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Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **87 (1994)**

Heft 1

PDF erstellt am: **28.04.2024**

Persistenter Link: https://doi.org/10.5169/seals-167450

Eclogae geol. Helv. 87/1: 265–292 (1994)

0012-9402/94/010265-28 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Origin of Chinese Tianshan by Arc-Arc Collisions

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Key words: Tianshan, are, back-arc basin, subduction, collision, mélange, pluton, schist

ABSTRACT

Four tectonic units are recognized in Chinese Tianshan: (1) North Tianshan Melange, (2) Middle Tianshan Arc, (3) South Tianshan Melange, and (4) Kelpin/Kuruktag Fold Belt. The Middle Tianshan and Kelpin/Kuruktag were early Paleozoic relic arcs, when the basement of Kunlun was the foundation of an outer volcanic arc on the "southern underbelly" of Asia. South Tianshan was a back-arc basin between the two relic arcs, and North Tianshan was a part of the Junggar Basin. Collapse of the South Tianshan Back-Arc Basin started in Ordovician, and its consumption led to the Devonian collision of the Middle Tianshan and Kelpin/Kuruktag Arcs. The basement and sedimentary cover of Middle Tianshan were thrust southward during late Paleozoic above the South Tianshan Melange and the Kelpin/Kuruktag Fold Belt. The North Tianshan Melange is a late Paleozoic accretionary wedge on the northern margin of the Middle Tianshan Arc, when the ocean lithosphere of the Junggar Basin was subducted southward down the Benioff Zone of that active margin.

ZUSAMMENFASSUNG

Es werden vier tektonische Einheiten im chinesischen Teil des Tianshan Gebirges unterschieden: Die nördliche Tianshan Mélange (1), der mittlere Tianshan Bogen (2), die südliche Tianshan Mélange (3) und der Kelpin/Kuruktag Faltenzug. Einheiten (2) und (4) waren frühe paläozoische Bogenrelikte, als das Grundgebirge des Kunlun den Sockel eines äusseren Vulkanbogens bildete, sozusagen im südlichen «Unterleib» von Asien. Das südliche Tianshan (3) wird als Hinterbogenbecken zwischen den beiden Bogenrelikten (2, 4) verstanden, während das nördliche Tianshan (1) einen Teil des Junggar-Beckens bildete. Der Zusammenschub des südlichen Tianshan-Beckens begann im Ordovicium, und seine Verschluckung führte zur Kollision des mittleren Tianshan mit dem Kelpin/Kuruktag im Devon. Sockel und Sedimenthülle des mittleren Tianshan wurden im späten Paläozoikum südwärts über die südliche Tianshan Mélange und den Kelpin/Kuruktag Faltenzug überschoben. Die nördliche Tianshan Mélange stellt einen spätpaläozoischen Akkretionskeil am Nordrand des mittleren Tianshan Bogens dar, gebildet während der Subduktion des Ozeanbodens des Junggar Beckens entlang der südwärts gerichteten Benioffzone des aktiven Kontinentalrandes.

Statement of Problems

Tianshan, a most prominent mountain range in Asia,·extends from southern Kazakhstan of the former USSR to Xinjiang Uigur Autonomous Region in Northwest China. The Chinese Tianshan lies in central Xinjiang between the Junggar Basin on the north and the Tarim Basin on the south (Fig. 1).

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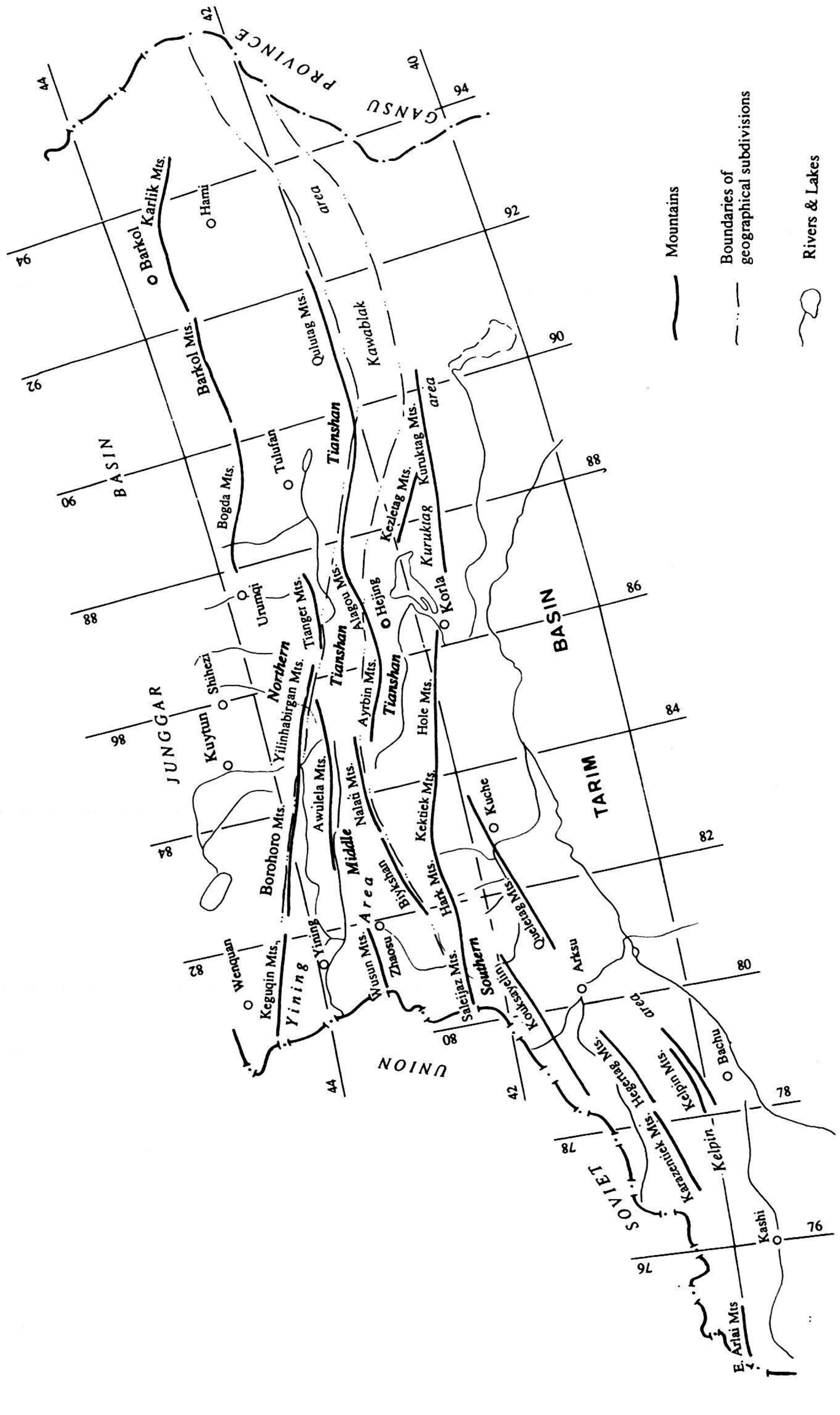

Fig. 1. Location map of mountains of Tianshan (After Geographical Atlas of People's Republic of China 1983).

The Tianshan montains are underlain by Precambrian and Paleozoic igneous and metamorphosed rocks. Nalivkin (1926) identified three Tianshan arcs, the northern, the central, and the southern, and postulated a progressive southward shift of magmatic activities. Nikolaev (1933) recognized a tectonic discontinuity, now called Nikolaev Line, between the central and southern Tianshan, and he pointed out the abundance of ophiolite south of the line. Fossil finds by Chinese scientists permitted stratigraphical taxonomy of Tianshan strata, and the tectonic evolution of Tianshan was interpreted with reference to the geosynclinal theory of orogeny (Yuan and Young 1934; Huang 1945): The Northern Tianshan Eugeosynclinal Folded Belt, the Central Tianshan Basement Uplift, and the Southern Tianshan Miogeosynclinal Fold Belt are the three major tectonic units on geologic maps of Xinjiang (1985).

Invoking the hypothesis of episodic diastrophism, Sinischin and Sinischin (1958) postulated a Central Tianshan Caledonide, flanked by Northern and Southern Tianshan Hercynides. This scheme was adopted by Chinese scientists who envisioned a Central Tianshan Geanticline flanked by Northern Tianshan Eugeosyncline and Southern Tianshan Mioeosyncline (Huang 1978; Huang et al. 1980). Li and others (1982) adopted the terminology of the plate-tectonic theory. The Northern Tianshan eugeosynclinal rocks were called ophiolite melanges, and they were considered the suture zone between the Sino-Korean and the Siberian Plates. Similar scenarios have been suggested, but the essence has been to postulate Tianshan deformation induced by a collision of micro-continents Tarim and Junggar; the ophiolite melanges in Tianshan mark the suture of this collision (e.g., Zhang 1983; Huang 1984).

Since the presence of more than one belt of ophiolite melange in Tianshan were recongized, Huang Jiqing and his associates invoked the theory of polycyclic orogeny and considered their new theory a synthesis of the classic geosynclinal theory of orogeny and the modern plate-tectonics theory. This synthesis, published in 1990 by the Xinjiang Bureau of Geology and the Chinese Academy of Geological Sciences, is however just another geosynclinal theory of mountain building (Wang et al. 1990). The essential idea is not much different from Bucher's (1933) hypothesis of alternating global extension and compression. Instead of global geosynclinal cycles and orogenic phases, compressional and extensional "phases" of regional synchroneity were assumed. The sediments of Tianshan were deposited in geosynclines of different ages, formed during repeated episodes of fragmentation of an old craton. As shown by a series of sketches in Figure 2, a Middle Tianshan Eugeosyncline came into existence between Tarim and Junggar Blocks during Proterozoic. The first suturing took place during Ordovician when this Middle Tianshan Eugeosyncline was consumed and a new West Junggar Eugeosyncline was born. The latter was deformed by a continental collision in Silurian/Devonian time. At about the same time but more to the south, a Southern Tianshan Eugeosyncline made its debut. That eugeosyncline was in turn eliminated by continental collision in Early Devonian, when an Eastern Junggar Eugeosyncline first appeared. This last eugeosyncline was again eliminated by continental collision during Carboniferous. Then a Northern Tianshan Eugeosyncline became the site of an ocean separating Siberia and North China. The last act was the Permo-Carboniferous Hercynian Orogeny when the two continents collided. The southern Tianshan rift was formed shortly after the collision.

There were, according to the theory by Wang and others 5 eugeosynclines, 5 continental collisions, and one rift valley formed by alternate phases of extension and com-

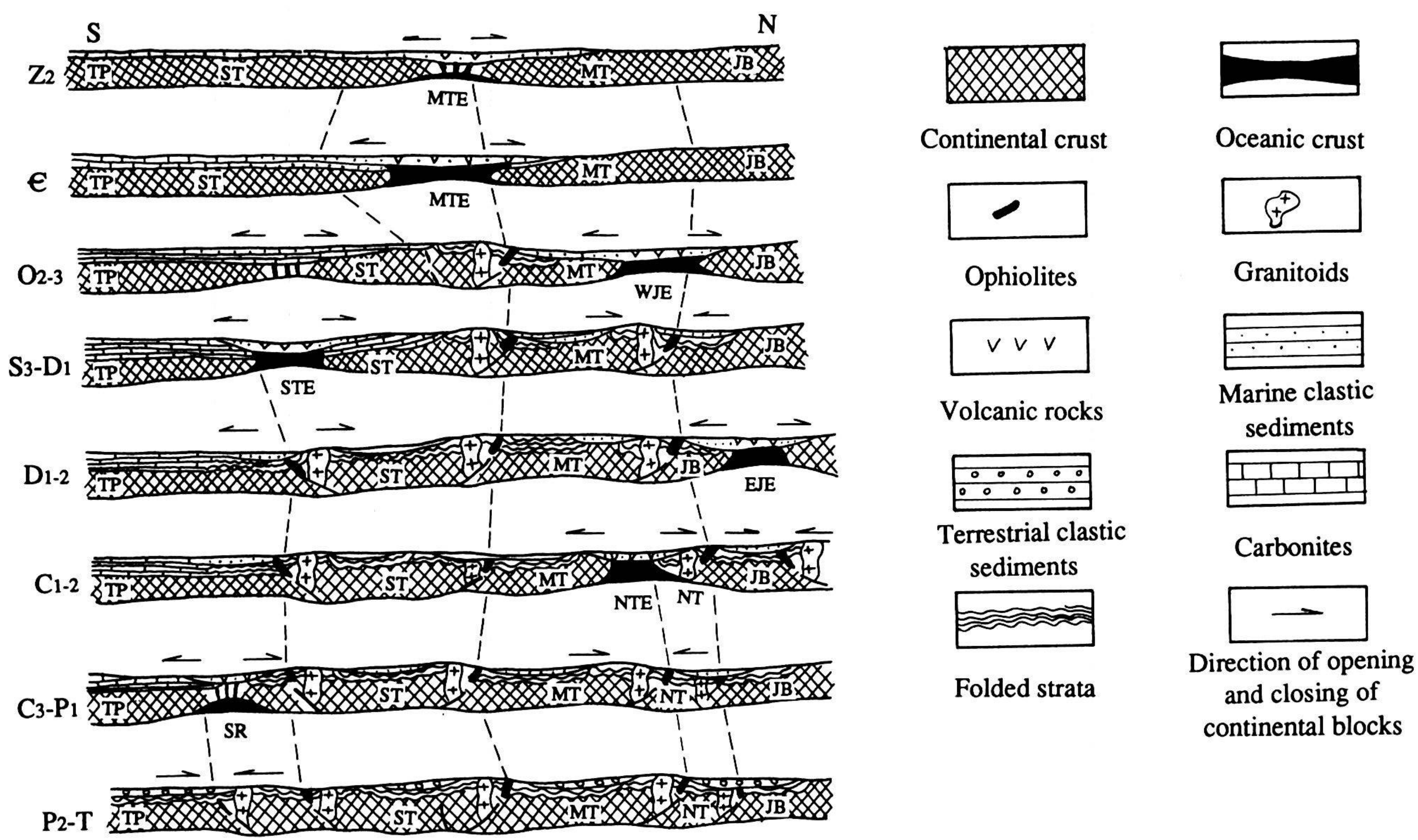

Fig. 2. Interpretation of the Tianshan geology on the basis of polycyclic geoosynclinal deformation. (After Wang et al. 1990).
MTE = Middle Tianshan Eugeosyncline, WJE = West Junggar Eugeosyncline, STE = South Tianshan Eugeosyncline, EJE = East Junggar Eugeosyncline, NTE = North Tianshan Eugeosyncline, JB = Junggar Basin, MT = Middle Tianshan, ST = South Tianshan, TP = Tarim Plate.

pression. This seemingly sophisticated interpretation relies, however, on a dogmatic assumption that each poorly dated ophiolite zone marks the suture zone of an inter-continental collision during an orogenic phase. Our studies of the Tianshan geology indicate the falsehood of the assumption, because we could find neither evidence for inter-continental geosynclines nor for episodic orogeny.

The main aim of this study is to interpret the geology of Tianshan on the basis of actualistic analogues. In carrying out this study as a part of a Sino-Swiss Program on Tectonic Facies Map of China, we have made literature surveys as well as field studies to calibrate descriptions and interpretations in geological literature on the basis of actual observations. The geologic information, unless specifically referenced otherwise, is abstracted from the publications of the Xinjiang Bureau of Geology (Xinjiang 1981; 1985). To verify the library information, field work was carried out in 1983, 1988, 1990, and 1992, and numerous traverses were made across Tianshan. K. J. Hsü and Sun Shu travelled from Urumqi to Tulufan in 1983 and recognized the occurrence of ophiolite melanges in northern Tianshan. Hsü, Li and Wang made an eastern transect in 1988 from Urumqi via Tulufan to Korla, and identified ophiolite melanges in southern Tianshan. They made another transect in 1990 from Urumqi via Shengli Daban (Victory Pass) to Korla. Finally K. J. and Peter Hsü made several transects in 1992 across central and western Tianshan: they investigated the stratigraphy of the Middle Tianshan Arc of the Yining region, the South Tianshan Melange north of Kuche and east of Hejing, and the Kelpin Folded Belt west of Arksu and north of Kashi. Invoking the principles of comparative tectonics, and identifying tectonic facies in the field, we arrived at the conclusion, as presented in this article, that the geology of Tianshan is a record of early Paleozoic back-arc seafloor spreading, middle Paleozoic arc-arc collision, and upper Paleozoic subduction. There were neither geosynclines nor continental collisions.

Tectonic Units of Tianshan

Suess (1909) recognized two major types of mountains – the Tethys and the Circum Pacific. Plate tectonic theory has related them to two different categories of plate interactions: the Circum-Pacific mountains result from subduction of oceanic lithosphere under continent, whereas the Tethyan mountains are formed by collisions, continent-continent, arc-continent, or arc-arc collisions (Dewey and Bird 1970; Hsü 1981).

After the recognition that the Junggar is underlain by ocean lithosphere, we had to abandon the classical postulate that the Tianshan Mountains were formed by continent-continent collision. We made an observation in 1988 that North Tianshan is underlain by melanges, and we postulated an origin of Tianshan by ocean-continent interaction during Paleozoic, when the ocean lithosphere under the Junggar Basin was subducted under Serindia, a micro-continent north of the Tarim Basin (Hsü et al. 1990). A transect of the range across the Shengli Daban in 1990 revealed, however, that the continental basement of Middle Tianshan is separated by another belt of melange, the South Tianshan Melange, from the Kelpin/Kuruktag Fold Belt. Furthermore, in consideration of the fact that the Tarim Desert is underlain by ocean lithosphere, the strip of the continental crust between Tarim and South Tianshan is very narrow; there could have been no continent, but only an island arc under the fold belt. We now recognize four tectonic units in the Chinese Tianshan Mountains, as shown by Figure 3:

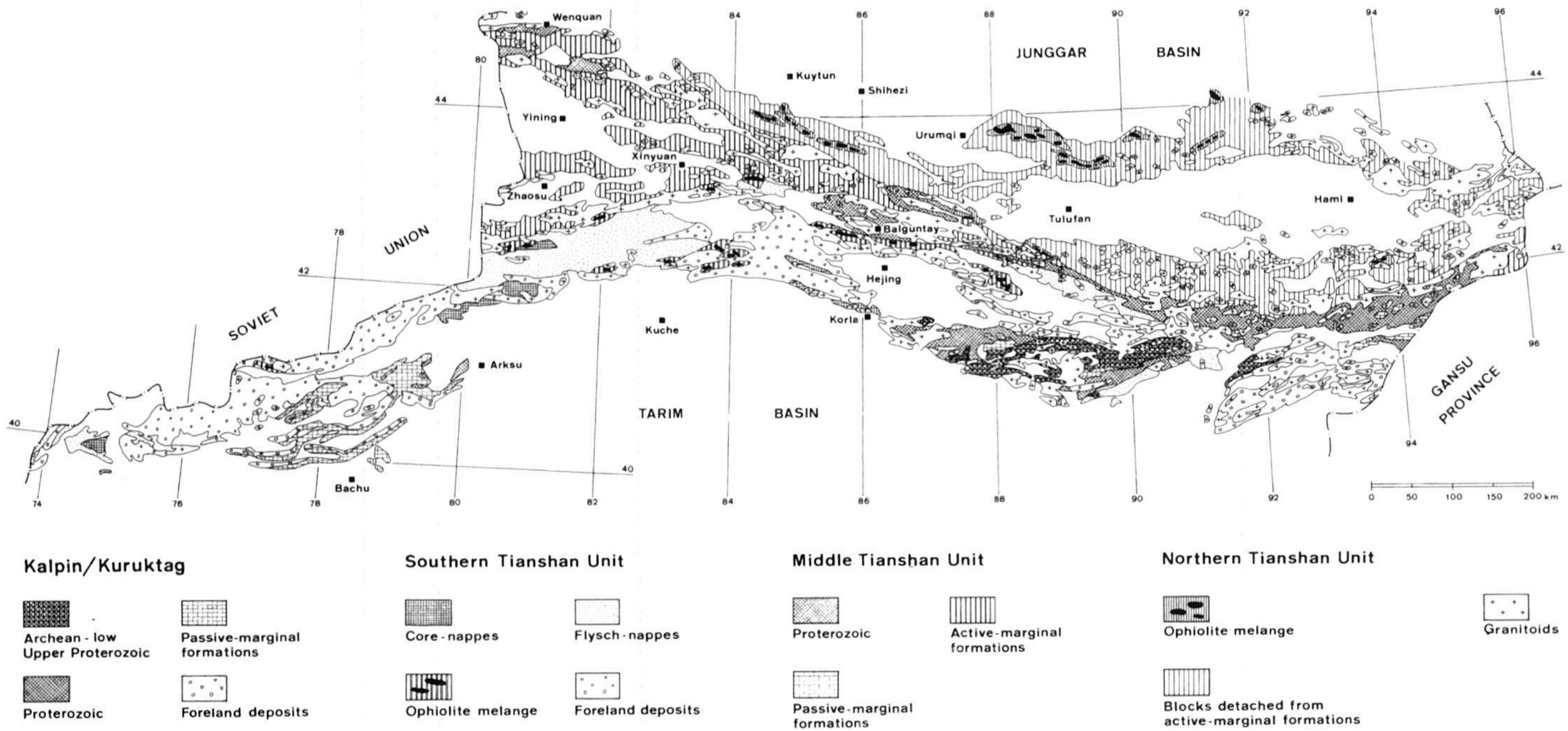

Fig. 3a. Sketch geological map of Tianshan (Modified after Xinjiang 1985).

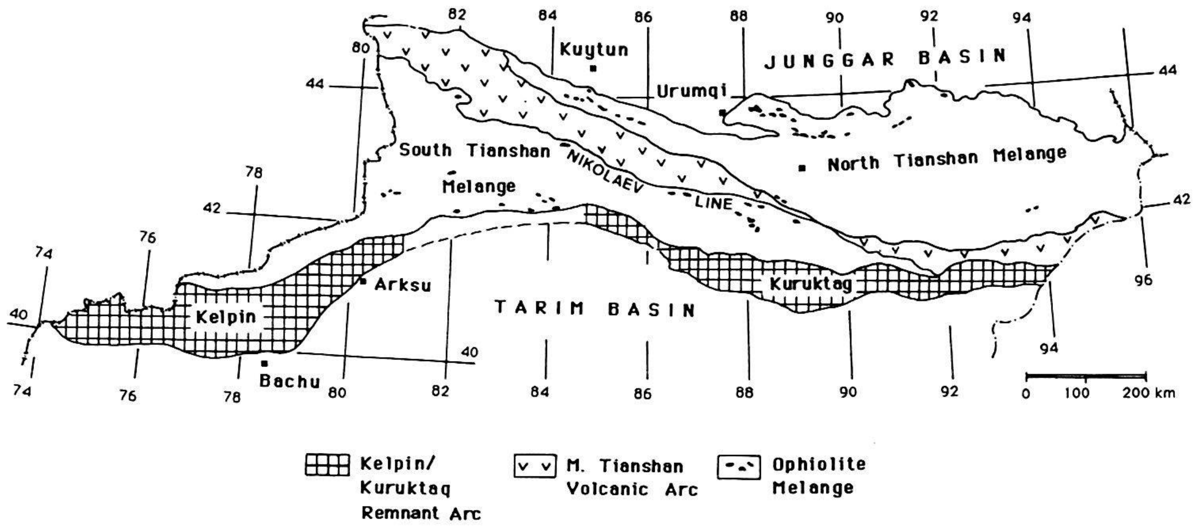

Fig. 3b. Tectonic facies map of Tianshan.

(1) North Tianshan Melange Belt
(2) Middle Tianshan Arc
(3) South Tianshan Melange Belt
(4) Kelpin/Kuruktag Fold-and-Thrust Belt

The North Tianshan is separated from Middle Tianshan by a shear zone. Mylonite in the shear zone crops out near Shengli Daban on the Urumqi-Korla Highway. Middle Tianshan is separated from South Tianshan by the so-called Nikolaev Line. Ophiolites, except those in Precambrian basement are absent in Middle Tianshan; they occur as exotic slabs in the South Tianshan Melange. The melange is separated from the foreland fold-and-thrust belt by a shear zone; mylonitized marble is present at the contact between the two units.

The Tianshan units are comparable to tectonic facies identified in other orogenic belts (Hsü 1991a; 1993). The deformed rocks from the overriding plate, the suture zone, and the underthrust plate, as exemplified by the Helvetic, Penninic, and Austroalpine nappes of the Swiss Alps, have been designated Raetide, Celtide, and Alemanide tectonic facies respectively (Fig. 4). North Tianshan is a celtide with a northerly vergence, and the alemanide is the Junggar Basin (Fig. 3). The geology of North Tianshan is thus comparable to that of circum Pacific mountains (Hsü et al. 1990). Middle Tianshan was an early Paleozoic remnant arc which became an active volcanic arc when the South Tianshan Ocean was subducted along a north-dipping Benioff Zone under the arc. The consumption of the ocean basin caused an arc-arc collision with southerly vergent deformation. Middle Tianshan, the overriding block, became the raetide, while foreland deformation took place in the Kelpin area of the Tianshan foothills and in the Kuruktag Mountains (Fig. 3). The South Tianshan Melange is the celtide suture, and the Kelpin/Kuruktag the alemanide of this arc-arc collision.

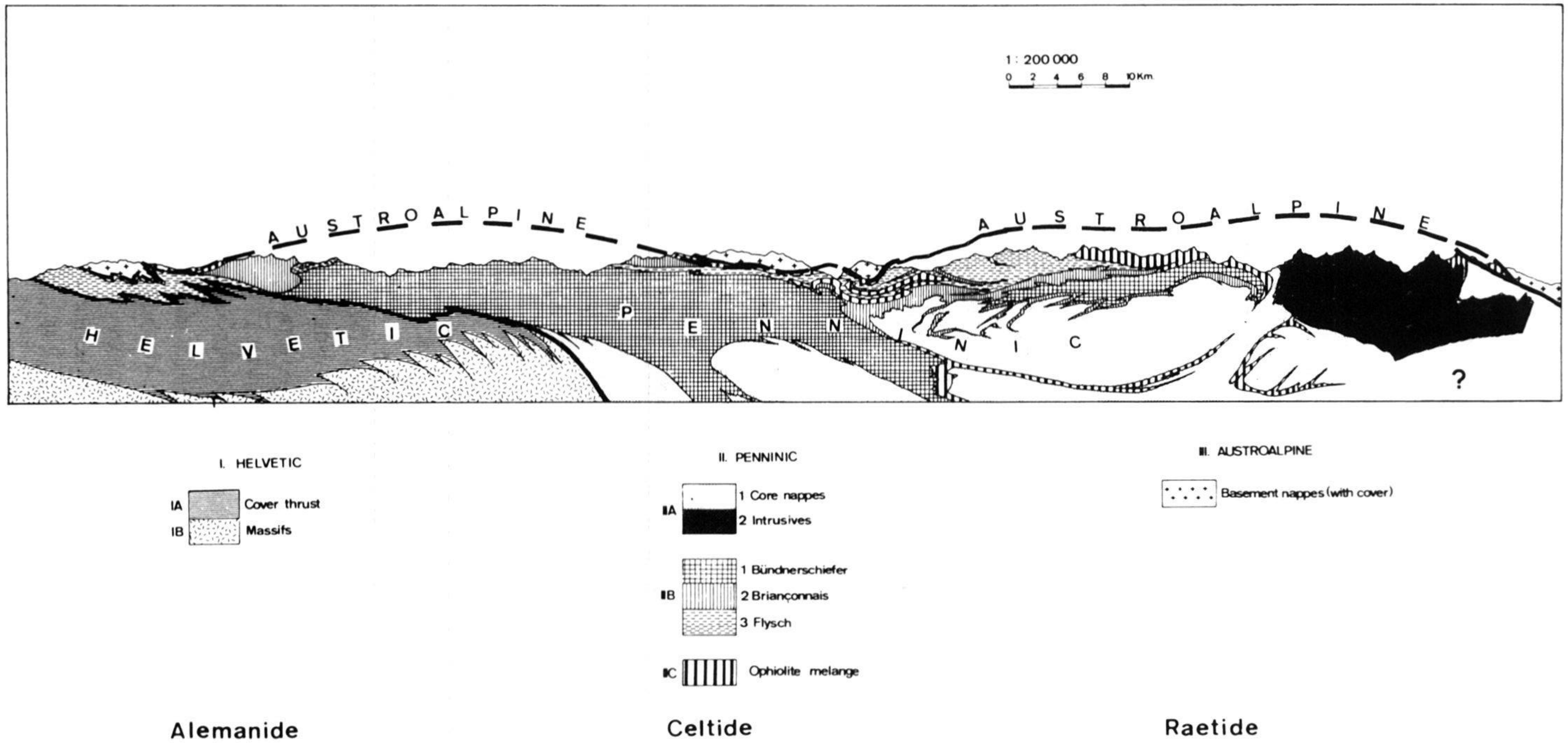

Fig. 4. Tectonic facies of mountains of collision type, exemplified by the Alpine geology (after Hsü 1991b). The three majoir tectonic units of the Alps are Helvetic, Penninic and Austroalpine, corresponding to Alemanide, Celtide and Raetide facies.

Tianshan Stratigraphy of Smithian Terrain

Where sedimentary formations have retained their lateral continuity, Laws of Superposition, of Lateral Continuity, and of Paleontological Dating provide the basis for geologic mapping; those areas have been called Smithian terrains (Hsü 1991b, 1993). Where layered rocks are separated by shear surface, these stratigraphical "laws" are not applicable; the principles of melanges (Hsü 1968) should be invoked to interpret the geology of non-Smithian terranes. Of the Tianshan rocks, those of the Middle Tianshan Arc and of the Kelpin-Kuruktag Fold Belt constitute Smithian terranes (Fig. 3).

The Precambrian and Lower Paleozoic of the Kelpin-Kuruktag Folded Belt

The oldest rocks of Tianshan are the Archaean of the Kuruktag Mountains, northeast of the Tarim Basin (Fig. 3). These rocks are granite, gneiss, schist, migmatite and marble. Their radiometric age ranges from 3200 Ma 1800 to 1900 Ma (Zhou 1987). Precambrian rocks with Rb-Sr age of 1700 to 1900 Ma have also been identified in the Kelpin area of southwestern Tianshan (Cheng et al. 1986).

The Proterozoic rocks of the Kuruktag Mountains (see Fig. 1 & 3), including both carbonates and terrigenous clastics, are metamorphosed. Middle and early Late Proterozoic microfloras are present in metamorphic limestones. Granite intruding into meta-sedimentary rocks has a whole rock Rb/Sr age of 920 Ma (Xinjiang Petroleum Co., unpublished information, 1989). Also identified as lower Upper Proterozoic are the volcanic rocks of the Kuruktag Mountains. They include andesites, basalt, tuffs, and acid volcanic rocks of calc-alkaline affinity (Cheng et al. 1986).

The upper Sinian, or the upper Upper Proterozoic, rocks crop out only west of Arksu in the Kelpin foothills (Fig. 1 & 3), where they underlie unconformably the Sinian and Paleozoic. The basement rocks include mica schist, green schist, phyllite, glaucophane schist and marble. A Rb-Sr whole rock age of the glaucophane schist is 1100 Ma (Liou et al. 1989). The phyllites and schists of the low greenschist facies were metamorphosed prior to the deposition of the overlying Sinian and Paleozoic sediments.

The geology of the Precambrian rocks now found in scattered outcrops of Tianshan has to be interpreted with reference to the Precambrian geology of China. Archaean, Lower, Middle, and lower Upper Proterozoic rocks of China, 1500 Ma or older, are the basement rocks of the Precambrian Asia. They crop out in various areas within the Sino-Korean Craton and they are identified in several Chinese orogenic belts (Fig. 5). The shallow marine Middle and lower Upper Proterozoic rocks of the Kuruktag and Borohoro Mountains were the sedimentary cover of this old craton. Upper Proterozoic volcanic rocks, granite plutons, and glaucophane schists occur in an east-west trending belt which extends from Tianshan, to Kunlun, Altun and Qinling, and from there to Yangtze and South China (Fig. 5). Late Precambrian volcanic rocks constitute the oldest Sinian formations of central and south China. Pre-Sinian granites of the I-type are dated 950 to 850 Ma. The radiometric ages of the ophiolite and of the metamorphic rocks range from 1100 Ma to 700 Ma (Liou et al. 1989; Nakajima et al. 1989). Invoking the plate-tectonic model, those latest Precambrian rocks are considered the product of arc-magmatism and the accretionary complex formed in the subduction zone of an active margin, where the lithosphere of a vast ocean was tucked under Siberia. The occurrences of those late

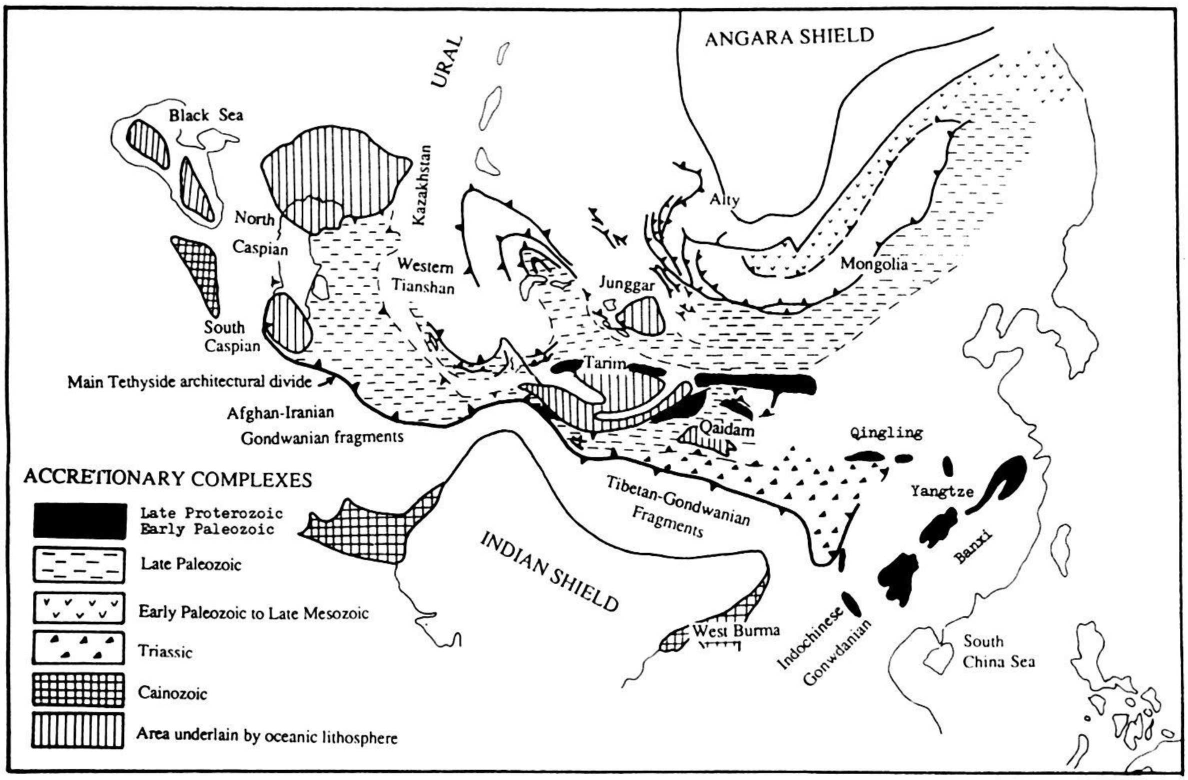

Fig. 5. Accretionary complexes of Asia (After Sengör & Okugullalri 1992).

Precambrian rocks from Tianshan to coastal China indicate, therefore, the presence of an Andean type of accretionary margin on the southern margin of the late Proterozoic Siberia.

The oldest sediments above the basement of the Kelpin Belt are Sinian (800 to 600 Ma). The basal Sinian formation, overlying unconformably the Upper Proterozoic, consists of pebbly conglomerate and sandstone (Fig. 6). The clasts are mainly well-rounded pebbles of black chert, and they are embedded in a quartzitic sandstone matrix. A few clasts of the underlying schists have been found locally (Liou et al. 1989). The mature petrography of the basal Sinian signifies deep-weathering of a continent (or island) of moderate or low relief. There is no sign of volcanism in the nearby-region. The basal conglomerate is overlain by shallow marine siltstone, sandstone, limestone, dolomite, and stromatolite carbonates. Tillite, diabase flows, and tuff layers are intercalated. The age, determined on the basis of the abundant microfossils, is correlative to that of the Sinian Tushantio and Denying formations of the Yangtze region. The Sinian strata of the Kuruktag Mountains consist of sandstone, silty mudstone, intercalated tillite, conglomerate and limestone (Fig. 7). The Sinian age of the microfloras is verified by the event-stratigraphy of late Proterozoic glaciation.

The Cambrian and Ordovician of Kelpin, overlying disconformably the Sinian, are mainly carbonates (dolomite and limestone) and shale above a basal phosphate deposit (Fig. 6); those strata are dated by trilobites, microfloras, algal stromatolites and other fossils. The Cambrian trilobites, like those of the Yangtze region, belong to the Pacific Faunal Province. The Ordovician fauna, including beside trilobites, graptolites, corals,

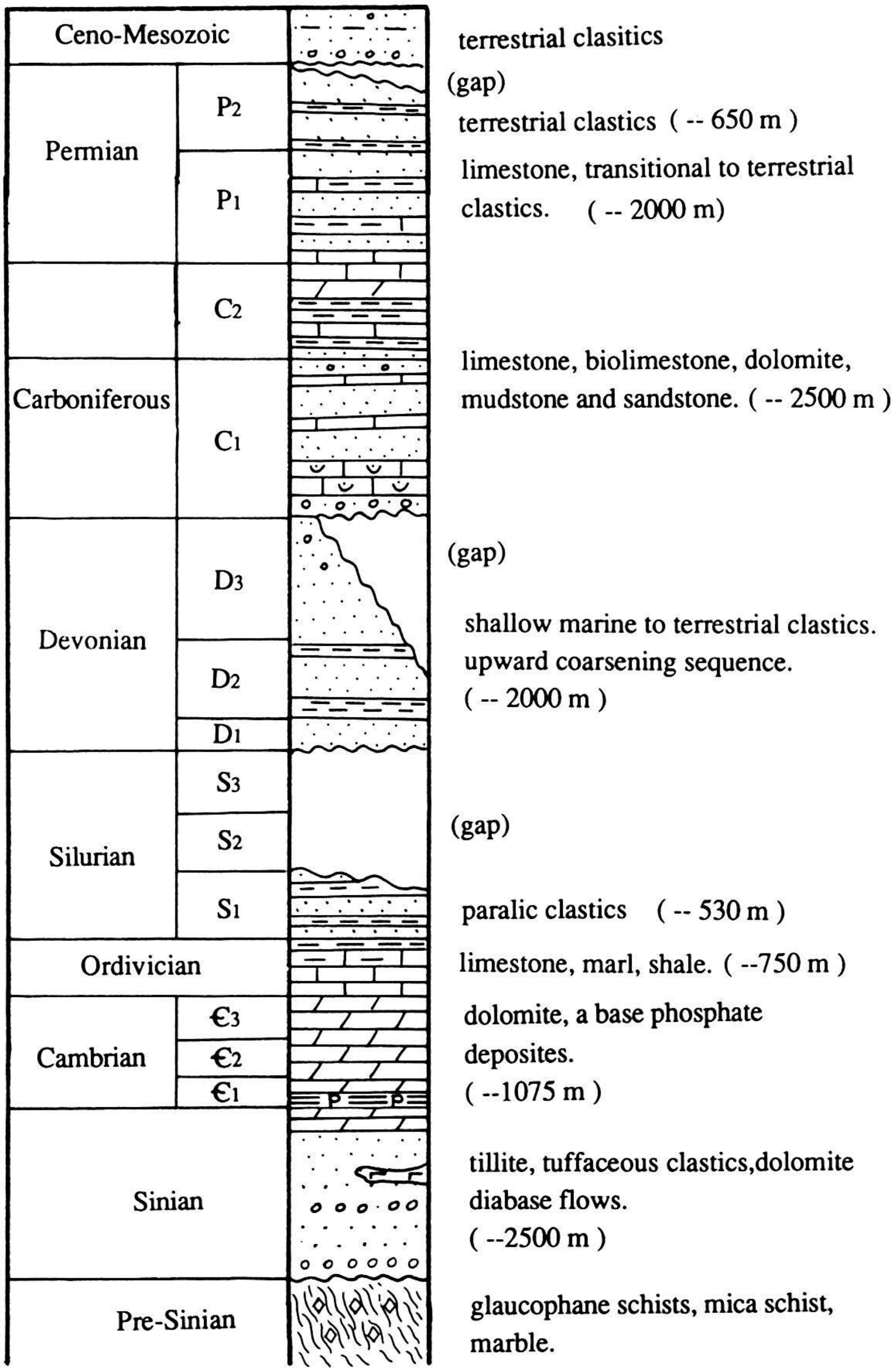

Fig. 6. Columnar stratigraphic section of the Kelpin area (After Xinjiang 1981).

conodonts, cephalopods, also shows affinity to the correlative fauna of the Yangtze region. The Silurian is terrigenous. Interbedded in shale and siltstone are graywacke beds. The Early Silurian faunas are charaterized by graptolites, trilobites, brachiopods, and pelecypods, correlative to those of the Yangtze in the east, and those of the Kazakhstan in the west.

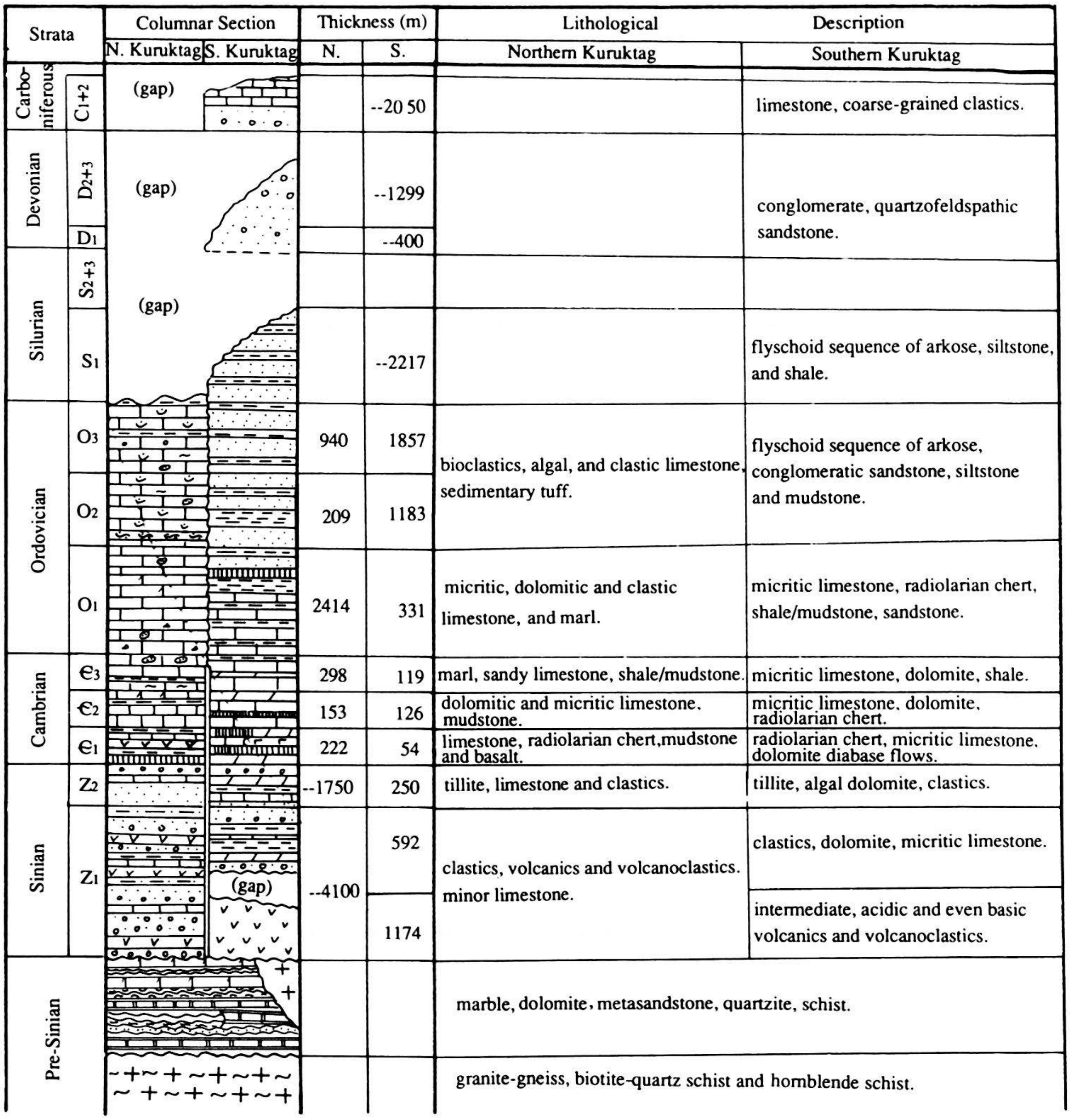

Fig. 7. Columnar stratigraphic sections of the Kuruktag Mountains (After Xinjiang 1981).

A lower Paleozoic shallow marine sequence, correlative with that of Kelpin, is also present in the northern Kuruktag Mountains (Fig. 7). The Lower Cambrian rocks include chert, cherty shale, phosphate, tuff, basalt, and andesite, grading upward to limestone, argillaceous dolomite, and calcareous sandstone. Aside from sponge spicules in chert, trilobite and brachiopod faunas are present. The Middle and Upper Cambrian strata are mainly shallow marine carbonates, including calcarenite, calcirudite, micritic limestone, dolomite, algal stromatolite, etc. The Cambrian trilobite faunas are correlative to those of the Yangtze region, of Australia, as well as to the Soviet Union.

The Lower and Middle Cambrian formations of the southern Kuruktag Mountains are mainly shallow marine carbonates, similar to those in the northern Kuruktag (Fig. 7). The Upper Cambrian consists, however, of interbedded limestone and shale, grading upward into Ordovician deep-water deposits. Those include flysch-like interbeds of siltstone, shale, and sandstone, as well as radiolarite, totalling 2000–3000 m in thickness. Whereas the northern Cambro-Ordovician faunas are mainly shallow marine benthic trilobites, brachiopods, pelecypods and corals, the southern faunas are dominated by pelagic forms such as graptolites, conodonts, and radiolarians. The Silurian strata of the Kuruktag Mountains are all deep marine, consisting of graptolite shale, siltstone and sandstone, ranging up to more than 2000 m thick.

The lateral facies change of the lower Paleozoic strata suggests a deepening of the Kuruktag margin southward, and that an Ordovician deep-water basin was present under the eastern Tarim Desert. This is verified by seismic and subsurface data: Tarim was a back-arc basin north of a North Kunlun island-arc (Yao and Hsü 1993). The central depression of the basin lay under the northeastern Tarim Desert. The deep-water Ordovician is not present in the Kelpin foothills, and the Ordovician strata penetrated by wells in the Korla-Kuche area of the northwestern Tarim Basin are also shallow marine sediments.

The Upper Paleozoic Formations of the Kelpin/Kuruktag Folded Belt

Overlying the lower Paleozoic strata of Kelpin, with a marked angular unconformity, are dominantly clastic Devonian, Carboniferous and Permian formations (Fig. 6). The Devonian consists of shallow marine siltstones, mudstone, and fine-grained sandstone, grading upward into redbeds of coarse sandstone and conglomerate, totalling locally more than 2000 m in thickness. Pelecypods and brachiopods are present. The Carboniferous strata, including siltstone, sandstone, shale, micritic and bioclastic limestone, and conglomerate are transgressive, and they overlie unconformably Silurian and older rocks. The Permian strata are carbonates and terrigenous clastics and interstratified basalt flows. The Permo-Carboniferous corals, brachiopods, conodonts, and fusulinids have close affinity to those of the Yangtze Province.

The stratigraphy of the upper Paleozoic sequence in the Kuruktags is similar. Overlying unconformably the older rocks are the Devonian and Carboniferous shallow marine and continental detrital deposits (Fig. 7). The Devonian red beds of the southern Kuruktag are arkoses and conglomerate. The Carboniferous are predominantly clastic deposits – conglomerate and sandstone, grading upward into an evaporitic shale, limestone and dolomite. Their age is indicated by plant fossils and brachiopod fauna.

The upper Paleozoic rocks of the Kelpin/Kuruktag Folded Belt are similar to those encountered by drilling in the Tarim Basin, where the sequence is a few thousand meters thick.

The Precambrian and Paleozoic of the Middle Tianshan Arc

The oldest basement rocks of Middle Tianshan occur in a belt which extends from the vicinity Balguntay southeastward till Hami (Fig. 3). Those gneisses and marbles, some Archean but mainly Proterozoic, occur as large slabs in schists (Xinjiang 1985). The

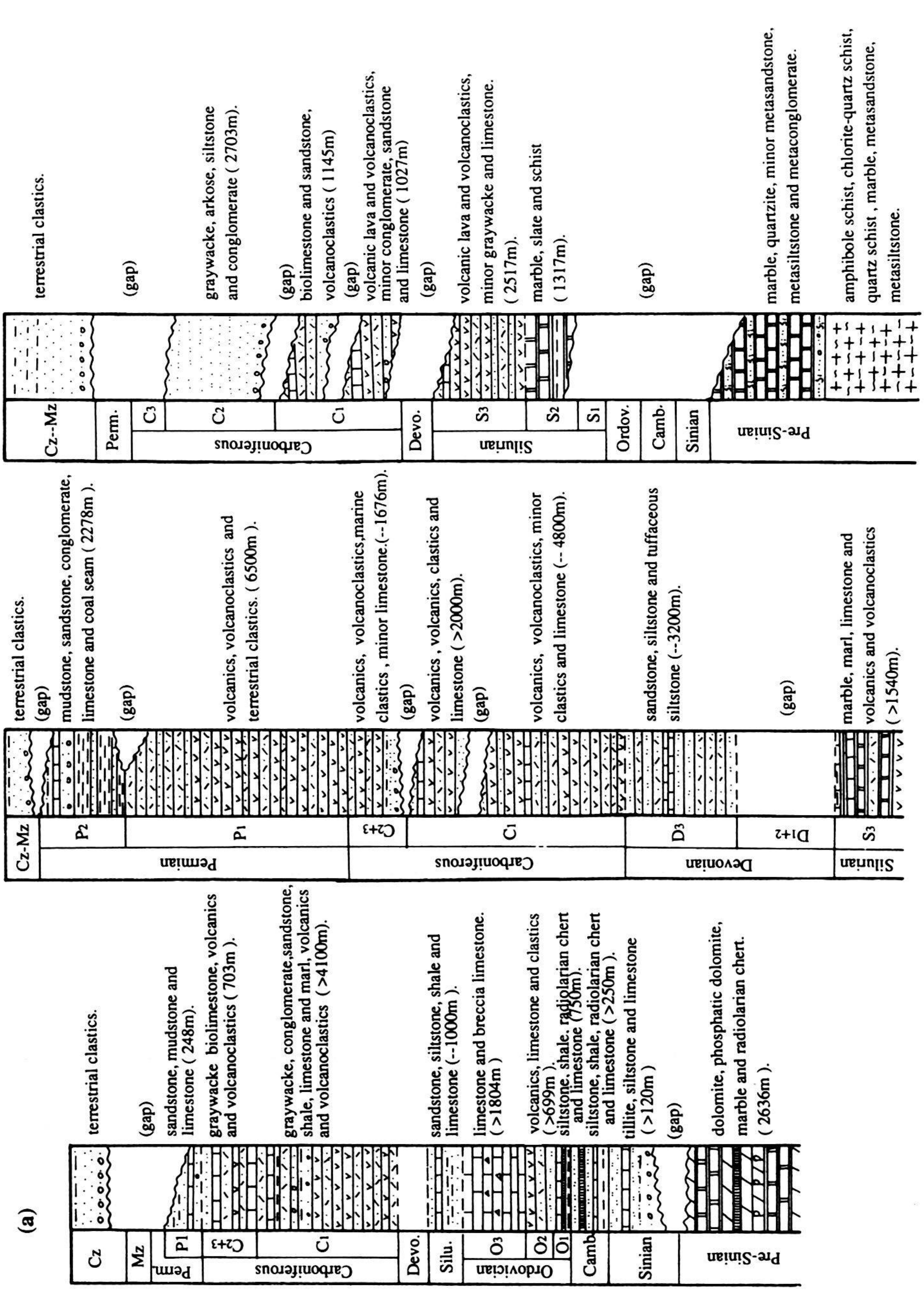

Fig. 8. Columnar stratigraphic sections of Middle Tianshan (After Xinjiang 1981).

sedimentary cover of the craton also crops out in the Borohoro Mountains north of the Yining Basin (Fig. 1 & 3). Stromatolitic, oolitic, cherty and other limestones and dolomite have been recrystallized to form marbles. They are dated lower Upper Proterozoic by microfloras and by stromatolite-chronology. The meta-sedimentary strata are overlain unconformably by the Sinian basal conglomerate.

Locally present in a melange are blocks of mafic and ultramafic igneous rocks, and they are also embedded in a schistose matrix. The Precambrian ophiolite melange bears a resemblance to those of the Altun Mountains southeast of Tarim Basin (Xinjiang 1985). Late Precambrian granitic intrusives, are found locally in Middle Tianshan (Xinjiang 1985). The quartz diorite near Balguntay gives a Rb-Sr age of 820 Ma and the augengneisses in east Tianshan are dated (U-Pb, zircon) 630 to 765 Ma (Wang et al. 1990). Those plutons are apparently the root of the arc-magmatism, and are correlative to those of similar ages on the same Andean-type of active margin in other parts of Tianshan, Kunlun, and South China (Fig. 5).

The Sinian strata of the Borohoro Mountains, north of Yining, are interbedded limestone, siltstone and shale terrigenous clastics (Fig. 8a). The intercalation of tillite and phosphate-bearing shale suggests a correlation to Sinian formations elsewhere in China by event-stratigraphy. The Cambrian beds are terrigenous and phosphatic in the lower part, grading into an Upper Cambrian of predominantly limestone, yielding rich trilobite and brachiopod faunas. The Ordovician formations of Borohoro include thick-bedded limestone, cherty limestone, and the Silurian consists of gray shale and thinbedded siltstone. Coral-brachiopod faunas are found in limestones and graptolite faunas in shales.

The Paleozoic stratigraphy east of Yining is somewhat different from that of the Borohoro Mountains. Volcanic flows and clastic rocks, including basalt, andesite, quartz porphyry, tuff, tuff breccia, chlorite-quartz schist, sericite-quartz schist, crop out in the Nilka Hills 50 km east of the city. The Nilka rocks are bounded by faults, and are considered Middle Ordovician (Xinjiang 1981, p. 191). Elsewhere in the Yining Basin Silurian andesitic tuffs, breccia, and porphyry, tuffaceous sandstone overlie unconformably the Proterozoic basement (Fig. 8b). In the mountains south of Yenin, the lower Paleozoic rocks are metamorphosed, forming chlorite schist, sericite schist with intercalated marble lenses, and they grade southward into the metamorphosed schistose matrix of the South Tianshan Melange (Fig. 8c). A Silurian coral/brachiopod/crinoid fauna has been found in the marbles, and those lower Paleozoic strata are overlain unconformably by upper Paleozoic volcanoclastic formations of Middle Tianshan.

The foreland basin deposits in the Tianshan Mountains range from Middle Devonian to Permian age (Fig. 6). The molasse of Middle Tianshan consist of coarse conglomerate, with granite boulders more than 1 m across. Farther to the south, in isolated outcrops, the Devonian and Carboniferous consist of sandstone, conglomerate, limestone, dolomite, and siliceous shales; those largely shallow marine deposits are characterized by coral/brachiopod faunas. The interbedded volcanic rocks and volcanoclastics are acidic or intermediate in composition. The Permian formations consist of sandstones, shales, andesitic and basaltic volcanic rocks, and they are dated mainly by plant fossils.

The Mesozoic and Cenozoic sediments on the margin of Tianshan and in the Yining and Tulufan basins of Middle Tianshan are mainly continental deposits.

Melanges

Melanges are present in North and South Tianshan, separated by rocks of the Middle Tianshan Arc. The sedimentary rocks in the melanges are mainly lower Paleozoic, more or less coeval with those in the Middle Tianshan and the Kelpin/Kuruktag areas.

Southern Tianshan Melange

The so-called Nikolaev Line (Fig. 3b) is a large Cenozoic fault separating the Smithian terrane of the Middle Tianshan Arc and the non-Smithian Terrane of the South Tianshan Melange. The fault extends from Saleijaz Mountains on the Soviet border, for 500 km eastward through Biykshan, Nalatis, Ayrbin to Kezletag (Fig. 1). Large slabs of ophiolites (peridotite, pyroxenite, gabbro and diabase) and of sedimentary rocks (flysch, radiolarite, and rare carbonate rocks) are embedded in a pelitic matrix of the melange (Fig. 3).

The melange is well exposed in the Muzat River section southwest of Zhaosu (Fig. 3). Serpentinite, gabbro, and greenstone, and radiolarite slabs, up to a few kilometers long, are present, and exotic metamorphic rocks include green schists, glaucophane schists, and amphiolites (Liou, et al. 1989). Also present ar slabs of granite gneiss, acidic volcanics, and marble; they have apparently been detached from the Middle Tianshan Arc.

Wang et al (1990, p. 120) described a mixture of the following rock types, cropping out along a north-south section south of Arlaton (Fig. 9a):

migmatite gneiss, garnet-biotite-plagioclase gneiss, augen gneiss, >10 km
light green chlorite-sericite schist, 30 m
weathered buff sericite-quartz schist, marble lenses, 20 m
medium-bedded metamorphosed siltstone, and conglomerate with pebbles up to 1 cm across, 5 m
gray muscovite-biotite schist, 10 m
gray-green sericite quartz schist, 12 m
weathered buff biotite-quartz schist, 15 m
weathered buff biotite-quartz schist with marble intercalations, 15 m
silver gray muscovite-biotite schist, 15 m
biotite schist, 15 m
Albitized gabbro, 5 m
serpentinized peridotite, 50 m
gray green quartz schist and plagioclase amphibolite, 5 m
glaucophane-phengite-plagioclase-quartz schist, chloritized, 12 m
spotted biotite-quartz schist, 20 m
weathered brown calcareous schist, 50 m
gray-green to green actinolite schist, 15 m
weathered diabase, 5 m
weathered buff chlorite-albite schist, 5 m
silver-gray garnetiferous mica schist, 20 m
gray striped marble, 10 m
gray-green glaucophane-phengite-quartz schist, 15 m
gray muscovite-plagioclase schist and calcite-muscovite-quartz schist, 20 m
quartz-mica schist, 10 m
light blue quartz-mica schist, 5 m
weathered yellow plagioclase amphibolite (vein), 15 m
light blue quartz-mica schist with marble intercalations, 20 m
light gray quartz-plagioclase gneiss, 10 m
green schist, 10 m

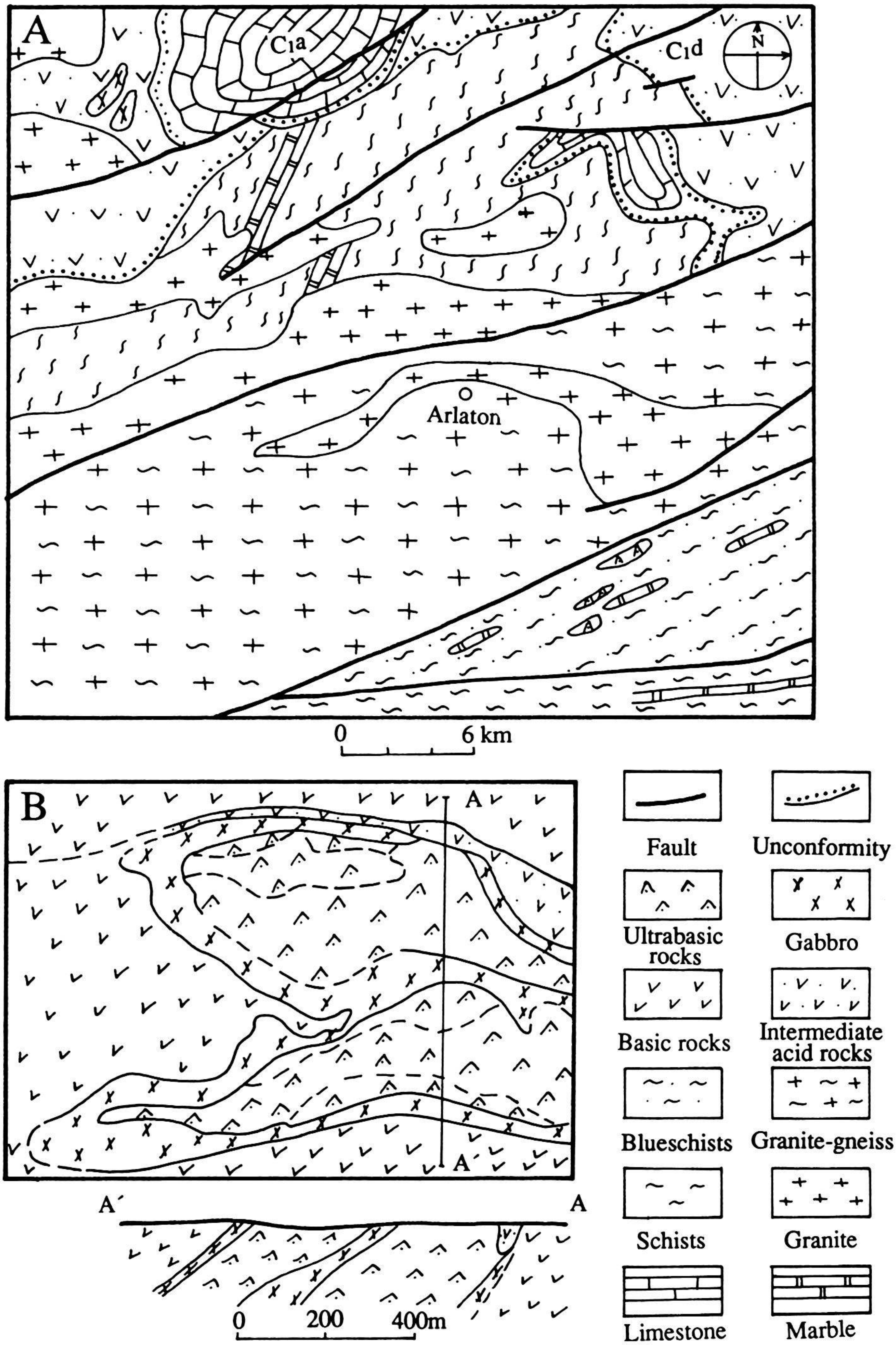

Fig. 9. Geologic sketch maps of the South Tianshan Melange (After Wang et al. 1990).
A Muzat River Section south of Zhaosu. B Ophiolite east of Hejing.

gray glaucophane-phengite schist, 30 m
light blue quartz-mica schist, 10 m
gray-green albite-chlorite schist (meta-diabase), 100 m
gray-green plagioclase amphibolite (vein), 5 m
gray garnet-plagioclase-muscovite schist, 100 m
light blue plagiocase-mica schist, with siltstone and marble intercalations, >100 m

The Precambrian gneiss, chlorite-quartz schist, quartzite, hornblende schist, and metavolcanic rocks south of Arlaton are lithologically similar to the Middle Proterozoic rocks of the Tianshan basement. This continental basement is overlain unconformably by Sinian strata, which have been metamorphosed to form quartz schist and marble. Those rocks are undoubtedly derived from the Middle Tianshan Arc and have been subjected to metamorphism during their descent down the Benioff Zone. This intimate mixture of the Middle Tianshan shallow marine sediments and continental basement and the South Tianshan ocean lithosphere suggests that a shear zone lies near the boundary between those two units. This is verified by the fact that the northern belt of melange lies just south of the Nikolaev Line.

The matrix of the South Tianshan Melange of the Muzat River section is metamorphosed during two stages, an earlier high-pressure low-pressure stage represented by the glaucophane-phengite assemblage, and a later medium-pressure/low-temperature stage represented by the sericite-chlorite assemblage. Chloritization of blue amphibole is common. The radiometric dating of metamorphism of the melange across the international border has yielded a 460 Ma date (Dobretsov et al. 1987; 1990), suggesting that the subduction process may have begun as early as Ordovician. Exotic blocks of Cambrian and Ordovician rocks are present in the melange in eastern Kouksayelin Mountains (Fig. 1 & 3); their age is indicated by *Agnostidae* tribolites in shale and by shelf-faunas in limestones. The subduction process continued, however, for some time during the early and middle Paleozoic, because the radiolarian faunas in radiolarite blocks in Southern Tianshan are mostly Late Silurian or Early Devonian (Li 1991), and the brachiopod/coral fauna in limestone blocks of the Muzat River section are Late Silurian (Wang et al. 1990). The melange is overlain locally by molasse deposits, the oldest of which are Middle/Upper Devonian or Carboniferous. The stratigraphic data suggest thus that the subduction of Southern Tianshan ocean lithosphere may have continued from 460 Ma till after 400 Ma.

Schist terranes of the western Tianshan crop out north of the Silurian Flysch belt, and they are also present south of the flysch terrane in a discontinuous belt extending from Arlai to Kouksayelin Mountains (Fig. 1 & 3). The metamorphic rocks are mainly quartzite, marble, mica schist, sericite-chlorite schist. In fact they are lithologically similar to the matrix of the northern belt of South Tianshan Melange, and they are distinguished from the melange only by the apparent absence of the ophiolite blocks. We have designated those rocks of continental affinity "core nappes" of the South Tianshan celtide on our tectonic map (Fig. 3), because their tectonic position is comparable to that of the Penninic core nappes of the Alps (see Hsü 1993). Such a tectonic correlation suggests that the underthrust basement of the Kelpin Arc was mobilized and metamorphosed, while its sedimentary cover was detached and thrust southward to form the foreland deformed belt in the foothills of Tianshan.

The southern belt of the South Tianshan Melange is separated from the northern belt by the Silurian Flysch Nappe. K.J. and P. Hsü investigated the melange in the Dalung

Lake area 150 km north of Kuche. The melange matrix is phyllitic, pervasively sheared but little metamophosed. The exotic blocks or slabs have been subjected to little internal strain. They include ophiolites, sedimentary rocks of deep-sea origin, and shallow marine limestone which was apparently detached from the underthrust Kelpin Arc. A melange of pillow lavas, diabase, serpentinite, and red radiolarite in a pervasively sheared siltstone matrix crops out on the west shore of the lake, under a large slab of massive Devonian limestone. Elsewhere red radiolarite is present in green and black schist to constitute a color-melange. Some 10 km south of the lake is an outcrop of very intensely deformed mylonite-marble, in a shear zone marking the boundary between the South Tianshan celtide and the Kelpin alemanide. The South Tianshan Melange is also well exposed in the Kezletag Mountains east of Hejing (Fig. 1). Flysch strata occur as large slabs in the area, other blocks include marbles, meta-volcanic rocks, as well as ophiolite. The brachiopod/coral faunas in the limestone are Late Silurian or Early Devonian. The southern belt of melange is overlain unconformably by Middle Devonian redbeds (Wang et al. 1990), but the foreland deformation in the Kelpin foothills continued until Permian.

An east-west trending zone of Silurian Flysch separates the northern and southern belts of the Southern Tianshan Melange. The Silurian deep-sea sediments were deposited on the abyssal plain or in the trench of the South Tianshan Back-Arc Basin. Their tectonic position is comparable to the Penninic Flysch nappes of the Alps (Hsü 1993).

Northern Tianshan Melange

Tectonic melanges are present in the Yilianhanbirgan, Qulutag, and Bogda Mountains, and beneath the Mesozoic and Cenozoic of the Tulufan Basin. The ophiolote slabs include peridotite, pyroxenite, gabbro, diabase, pillow basalt and pillow breccia (Fig. 9b), and those of sedimentary rocks are mainly flysch sandstone and siltstone and radiolarian chert. They are embedded in a fine-grained matrix.

A very large slab of of lower Paleozoic rocks is present in the Kawablack area south of Qulutag Mountains (Fig. 1). The Cambrian formations consist of terrigenous clastics, radiolarian chert, and tuffaceous sediments, yielding trilobite and brachiopod fossils (Fig. 10). The Ordovician are interbedded siltstone, shale, radiolarite, sandstone and argillaceous limestone. The Ordovician faunas are pelagic, including graptolites and cephalopods. Associated with those sedimentary formations is a melange of marble, metagraywacke, chlorite-quartz schist, amphibolite, gneiss, mafic and ultramafic rocks. We are not certain if the melange is a fragment of the Proterozoic basement detached from the Middle Kunlun Arc, or if the ophiolites were the ocean floor of a Paleozoic back-arc basin.

North of the summit of the Borohoru and Yilianhabirgan Mountains and extending eastward to Qulutag and Bogda, the outcropping rocks are mostly volcanic and volcanoclastic, including andesite, basalt, acid and intermediate flows and tuffs (Fig. 11). The slabs are embedded in a melange matrix of flysch siltstone and phyllite (Fig. 12). Silurian faunas are found in siltstone and limestone in the Bogda Mountains and in the Barkol area north of Hami (Fig. 3). Devonian, Carboniferous and Permian corals and brachiopods are present in limestone exotics. Radiolarian fauna and an ammonite collected from the flysch give a Carboniferous age (Tomlinson, Stanford University, personal communication).

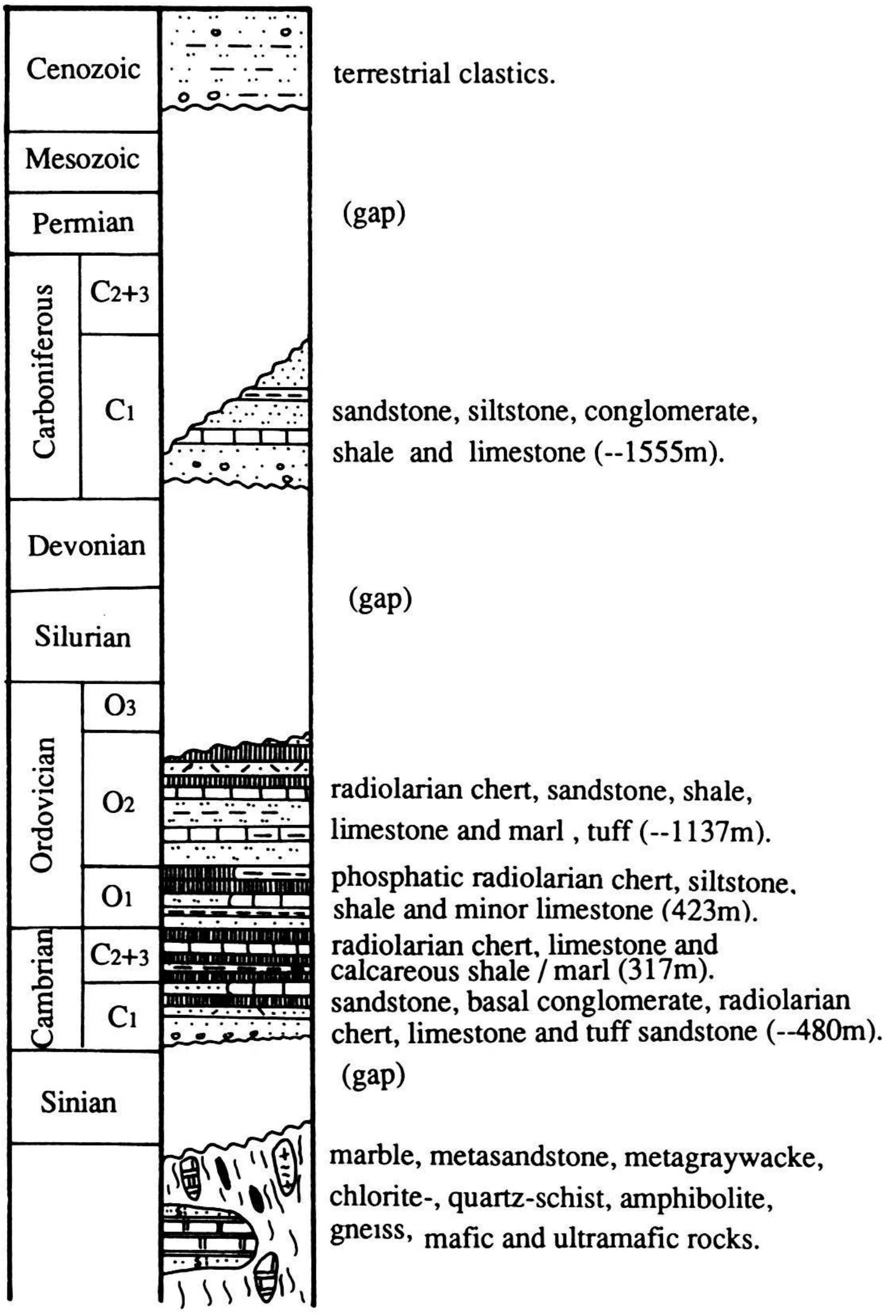

Fig. 10. Columnar stratigraphic section of the Kawablak area, eastern North Tianshan (After Xinjiang 1981).

Hsü, Wang and Li made a traverse across Tianshan south of Urumqi. The North Tianshan Celtide section is very similar to that of the Penninic Alps. The front range is underlain by slightly metamorphosed hemipelagic sediments, resembling the Bündnerschiefer of the North Penninic Alps. Those are followed by tectonic melanges, characterized by the presence of slabs of ophiolite, volcanics and of Paleozoic limestones. Toward the Shengli Daban (5000 m), the melange matrix is a green schist, and the slabs are severely strained. The metamorphic melange resembles the *schistes lustrés* of the

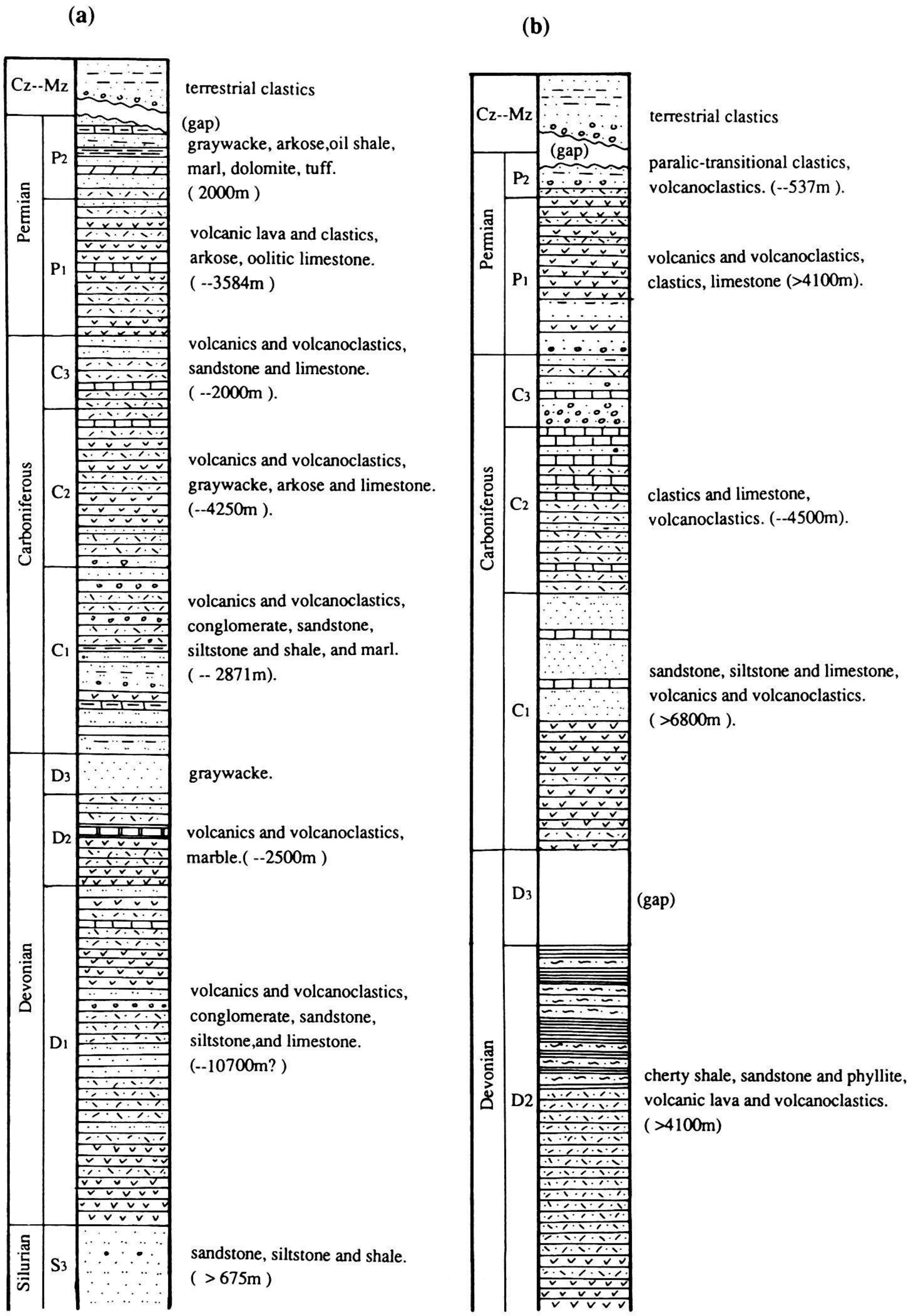

Fig. 11. Columnar stratigraphic section of North Tianshan (After Xinjiang 1981).
(a) Bodga Mountains (b) Yilianhabirgan Mountains.

South Penninic Alps. Mylonites, typically those found at the base of rigid-basement nappes (raetide), are found near the summit of the pass, and granite plutons of the Middle Kunlun Arc are found on the other side. The North Tianshan Melange can also be observed at roadcuts on the Urumqi-Tulufan Highway. Green ophiolite and red radiolarite constitute a colorful melange.

The age of volcanic rocks in the Northern Tianshan indicates that the subduction of the Junggar ocean lithosphere took place during late Paleozoic. The subduction was terminated prior to or during Permian; the Permian flysch and Triassic molasse overlie unconformably the North Tianshan Melange.

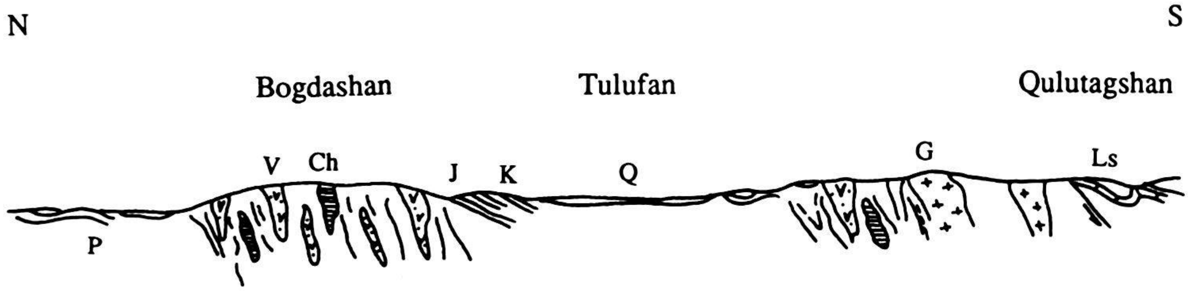

Fig. 12. Sketch cross-section across North Tianshan Melange.
V = volcanics; Ch = chert; Ls = limestone; Q = Quaternary; K = Cretaceous; J = Jurrasic; Tr = Triassic; P = Permian. The size of exotic blocks in melanges is not drawn to scale and their distribution is schematic.

Plutons

Proterozoic, early Paleozoic, and late Paleozoic granites are present in the Tianshan Mountains (Liu et al. 1989). The Proterozoic granites constitute a part of the basement of the Middle Tianshan Arc and of Kelpin Arc. The oldest Paleozoic granites are those intrusive into the Cambrian and Ordovician strata of the Borohoro Mountains; they are overlain unconformably by Devonian terrigenous clastic strata.

The late Paleozoic granite intrusives of Middle Tianshan crop out in two belts. The southern belt extends from the Biykshan/Nalatishan/Ayrbinshan to the Kezletag Mountains east of Hejing (Fig. 1 & 13). They are intrusive into the Silurian and Devonian strata and are overlain by the Lower Carboniferous. The trend of increasing potash in the southern intrusives suggests, according to a suggestion by Dickinson (1968; 1972), an origin of magma by partial melting of a northerly dipping subducted plate. The granites of the northern belt extends from the Yilianhabirgshan to the Qulutag and Bogda Mountains, where they are intrusive into Lower Carboniferous formations. The granites have yielded radiometric ages ranging from 295 to 340 Ma (Wang et al. 1990; Xinjiang 1985). The trend of increasing potash in those northern intrusives is, however, southward, indicating their origin from a southerly dipping subducted plate. The granites along Qulutag Mountains has an initial Sr^{87}/Sr^{86} ratio of 0.7076 to 0.7084, similar to that found on an Andean margin (Wang et al. 1990).

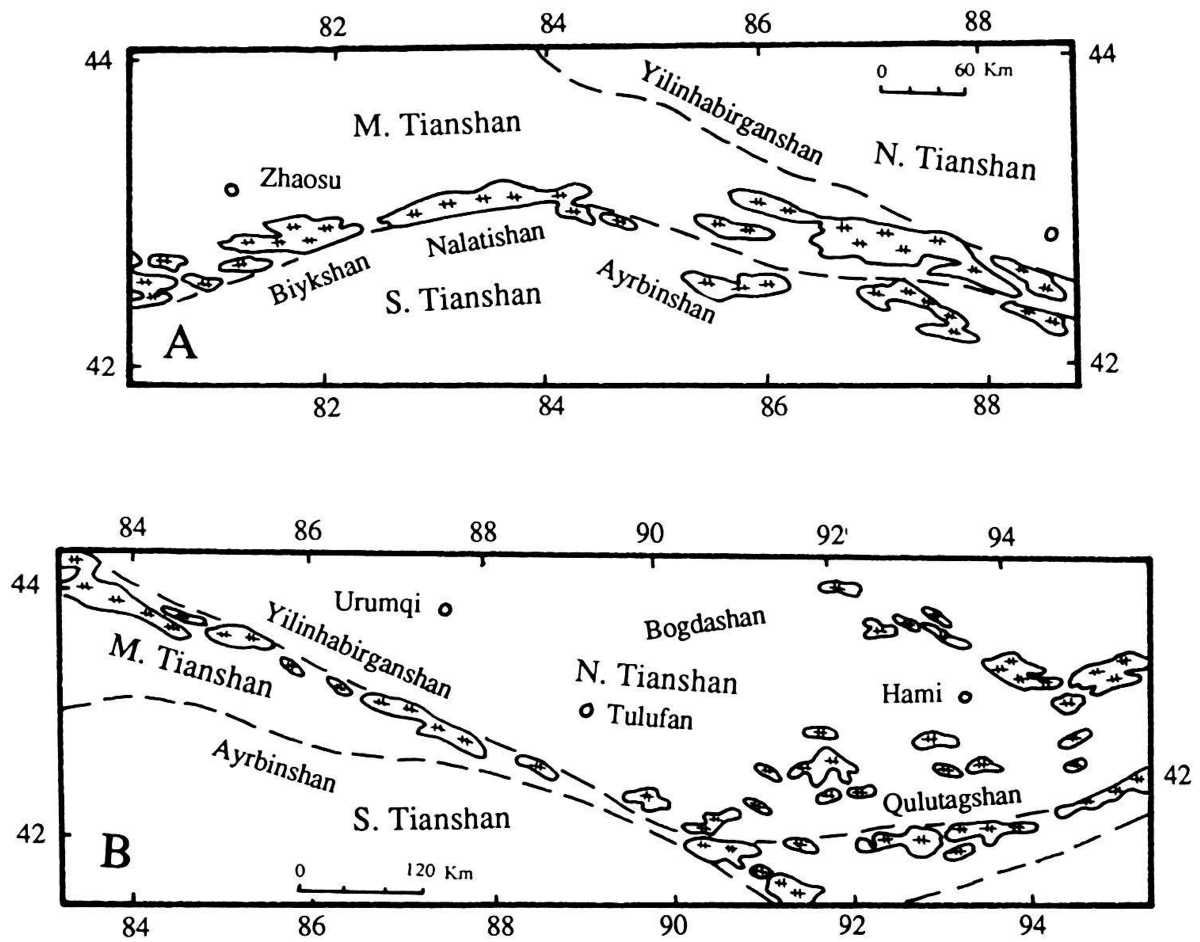

Fig. 13. Sketch map showing distribution of Paleozoic granites in Tianshan (Modified after Wang et al. 1990). A Southern belt; B Northern belt.

Granites of Permian age are present in the Kouksayeling Mountains and other areas of southwestern Tianshan (Fig. 1 & 3). Those small and mainly alkali syenite and alkali granite, yielding radiometric age of 260 Ma, are late intrusives into foreland basin deposit.

Geologic History of Tianshan

The Kelpin/Kuruktag and the Middle Tianshan terranes are underlain by Precambrian continental crust. They were a part of a Precambrian craton, but became an active continental margin during the Proterozoic, when the Proto-Tethys was subducted along a north-dipping Benioff zone under the Siberian Craton (Fig. 14a). The active-margin rocks are mostly upper Middle Proterozoic in Middle Tianshan but Upper Proterozoic in Kelpin/Kuruktag, and the site of magmatic activities moved during late Sinian time to an outer arc, which is identified as the Middle Kunlun Arc (Yao and Hsü 1993). The high-pressure metamorphism of the Kelpin blue schists indicates that those rocks were taken to 30–50 km depth down the Benioff Zone during late Proterozoic, before they were jacked up by the under-plating of an accretionary prism (see Hsü 1990c). The Proterozoic volcanic and plutonic rocks of the area are evidence of active-margin magmatism.

Seafloor spreading behind the magmatic arc caused the separation of an island arc from the Siberian Craton, the Junggar Basin was the back-arc basin north of the arc (Fig. 14b). The basement of the island arc included Precambrian rocks now found in the Kunlun, Central Tarim Uplift, and the Tianshan Mountains. Continued seafloor spreading caused the rifting of the arc into an outer arc and several remnant arcs, viz., the Kunlun Arc, the Central Tarim Arc, the Kelpin/Kuruktag Arc, and the Middle Tianshan Arc (Fig. 14c & 14d). The last two were relic island arcs from late Sinian to early Paleozoic; shallow marine sedimentary sequence was deposited on the continental basement of those subsiding arcs. The facies change of lower Paleozoic sequences indicates deepening of the marginal sea from the Kelpin/Kuruktag arc southward to the North Tarim Basin, and northward to the abyssal plain of the South Tianshan Back-Arc Basin: Ordovician pelagic and hemipelagic sediments and Silurian flysch were deposited in those basins.

The Middle Tianshan became an active arc when the South Tianshan Back-Arc Basin was subjected to compressive deformation (Fig. 14d). This timing of the change, when the South Tianshan ocean lithosphere was subducted under the Middle Tianshan Arc, is indicated by

1) the Middle Ordovician high-pressure metamorphism (460 Ma) in western Tianshan,
2) the Ordovician granitic intrusion (400 Ma) in Middle Tianshan,
3) the occurrence of the Middle Ordovician flysch in Ayrbin Mountains,
4) the first occurrence of Middle Ordovician andesitic volcanic rocks in Middle Tianshan.

Silurian to Devonian volcanic rocks in Middle Tianshan are evidence of the continuation of the consumption of South Tianshan ocean-lithosphere down a north-dipping subduction zone, while flysch and abyssal-plain sedimention continued in the ever-smaller back-arc basin (Fig. 14d).

The accretionary-wedge complex on the northern active margin, the northern belt of the South Tianshan Melange, was overlain unconformably by Middle Devonian red beds, but compressive deformation continued. The back-arc basin was finally consumed and changed into a Devonian foreland basin, after the Middle Tianshan Arc collided with the Kelpin-Kuruktag Arc (Fig. 14e). The Kelpin sequence was deformed by foreland thin skinned deformation after the arc-arc collision. The upper Paleozoic post-collisional sequence consists of typical foreland-basin deposits. Devonian and Carboniferous deposits are coarse conglomerates in Middle and South Tianshan, but they are finer-grained clastics and marine carbonates and evaporites in the Tarim region (Fig. 14f).

This North Tianshan Melange owed its origin to deformation in an active margin between the Middle Tianshan Arc and the Paleozoic Junggar Ocean. The discovery of Ordovician glaucophane schist in the West Junggar Mountains by Coleman et al. (1989) suggested an early Paleozoic age for the Junggar Ocean. Subduction of the Junggar ocean lithosphere along its northern margins, forming the melanges of the West Junggar and the Altai Mountains, started during Ordovician. The North Tianshan margin re-

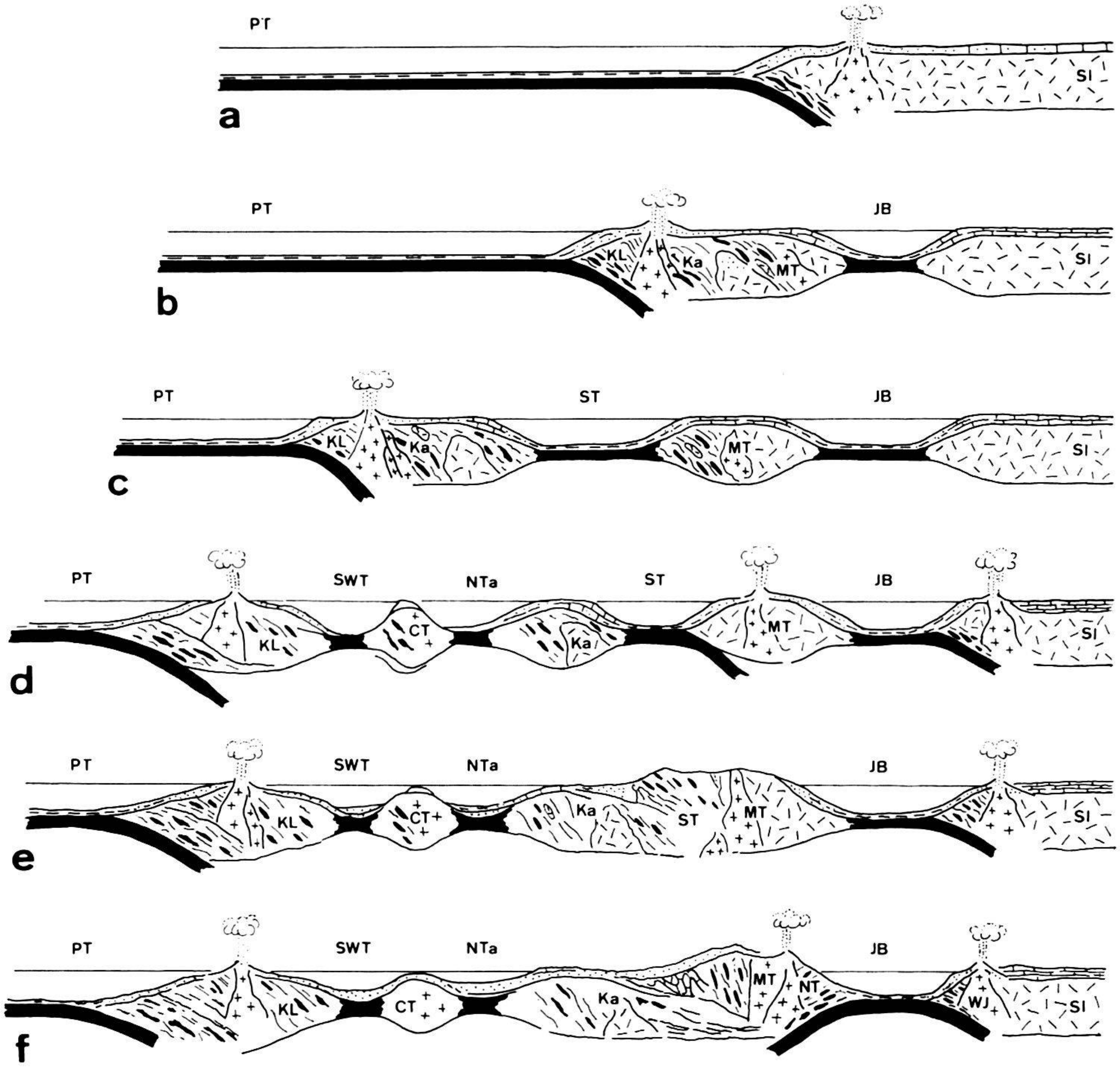

Fig. 14. Precambrian and Paleozoic evolution of Tianshan moutains:

a Middle to early Late Proterozoic: Subduction of oceanic lithosphere of Proto-Tethys (PT) along north-dipping subduction zone on an active margin of Siberia (Si).

b Sinian Separation of the Kunlun/Kelpin/Middle Tianshan (KL/Ka/MT) Arc from Siberia, forming the Junggar Back-Arc Basin (JB).

c Cambrian to Early Ordovician: Separation of Kunlun/Kelpin from Middle Tianshan. Deposition of passiv-margin sediments on both sides of South Tianshan Back Arc Basin (ST).

d Middle Ordovician to Early Devonian: Separation of Kunlun Arc from Kelpin, forming the North and South-west depressions of Tarim (NTa, SWT), which were separated by the relic arc of the "Central Tarim High" (CT). Back-arc collapse of South Tianshan, subduction of ocean-lithosphere along north-dipping Benioff Zone under, and magmatic activities on, Middle Tianshan Arc.

e Middle Devonian: Collision of Kelpin/Kuruktag Arc with Middle Tianshan Arc.

f Late Devonian to Carboniferous: Foreland basin above the collision zone in South Tianshan and Kelpin areas. Subduction of Junggar ocean-lithosphere along south-dipping Benioff Zone under, and magmatic activities on, Middle Tianshan Arc. Sedimentary in-filling of Tarim depressions (SWT & NTa).

mained, however, a passive margin till the Silurian at least, when the Silurian shallow marine sediments of the Barkol area were deposited. The margin was changed into an active margin during Devonian or Carboniferous (Fig. 14f). Late Paleozoic active-margin volcanism is evidenced by the presence of basic and acid volcanic rocks in North and Middle Tianshan, and the subduction tectonics is manifested by the accretionary wedge which now crops out as the North Tianshan Melange (Fig. 14f). The Junggar Basin became a relic back-arc basin during Permian, when back-arc collpase via subduction ceased to be active. The Permian turbidite and shale on the margin of Junggar Basin constitute a flysch-like sequence and the Triassic conglomerate, sandstone and siltstone are the molasse deposits of a foreland basin. The younger Mesozoic and the Cenozoic strata are the sedimentary-infill (Hsü et al. 1990).

Summary and Conclusion

This article on Tianshan is the outcome of a continuing attempt to reinterpret the geology of China. The basic methodology is an application of the tectonic-facies concept to identify the sedimentary and tectonic setting of various map units, and the basic philosophy is the Occam's razor to seek a simplest logic solution of all available data. The tectonic evolution of Xinjiang could be compared to that of the Southwest Pacific. Continental crust was split off from mainland to form island arcs (Middle Tianshan, Kelpin/Kuruktag) and back-arc basins (South Tianshan, Junggar/North Tianshan). Their deformation was effected through back-arc basin collapse via ocean-lithosphere subduction (South Tianshan Melange, North Tianshan Melange). The South Tianshan Back-Arc Basin was eliminated when the Middle Tianshan Arc collided with the Kelpine/Kuruktag. The Junggar basin became a restricted relic back-arc basin in Permian when subduction on all Junggar margins ceased, and it was a Mesozoic/Cenozoic inland basin for continental sedimentation. The tectonic events of the Tianshan region permit correlation with other tectonic units of Nortwest and North China. The late Proterozoic of Tianshan was situated on the same active margin as the Qinling and Yangtze. The occurrence of the Sinian tillite and the affinity of the Cambro-Ordovician faunas indicate that the shallow marine sequence of the Kelpine/Middle Tianshan arcs had an equivalent in the Yangtze region. The change from a passive to an active Middle Tianshan margin during the Ordovician was apprioximately synchronous to that in the Beishan and that of the Neimonides (see Hsü et al. 1991; 1992). The late Silurian or Devonian collision of Middle Tianshan and Kelpin/Kuruktag was more or less synchronous to the arc-arc collision of the Jilian Mountains.

Acknowledgement

The Tianshan study is a part of a Sino-Swiss Tectonic Map Project, initiated in 1983 under the joint sponsorship of the Chinese Academy of Sciences and the Swiss Federal Institute of Geology. The field word by K. J. Hsü, Wang, and Li during the 1983, 1988 and 1990 seasons was jointly supported by those institutions. The work continued as a program of basic research by the Chinese National Petroleum Corporation in connection with their oil-exploration activities in the Tarim Basin. K. J. and Peter Hsü acknowledge the logistical support by CNPC during their 1992 field season. Hao Jie is awarded an ETH fellowship and Yao Yongyun the *Kenneth J. Hsü Stipendium* of CNPC for their research appointments in Switzerland.

The manuscript was read critically by Celal Sengör, Chen Haihong, among others, and we acknowledge with gratitude their constructive critiques. This article is dedicated to the memory of the late Yao Yongyun, who wrote the first draft of the manuscript.

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Manuscript received December 18, 1992
Revision accepted October 25, 1993