unit
A 1. Sonid-Zouqi Metamorphics
2. Variscan Granites (Paleozoic Intrusives)
B 1. Bayan opo Unit (Huabei Cover Mobilized)
2. Bainaimiao Unit (Huabei Cover Mobilized)
B 3. Honggermido Flysch
4. Paleozoic Volcanics & Sediments
C 1. Ondorsum Melange (mainly L. Paleozoic)
2. Hegenshan Melange (mainly U. Paleozoic)
III. Uliastai Unit
A Variscan Granite (Paleozoic Intrusives)
B Hanwula Unit, Siberian Cover (mainly L. Paleozoic)
C Baogeli Unit, Siberian Cover (mainly U. Paleozoic)
MESOSOZOIC & CENOZOIC
Yanshan Granites
Mesozoic & Cenozoic Volcanics
U. Permian & Mesozoic
U. Cretaceous & Cenozoic