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Tectonic evolution of Qinling Mountains, China[1])

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ABSTRACT

The Qinling Mountains can be divided into four tectonic units. They are from north to south: 1. Precambrian basement with its Sinian and Paleozoic cover of North China facies; 2. Metamorphic complex with ophiolitic blocks; 3. Flysch nappes; 4. Folded Paleozoic and Triassic strata of Yangtze facies. Using comparative tectonics, the Qinling Mountains are interpreted to be an orogenic belt of the collision type: The Qinling structures were formed mainly during the early Mesozoic Orogeny when the Yangtze Block of South China collided and was thrust under North China. The rigid Precambrian basement and its cover form an overthrust complex comparable to the Austroalpine Nappes. The metamorphic complex is comparable to the Penninic Nappes, including the ophiolite melanges of the suture zone, the mobilized underthrust basement, and the metamorphosed sediments of the Paleotethys. The Flysch nappes are equivalent to Prealpine Flysch. The foreland fold belt is characterized by thin-skinned deformation, and has a tectonic role equivalent to the Helvetic Nappes of the Alps. Mesozoic granites owe their origin to partial melting of the underthrust crust after the Triassic intercontinental collision.

ZUSAMMENFASSUNG

Die Qinling-Berge werden in vier tektonische Einheiten gegliedert (von Norden nach Süden): 1. Präkambrischer Sockel mit seiner sinischen (spätpräkambrisch) und paläozoischen Bedeckung in nordchinesischer Fazies (Tabelle). 2. Metamorpher Komplex mit ophiolitischen Blöcken. 3. Flyschdecken. 4. Gefaltete paläozoische und triadische Serien in Yangtze-Fazies (Tabelle). Anhand vergleichender Tektonik werden die Qinling-Berge als Orogen des Kollisionstyps interpretiert. Die Hauptphase datiert vom frühen Mesozoikum, als der südchinesische Yangtze-Block mit Nordchina zusammenstiess und unter dieses geschoben wurde. Das starre Präkambrium und seine Bedeckung bilden eine Überschiebungsmasse, ähnlich jener der Ostalpinen Decken. Der metamorphe Komplex ist mit den penninischen Decken vergleichbar, inklusive der Ophiolith-Melanges längs der Suturzone, dem mobilisierten unterschobenen Sockel und der metamorphen Sedimente der Paläotethys. Die Flyschdecken entsprechen dem präalpinen Flysch (Gurnigel). Das Vorlandfaltenbündel ist charakterisiert durch sogenannte «thin-skinned»-Tektonik, und stellt ein Äquivalent der Helvetischen Decken dar. Die mesozoischen Granite sind Produkte der partiellen Anatexis der unterschobenen Kruste in der Folge der triadischen Kontinent–Kontinent-Kollision.

Introduction

The Qinling Mountains traverse the Gansu, Shaanxi, and Henan Province of China (Fig. 1) and is the central segment of an E–W trending mountain chain, which extends westward to the Kunlun, the Pamir, and eastward to the Dabie Mountains (HUANG 1976). The geological investigations first began during the last century, and geologic mapping of the region on a 200 000 scale has been completed. There is, however, little

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concensus concerning the genesis of this important mountain range between North and South China. It is now commonly agreed that the Qinling Range owed its origin to inter-continental collision, but the age of the terminal collision has been an controversial issue: It has been variously considered a Caledonian, a Hercynian, or an Indosinian mountain chain (see HUANG 1945, 1976, 1978; JIANG et al. 1963; WANG & SUN 1973; ZHANG 1980; KLIMETS 1983; REN 1984; MATTAUER et al. 1985; SENGÖR 1985; WANG et al. 1985; YANG et al. 1986; LI et al. 1986). The unsatisfactory state of affairs is best illustrated by the recent debate between Mattauer and Sengör. Within one month their two papers appeared in the same journal, the Nature: MATTAUER et al. postulated that the Qinling Mountains were formed during the Caledonian Orogeny by intra-continental subduction. SENGÖR, on the other hand, presented arguments to show that the Qinling structures were mainly the product of an early Mesozoic continental collision, which has been referred to as the Indosinian Orogeny. This latter opinion has been the working hypothesis of one of us (HSU 1981). A Sino-Swiss cooperative project was initiated in 1983 to investigate the plate-tectonic evolution of Qinling and of South China. The co-authors of this paper and their colleagues in the Northwestern University of Xi'an, China, have visited crucial outcrops and carried out sedimentological studies to test the hypothesis of Mesozoic collision. This paper presents our preliminary conclusions.

Tectonic subdivisions

The Qinling Mountains are separated from the North China Block by Cenozoic faults, namely the E–W trending Fenwei Fault and the WNW-trending Liupanshan Fault (Fig. 1). The southern limit of Qinling can be placed at the boundary thrusts of Daba and Longmen Mountains (Fig. 1), where the sediments originally laid down on the northern margin of the Yangtze Block have been thrust back onto the Yangtze carbonate platform.

Within the Qinling orogenic belt, we propose the following subdivisions:

1. Precambrian basement and its sedimentary cover
2. Qinling metamorphic complex
3. Flysch nappes
4. Foreland folded belt

Each of the four divisions are characterized by a sedimentary sequence with its own distinctive facies development, and by a characteristic style of deformation.

Stratigraphy

North China Block

Archaean gneisses and Lower Proterozoic metamorphic rocks constitute the crystalline basement of North China Block. Those rocks are mostly buried under a thick sedimentary cover and crop out only at a few places on the southern margin of the Ordos Basin (see Table).

A conformable sequence of sedimentary strata, ranging from late Precambrian to Cretaceous in age are present on the southern margin of the Ordos Basin north of the Yellow River.

Table: *Stratigraphy in the Qinling Mountains.*

	N. China & its margin	Yangtze Block & its margin	W. Qinling & Songpan	Metamorphic Complex
T_3 -K	terrestrial sandstone and shale with coal measures			
T_{1-2}	hemipelagic and turbidite	platform carb. & evap. / slope hemip., Turb.	Flysch & pelagic Lm, Sh. Ss.	
P	marine and terrestrial Ss., Sh., Coal.	marine bed, chert or coal		
C		shallow marine Carb.	pelagic Lm., marls	
D	Non-deposits	pelagic Lm.	pelagic Lm. & phyllite	i) ophiolite; ii) mobilized basement; iii)metamorphic sedimentary cover & associated submarine volcanics.
S		non-deposits / graptolite Sh.	slates, meta-sandstones, pelagic sediments, volcanic rocks, pyroclastics	
O	shallow marine limestones	marine Carb. & shales		
Cam				
Z	shallow marine sandstone & dolomite.	shallow marine Carb. Ss. Sh. & tillite.		
Pre-Z		crystalline basement (gneisses & granites)		
Ar	crystalline basement (gneisses & granites)			

Carb.: carbonate rocks; Lm: limestone; Sh: shale;
Ss.: sandstone; Turb.: turbidite; Z: Late Proterozoic

The oldest sediments are the thick Sinian strata of Upper Proterozoic age. They are mainly sandstones, dolomites and siliceous carbonates, deposited in a shallow marine environment, and this facies development is typical of North China.

The Cambrian and Ordovician consist mainly of shallow marine limestone. Phosphorites are present near the base of Cambrian. Conglomeratic rocks of late Ordovician age are present locally. The lower Paleozoic strata north of Qinling are also typical of North China and have been correlated to those in Shanxi Province and those in Inner Mongolia.

As is typical of North China, Silurian and Devonian strata are mostly absent on the southern margin of the Ordos Basin, so that Permo-Carboniferous sediments overlie disconformably the lower Paleozoic strata. The upper Paleozoic sequence of the region consists of marine and terrestrial sandstones, shales, and coal measures, more than 1000 m thick, and the Permo-Triassic rocks are hemipelagic sediments and turbidites.

The terrestrial Upper Triassic, Jurassic and Cretaceous overlie uncomformably older strata in the Ordos Basin. A thick sequence of fluvial and lacustrine sandstones, shales, and coal beds have been encountered in wells drilled for oil exploration.

The Ordos Basin has a thin Cenozoic cover, but very thick Cenozoic sediments are present in the Fenwei Basin.

The sediments of the North China facies north of Qinling have been locally deformed by the back-thrusting, related to the deformation of Qinling. They now form a homoclinal sequence on the southern edge of the Ordos Basin, but are deeply buried in the Fenwei area.

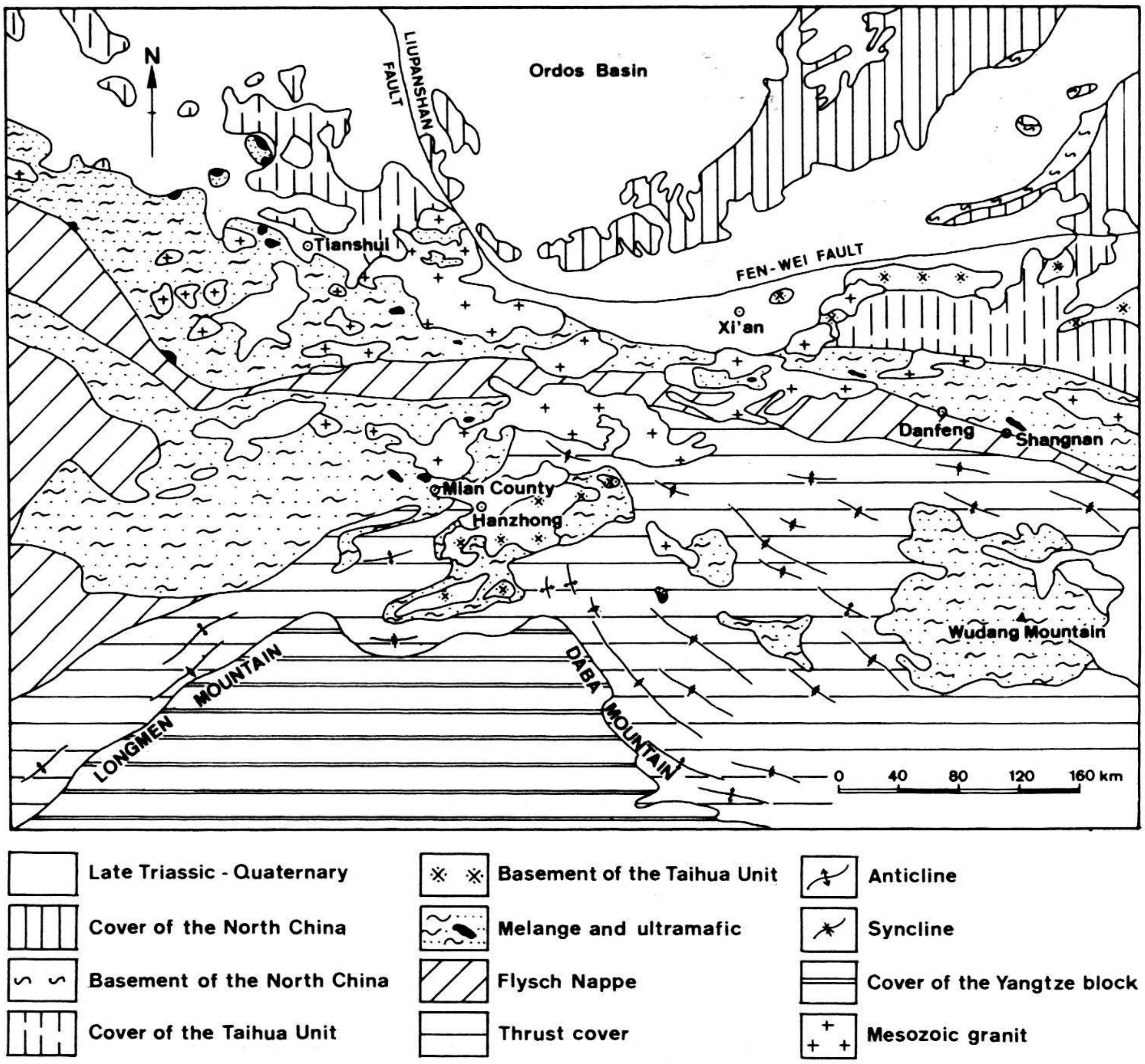

Fig. 1. Geologic sketch map of Qinling. The Qinling is a mountain range formed by the collision of the North China and the Yangtze Blocks. The northerly belt of melange and ultramafic rocks constitute the suture zone. The melange and ultramafic rocks of Mian County and of Wudang Mountain are tentatively interpreted as ophiolite nappes which have been thrust on top of the foreland fold belt.

The Precambrian basement, just south of the Fenwei Fault near the northern margin of East Qinling, has radiometric age greater than one billion years (Zhang 1980). The granite and gneiss, known locally as the Taihuan Group, underlie Sinian and Paleozoic sedimentary rocks (Fig. 1 and 2). Those sediments within the Qinling Mountains have a facies development typical of North China, although, as a rule, only the lower half of the sequence is preserved from erosion. Devonian strata of continental facies are present locally in northern Qinling, and their occurrence is indicative of the mid-Paleozoic regression of North China, which might have some relationship with early subduction of the Paleotethys.

Yangtze Block

The Yangtze Block was a micro-continent before its Mesozoic collision with North China to produce the Qinling Range, and with Huanan Block to form the South China

Mountains (HSU et al. 1986). The sedimentary sequence on top of the block was deposited mainly on a carbonate platform and those on the periphery are passive-margin deposits. The platform sequence is now largely buried under the Mesozoic terrestrial deposits of Red Basin south of Qinling, but crops out in the Yangtze Folded Belt to the east and southeast of Sichuan. The marginal sediments are deeper marine.

The Pre-Sinian basement of the Yangtze Block, exposed in the Yangtze Gorge area, consists mainly of gneisses, granites and metasedimentary rocks.

The Sinian strata of the Yangtze Gorge is reference section for the Yangtze Block. Several formations of sandstones, shales, carbonates, cherts and phosphorites have been recognized, with tillite beds (Nantuo Tillite) intercalated in the lower part. Those shallow water and glacial sediments were deposited on a broad platform and the distinctive formations are easily recognized in several provinces, where they constitute the oldest strata of the Yangtze Fold Belt.

The Cambrian and Ordovian are composed mainly of marine carbonates, argillaceous limestones, and shales, up to 2500 m thick. Silurian strata are largely missing on top of the Yangtze Platform, but thick Silurian graptolite shales are present in the more peripheral parts of the Yangtze Block.

The Devonian and Carboniferous strata of the Yangtze region are mainly shallow marine clastics and carbonates. They form thick passive margin sequences in the mountains northwest and west of the Red Basin, but are missing on top of the Paleozoic platform, where Permo-Triassic strata overlie unconformably Lower Paleozoic rocks.

The Permian formations are widespread in the Yangtze region. Those marine units include, on the one hand, radiolarian chert and, on the other hand, coal measures.

The Lower and Middle Triassic consists of marine carbonates and evaporites in the Red Basin of Sichuan, which was a carbonate platform in the midst of an open sea. Triassic sediments have been deposited on continental slopes and deep sea basins north, west, and southeast of the Sichuan Platform.

The Upper Triassic and Jurassic strata are terrestrial clastics with coal beds. The Cretaceous are the red beds whose color gave the name to the Red Basin.

The sedimentary sequence in the Qinling Folded belt has a facies development similar to that of the Yangtze Platform, but is thicker, more continuous, and contains more clastic components than that on the platform. The folded-belt sediments belong apparently to a passive-margin sequence and were laid down in deeper water environments.

The Cambrian and Ordovician strata of the folded belt are also dominantly carbonates, but a carbonaceous clastic formation is present in the Lower Cambrian, and graptolite shales are common in the Upper Ordovician. Whereas the Silurian is largely missing on top of the platform, a graptolite-shale sequence is present on the northern Yangtze margin.

The marginal facies of the Devonian and Carboniferous are also very thick, and they consist largely of pelagic limestone with interbeds of reef limestone and siliciclastics.

Shallow marine limestones of Permian age are present, but the bulk of the Permo-Triassic on the margin are hemipelagic and turbidite sediments, deposited in deep water north of the Yangtze Platform.

The Upper Triassic and Jurassic are predominately terrigenous clastics, with intercalated coal beds. Those continental sediments overlie unconformably folded marine strata.

West Qinling and Songpan Facies Belts

The pre-Devonian sequences of West Qinling and of the Songpan region consist of slates, meta-sandstones, pelagic sediments, and of volcanic and pyroclastic rocks.

The Devonian strata of West Qinling are very thick; the phyllites, slates, and calcareous sandstones with intercalated pelagic limestone have an estimated thickness of 12 000 m. The occurrence of shallow marine carbonates of Devonian age in this facies belt has been reported. We are, however, not certain if they are autochthonous or exotic. The Devonian of the Songpan belt is also very thick, including some 8000 m of siliciclastics and pelagic limestones.

The Carboniferous sequences of both facies belts are a few thousand meters thick; they consist mainly of pelagic limestones and marls, but the occurrences of reef-limestone and sabkha-dolomites have also been reported.

The Permian strata of both facies belts are also thick, deep-water sediments, characterized by the presence of pelagic limestones, hemipelagic shales, and turbiditic sandstones.

The Middle and Lower Triassic strata constitute the bulk of the Qinling Flysch Nappes, and they are the thickest and the most widespread formations of the Songpan facies belt. The thickness of the Triassic Flysch in Songpan area has been estimated to be more than 10 km.

Nowhere in West Qinling or within Songpan facies belt has an indication of continental basement been found. Whereas the Qinling Flysch may represent accretionary complexes on continental margin(s), the major parts of the Songpan facies belt may have been, and probably is still, underlain by ocean crust (SENGÖR & HSU 1984).

The Upper Triassic and Jurassic of West Qinling and of Songpan are continental sediments of the molasse facies.

Metamorphic complex

The metamorphic complexes of Qinling has been commonly considered Precambrian, mainly because they are not fossiliferous. When fossils are discovered in a complex, the fossil-bearing strata would be excluded from the complex and thus the unfossiliferous portion could continue to be referred to as Precambrian. This practice led to misconceptions about the geologic significance of the metamorphic complex of Qinling.

The metamorphic rocks are present in an E–W trending belt south of the rigid basement unit (Fig. 2), and they are separated by a major fault (the Heigou Fault). The metamorphic complex is separated by another major fault (the Shang-Dan Fault) from the flysch nappes and the foreland folded belt (Fig. 2). Several large areas south of the southern boundary fault are also underlain by metamorphic rocks. They are probably klippen or erosional remnants of a large nappe-complex of metamorphic rocks correlative to those north of the southern boundary fault.

The metamorphic complexes of Qinling were designated Qinling Group by HUANG and others (HUANG 1931; ZHAO & HUANG 1931) during their reconnaissance study of this range. An unfortunate practice was introduced, however, during the 1950s when metamorphic rocks of vastly different origin were subdivided not on the basis of their lithology, or degree of metamorphism, but on the basis of their separation by late Mesozoic or Cenozoic faults. Thus, all rocks between two major faults are considered one

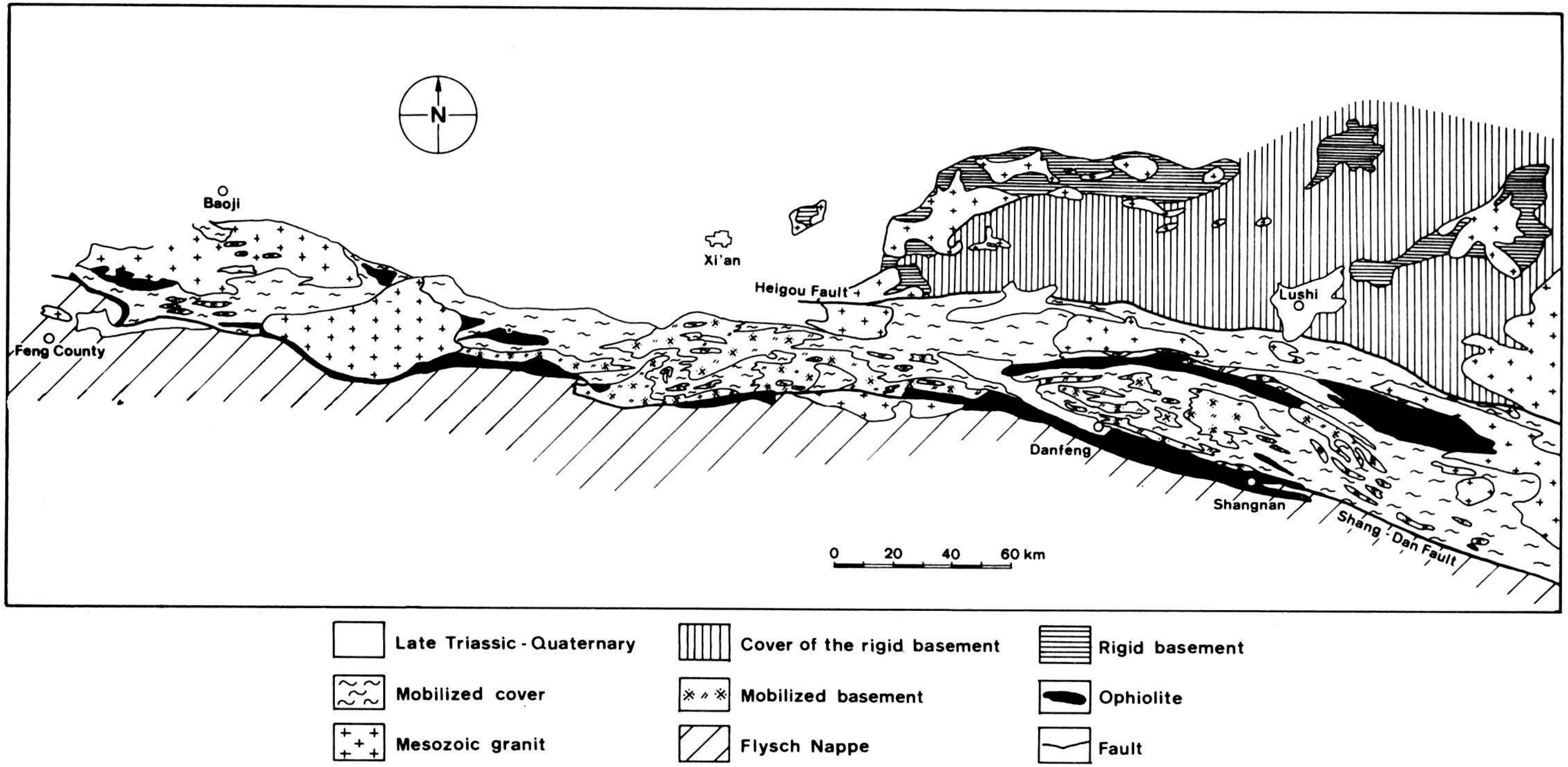

Fig. 2. Geologic sketch map of East Qinling. The melange zone between the rigid-basement and flysch nappes consists of rocks of very different origins. Ophiolite and mobilized cover were the oceanic lithosphere and the oceanic sediments of the Paleo-Tethys. Mobilized basement represent older continental crust metamorphosed during the late Paleozoic and/or Triassic deformation. The Mesozoic granite has been emplaced after the Qinling collision.

unit. Names such as Kuanping Group, Taowan Group, etc., were introduced and considered stratigraphic units distinct from those in other fault blocks, even though they are not distinguishable from one another by lithology or by lithologic association. Since neither descriptive nor genetic criteria are given for the subdivision of the metamorphic complex, the practice led to confusion and misunderstanding. We prefer, therefore, to return to the sound reconnaissance practice and shall refer to those rocks as the Qinling Metamorphic Complex. On the basis of available information, we propose a three-fold subdivision of the various rock bodies within the complex, namely 1. ophiolites, 2. mobilized granite basement, 3. metamorphosed sedimentary cover and associated submarine volcanics. We plan to carry out field mapping during the next few years to delineate the ditribution of each.

The most distinctive rock types within the Qinling Complex belong to the ophiolite suite. Ultramafic rocks, mafic intrusive rocks, spilites, greenstones, and pillow lavas occur as lenticular blocks of various sizes in matrix which has been subjected to various degrees of regional metamorphism. The ophilites are particularly well exposed in a WNW-trending belt between Danfeng and Shangnan in East Qinling; an exotic slab of metamorphosed ophiolites is about 8 km thick near Danfeng. Ophiolitic blocks of various sizes are present in the metamorphic terranes elsewhere. The rocks of the ophiolite suite are apparently ocean crust and mantle, and they have been disrupted and occur now as exotic slabs or blocks in melanges within the Qinling complex.

A second category of rock types is granitic, and those deformed granites have been mapped as "Paleozoic intrusives" (Fig. 2). We observed, however, that their contact with other rocks, is invariably tectonic. They may in fact be the continental basement of the

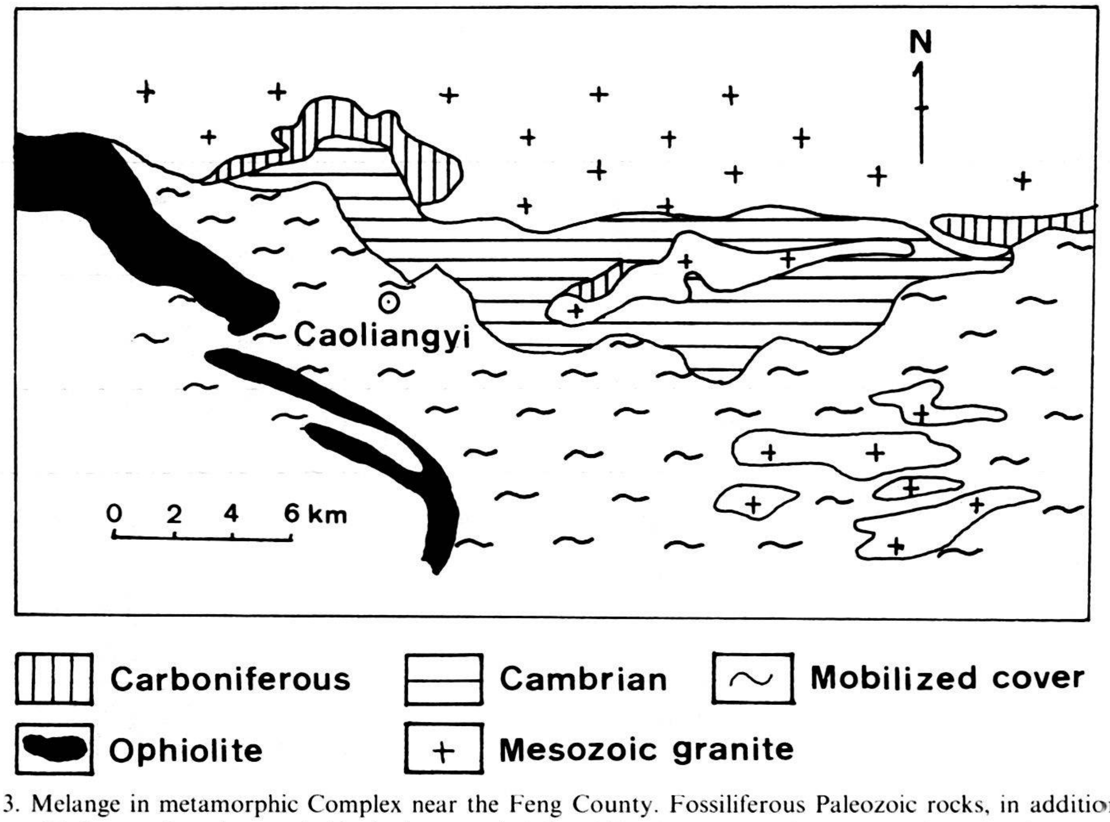

Fig. 3. Melange in metamorphic Complex near the Feng County. Fossiliferous Paleozoic rocks, in addition to ophiolite, are found as exotic blocks in a matrix (of mobilized cover) in this metamorphosed melange.

southern margin of the Paleotethys, which has been underthrusted, mobilized and metamorphosed again during the early Mesozoic continental collision, which gave rise to Qinling.

The layered sequences and the matrix materials of the melanges in the Qinling Complex are mainly sedimentary rocks that have been subjected to various degrees of metamorphism. The pelitic rocks have been converted to slates and sericitic phyllites where the metamorphism has been slight, and to mica schists and garnetiferous quartz-feldspar schists, even kyanite schist or gneisses where the metamorphic grade is high. Marbles and quartzites are not uncommon, but few sedimentary structures are preserved to permit a recognition if they were originally shef sediments or pelagic deposits. Green schists include mainly chlorite-albite schists, may owe their origin to the penetrative deformation and metamorphism of submarine volcanics; they are common in layered metamorphic sequences, and also occur as matrix in ophiolitic melanges.

The age of the metasedimentary rocks have been controversial (see ZHANG 1980). Paleozoic fossils are not uncommon in the less metamorphosed rocks of the Qinling Group, and they have been dated as Cambro-Ordovician, Silurian, Devonian, and/or Carboniferous. Field relations indicate that the fossiliferous and unfossiliferous rocks constitute tectonic melanges (see Fig. 3), so that fossils found in individual rock bodies cannot be used to date the age of the whole melange complex, nor could the lithology of individual melange blocks be considered representative of the depositional environments of all metamorphosed sediments. Nevertheless the repeated discoveries of Paleozoic fossils in the Qinling Complex suggests they were the sediments of a Paleotethys Ocean, which separated the North and South China during much (if not all) of the Paleozoic until the Triassic continental collision.

It should be noted that the bulk of the Qinling Complex consists of unfossiliferous phyllites and pelitic schists. Their paleogeographic position and their role in tectonic deformation are comparable to the great *schistes lustrés* or *Bündnerschiefer* mass of the Penninic Nappes of the Alps. This comparison led to our interpretation that the metamorphosed pelitic rocks of Qinling may be the hemipelagic sediments of the Paleotethys. They were laid down in part on ocean crust, which is now found as exotic slabs or blocks in melanges, and in part on continental crust which has been remobilized during the Qinling deformation.

Tectonic evolution of Qinling

E–W trending faults are common in the Qinling Range. Lateral movements along those faults have been active during the Cenozoic, and their genesis has been related to the "extrusion tectonics of Asia". After the Eocene collision of Indian and Tibet, continuing compression led to intra-plate deformation in the form of large strike-slip faults (MOLNAR & TAPPONIER 1975). Cenozoic faulting may have fragmented the Qinling Orogen and caused the displacements of the disrupted parts. The internal structures of Qinling are, however, comparable to typical collision-type of mountains such as the Alps or the Appalachians.

Plate-tectonic model of orgenesis by continental collision (HSU 1981) recognizes three major elements: (i) an overriding crustal wedge and its sedimentary cover, (ii) a collision melange, and (iii) one or more underthrusting crustal wedges (Fig. 4). In the Alps, the overriding crustal wedge has been sliced up to form a pile of rigid-basement nappes – the

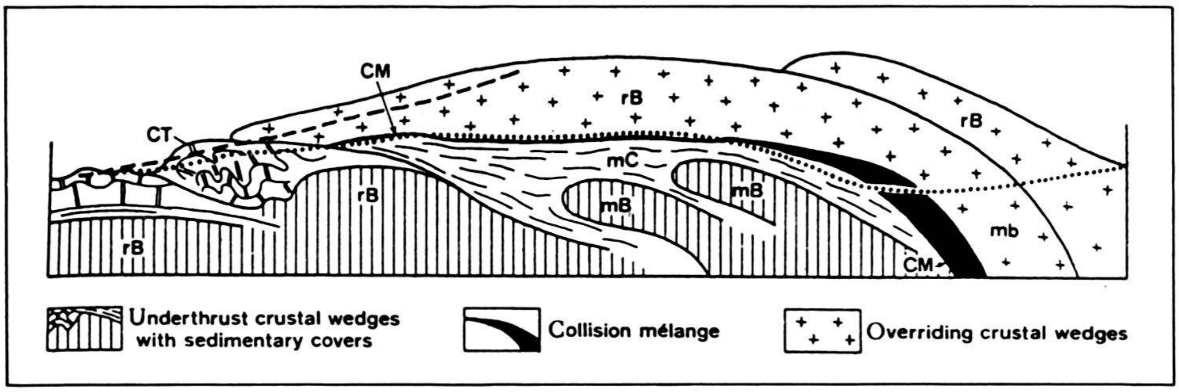

Fig. 4. A model of collision type of orogeny (modified after Hsu 1981). The suture is marked by a zone of collision melange (CM). The basement (mB) and the sedimentary cover (mC) are metamorphosed, where they have been deeply buried under tectonic burden. The basement (rB) is rigid where the tectonic overburden is moderate or slight. The sedimentary cover of the underthrust block has been stripped off to form the cover-thrust unit (CT).

Austroalpine Nappes; both the basement and its sedimentary cover has been little metamorphosed during the Alpine deformation. The collision melange is represented by the ophiolite melange of the Arosa Schuppen Zone in eastern Switzerland, and Saas–Zermatt zone of ophiolites and metamorphosed melanges in western Switzerland. They have been referred to as High Penninic Nappes of the Alps. The underthrust crustal wedge is split into two tectonic units. Its sedimentary cover has been largely peeled off to form the cover nappes of the High Calcareous Alps of Switzerland – the Helvetic Nappes, whereas the underthrust basement and the sediments on continental margin have been deformed and metamorphosed during the Alpine deformation and form the Middle and Lower Penninic nappes of the Alps. The mobilized basement became the granitic gneisses and the sedimentary cover became the *schistes lustrés* or the *Bündnerschiefer* of the Grand St. Bernhard and Monte Rosa Nappes of western Switzerland, the Tambo/Suretta Nappes of eastern Switzerland, or the Lepontine Nappes of southern Switzerland.

Studies of comparative anatomy of the mountains suggest that the Alpine model can be applied to various collision-type of orogens. The "vertebrae" of a mountain belt is the collision melange. In the Qinling Mountains, a W–E trending zone, which extends from Tianshui in Gansu Province to Nanyang in Henan Province, includes many exotic blocks or slabs of ophilites. The matrix, in which the blocks are embedded, is composed of shale, slate, or phyllites with pervasive shearing planes, where the degree of metamorphism is slight, but consists of green schists or mica schists in more highly metamorphosed areas. The size of the blocks varies from 2 mm to several kilometers. The lithology of the melange blocks are also various, but the common presence of ophiolites indicate the genesis of the melange (or melanges) through the suturing of colliding continents.

Field investigations revealed the presence of two belts of ophiolite blocks within the Tianshui/Nanyang Zone (Fig. 1 and 2). A northern, or more internal belt occurs, near the northern boundary fault (Heigou Fault) or under the Precambrian basement, as half windows. A southern, or external zone occurs near the southern boundary fault (Shang-Dan Fault), just north of the Flysch nappes. Between the two are terranes underlain by granites and mica schists. Whereas the ophiolite melanges are considered equivalent to the High Penninic ophiolite nappe(s) of the Alps, the granites and schists are correlated to the Middle/Lower Penninic Nappes of mobilized basement in the Alps. We are not certain if the two outcropt belts of ophiolite melanges are in fact one and the same, exposed on two limbs of an antiform, or if they represent the suturing of two oceanic realms. In either case the granites represent the mobilized basement of the continent south of Paleotethys, or that of a micro-continent between the two oceans. This is one of the several major problems to be clarified by our on-going investigations.

The Pre-Sinian basement rocks north of the melange belt, called the Taihua Group, have yielded metamorphic ages older than 1 billion years: they have obviously not been subjected to deep burial or mobilization during the Qinling deformation. The sedimentary cover of the basement belongs to the North China facies, identifying its paleogeographic position north of the Paleotethys Ocean. Occupying a tectonic position similar to that of the Austroalpine Nappes of the Alps, we consider the Taihua unit a part of the overriding crustal wedge; the Taihua basement and its sedimentary cover form a series of rigid-basement nappes in Qinling, which owe their origin to southward overthrusting of the North China Block during the intercontinental collision.

The foreland folded belt of southern Qinling are underlain by the passive-margin deposits of the Yangtze Block. The deformation of this sequence is typical of the thin-skinned deformation of a peeled-off sedimentary cover: the layered sequence form anticlines and synclines with well-developed axial-plane cleavage. The style of the cover-deformation in Qinling is thus less comparable to that of the recumbent folding in the Helvetic Alps, but more similar to that of the foreland folded belt of the Valley and Ridge Province in the Appalachians. All the three units share one feature in common, however, namely, the basement has not been deformed together with its sedimentary cover.

Between the foreland fold belt of Southern Qinling and the Tianshui/Nanyang melange(s) is a zone of sedimentary rocks of the flysch facies. The strata were folded, forming recumbent and isoclinal folds, and overthrust to the south: the axial planes of the folds dip commonly northward. The Flysch of West Qinling has been dated by ammonite fossils and by its stratigraphic relation to underlying Permian strata. The sediments of the Flysch Nappe probably constituted the accretional wedge on the active margin of the Paleotethys, where the ocean floor was being subducted under the North China continent during the Triassic. The Flysch of East Qinling has been mapped as Devonian (Geologic Map of China, 1976). The age assignment was made on the basis of an incorrect practic to date all rocks between two major faults on the basis of the only fossils found in those. The Devonian fossils of the Flysch Nappe of East Qinling are corals in a block embedded in sediments of the wildflysch facies (Zhang Guowei, Northwestern University, Xi'an, pers. comm., 1985). They represent only the age of that exotic component in the Flysch, and cannot be used to date the Flysch itself (see Hsu 1968, 1974). Field work suggests a correlation of the Flysch sediments of East Qinling to that of West Qinling, and that its age is largely Triassic, not Devonian.

The tectonic position of the Flysch nappes is comparable to that of the Flysch nappes in the Alps, but the application of the principles of comparative tectonics is made difficult by the fact that the problem of the Alpine Flysch is not completely resolved. There is evidence that subduction of the Tethys Ocean floor took place along a south-dipping Benioff Zone under the southern Tethyan margin, and that the Upper Cretaceous South Penninic constitute the accretional complex at that active plate margin. The Flysch was overthrust onto the foreland during an earlier phase of deformation, but the Flysch nappes were locally overriden by ophiolite nappes during a later deformation. Assuming

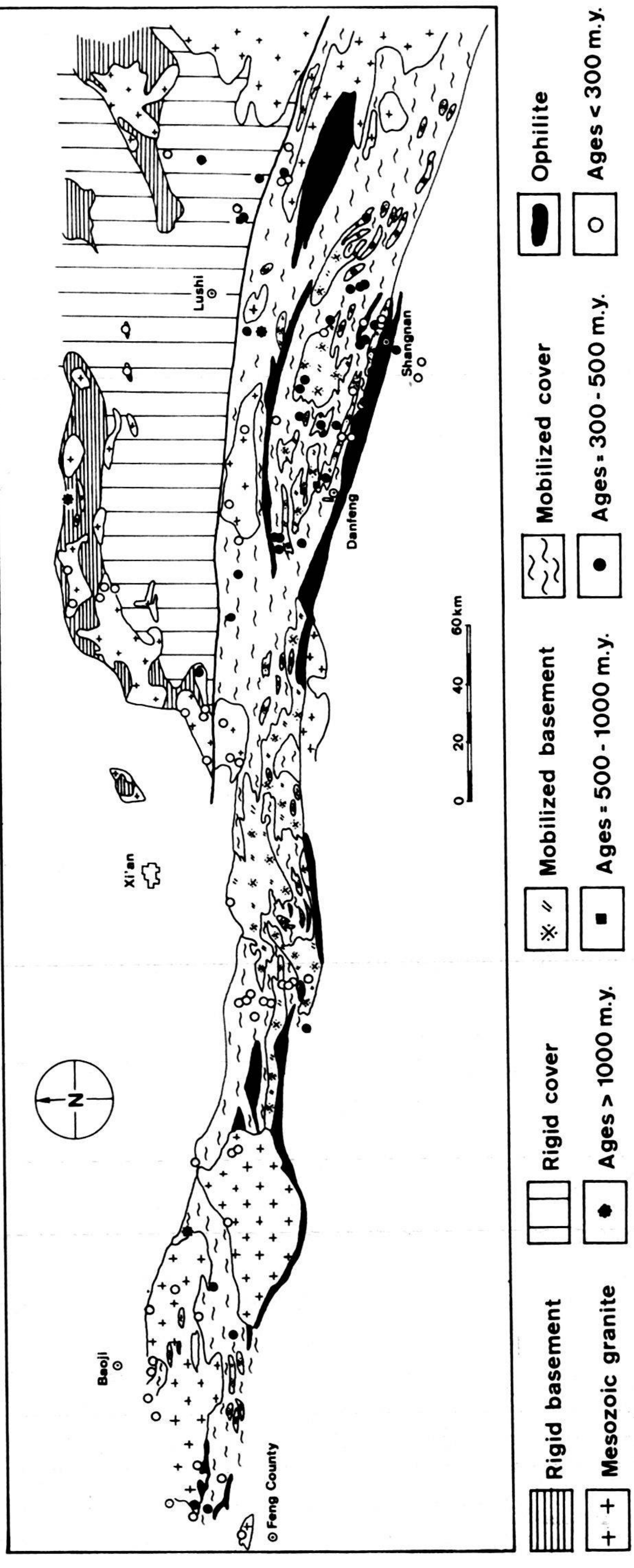

Fig. 5. Geographic distribution of radiometric ages of metamorphic and igneous rocks of Qinling.

that the Qinling Flysch has a role similar to that of the South Penninic Flysch, we might suggest that the Triassic Flysch was laid down on the northern margin. During the Triassic deformation those youngest sediments of the Paleotethys Ocean have been pushed forward by the plunger action of a *traîneau ècraseur*, which is the rigid basement nappes of the Taihua unit; Taihua is thus equivalent to the Silvretta Nappe of the Austroalpine Unit. In addition to the South Penninic Flysch, flysch sedimentation may also have taken place on the northern Tethyan margin during the latest Cretaceous and early Tertiary phase of the Alpine deformation, and those Flysch were overriden by ophiolite nappes. Similarly, not all Qinling Flysch sediments were laid down on the northern margin of the ocean, some, such as those in nappes below the metamorphic complex may have a southern Paleotethyan origin.

The most puzzling element of the Qinling Geology is the occurrence of the rocks of the Qinling Group in areas south of the Tianshui/Nanyang Zone. We visited the outcrops west of Mianxian and found assemblages of rocks including granites, schists, and ophiolites. Their tectonic evolution is hardly distinguishable from that of those rocks within the suture zone. We propose, therefore, that those metamorphic rocks are klippen of a large nappe complex of ophiolite/mobilized basement. The Mianxian Klippe has been thrust on top of the Flysch Nappes. The Wudangshan Klippe has been thrust even more southward to lie on top of the foreland fold belt.

Still more puzzling is the occurrence of Precambrian basement and basic volcanic rocks in the mountains south of Hanzhong (Fig. 1). It is commonly interpreted as an autochthonous massif, comparable the Aar Massif of the Alps. Their structural trend is, however, discordant to that of the Daba Mountains. Furthermore, the assumption of granitic autochthonous massif does not explain the occurrence of basic volcanic rocks, which are probably ophiolite blocks in a melange. We propose, therefore, that the Precambrian granites and the underlying basic volcanic rocks south of Hanzhong are the erosional remnants of far-travelled nappes. According to this idea, the Hanzhong Klippe is a rigid basement nappe riding on top of an ophiolite melange, and the klippe, like the klippen of central Switzerland, has been thrust more than 100 km to lie on top of the foreland fold and thrust belt.

In contrast to the Alps where Alpine intrusives are uncommon, the Qinling Mountains have been intruded by numerous Mesozoic granites. The best example are the cliff-forming granites of Huashan east of Xian. The radiometric ages of the intrusive granites commonly range between 235 and 185 m.y. (CHEN 1975; HUANG 1976). The Sr-isotope value ranges from 705 to 710 (Zhang Guowei, pers. comm., 1985), typically the values of the S-type of granites (PITCHER 1983). Their genesis suggests partial melting of deeply buried continental crust, which was thickened when one or more wedges of continental crust had been underthrust after continental collision.

Age of Qinling deformation

Our kinematic analysis suggests that the Qinling Mountains were formed as a result of the collision of North China and Yangtze Blocks after the Paleotethys Ocean was consumed in Triassic. This interpretation is, however, at odds with a previous interpretation that the Qinling is a Caledonian mountain range, – an opinion based upon the observation of a slight angular unconformity between the Devonian and the older

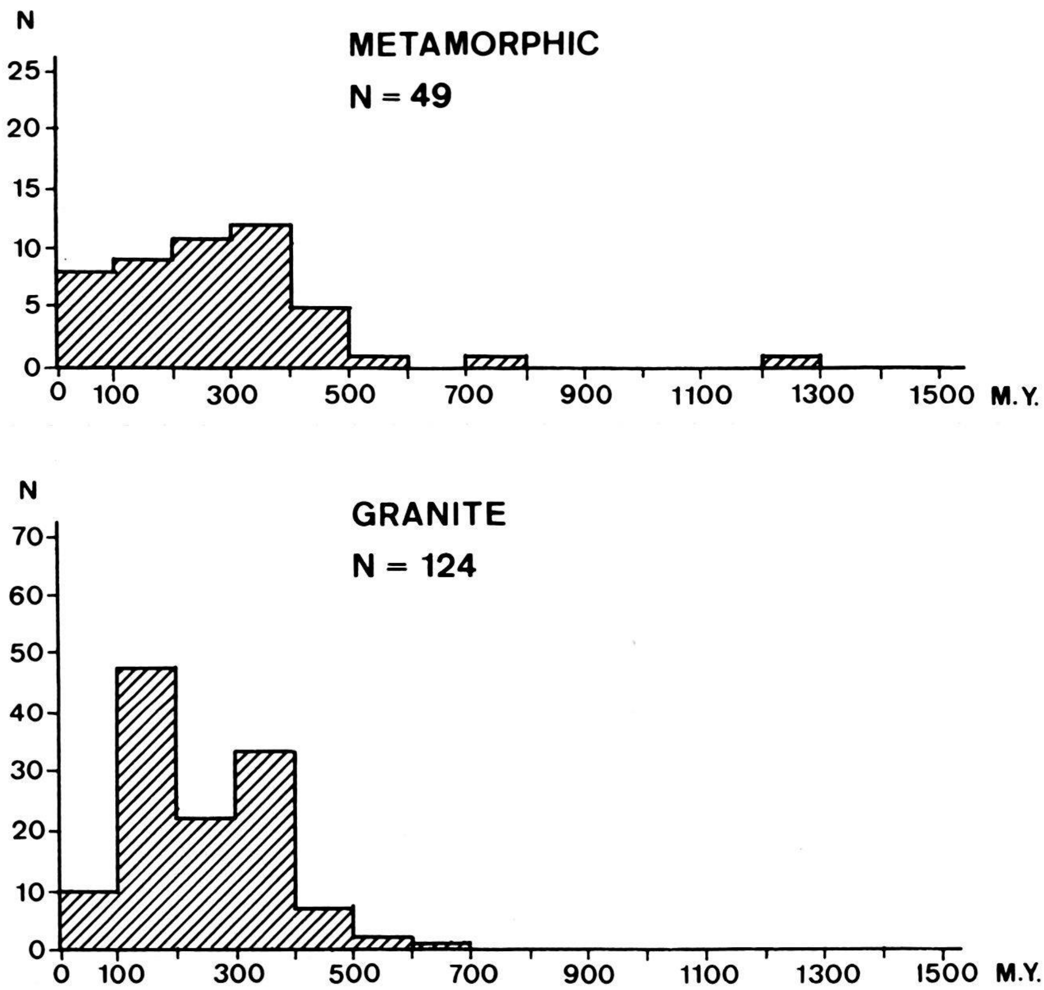

Fig. 6. Frequency distribution of radiometric ages of metamorphic and igneous rocks of Qinling.

sedimentary cover. The postulate of pre-Devonian deformation naively over-emphasized the unconformity which may signify not much more than a regression of the sea from the platforms during the mid-Paleozoic. A major collision event in collision-type of mountains should be recorded by the widespread occurrence of post-collision continental deposits of the molasse facies. The Qilian Mountains of Gansu Province, for example, are very probably a Caledonide, having originally resulted from pre-Devonian continental collision. The Devonian sediments of eastern Gansu are indeed thick red beds, typical sediments of the molasse facies. They are, on the whole, absent in the Qinling Mountains. The eastern extention of the suture zone of mid-Paleozoic intercontinental collision, which formed the Qilian Mountains, if present, is very probably buried under the late Paleozoic and Mesozoic sediments of the Ordos Mountains.

A second argument for a Caledonian collision is based upon the reportedly mid-Paleozoic dates of the metamorphic rocks in Qinling. As shown by Figures 5 & 6, the radiometric ages of metamorphic minerals in numerous samples, or some ⅓ of the total, of the Qinling Group range from 300 to 500 m.y., which are commonly considered indicative of Caledonian or Hercynian deformations (ZHANG 1980; CHEN 1975; MATTAUER et al. 1985). Not to be overlooked is, however, the fact that most samples, or the majority, have latest Paleozoic or early Mesozoic ages of Indosinian metamorphism.

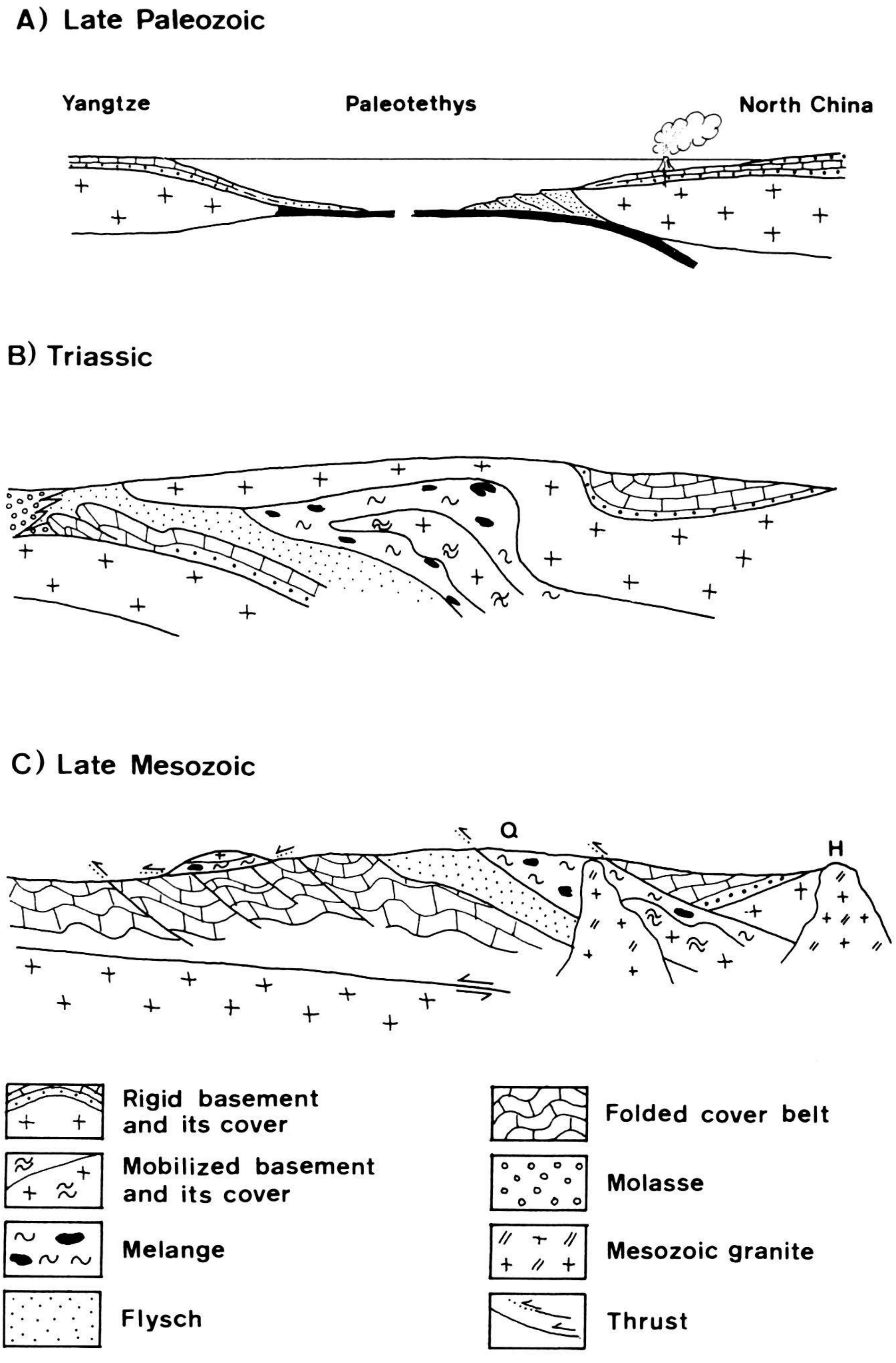

Fig. 7. Schematic diagrams showing the tectonic evolution of Qinling. A. Subduction of the oceanic lithosphere under the North China Blocks and the deposition of thick clastic wedges (Flysch) on this active plate-margin during the late Paleozoic and early Triassic. B. Qinling after terminal continental collision during the Triassic. C. Continued deformation after continental collision during the Jurassic and early Cretaceous. Numerous discordant granitic plutons intruded the North China Block and the suture zone during this phase of post-collision deformation.

We have to recognize the fact that many different lines of evidences have to be taken into consideration to interprete the radiometric ages.

The most reliable method of dating continental collision is base upon the determination of the stratigraphical ages of the sediments on the margins of the colliding continents. The evidence on the Yangtze margin, fringing the Paleotethys on the south, is clear: The sequence is typically that of continuous sedimentation on a passive continental margin which continued from Sinian (late Precambrian) to Triassic. The marine sedimentation was interrupted by a Triassic deformation so that Upper Triassic, Jurassic and younger sediments are all terrestrial deposits.

The evidence on the northern margin of the Paleotethys is more equivocal, but the available data also point to a date of Triassic collision. A thick marine sequence of the Permian to Triassic strata is present in West Qinling, and the thick Triassic Flysch sediments were laid down before they were deformed by continental collision (Jiang et al. 1979). Marine Permo-Triassic sequence of more than 3000 m thick has also been recognized in East Qinling (Ding et al. 1982). The stratigraphy of West Qinling and of the Songpan region clearly suggests continuous sedimentation from early Paleozoic until Triassic, the first continental sediments were laid down during the Late Triassic. Obviously the consumption of the Paleotethys Ocean was a Triassic, or "Indosinian" event.

The ages of granitic intrusives give an indirect evidence for continental collision. We have mentioned that the Qinling Mesozoic granites owe their origin to partial melting of underthrust continental crust. The fact that the oldest such granites are late Triassic is in accordance with the postulate of mid-Triassic continental collision.

A still another line of evidence to estimate the timing of collision has been provided by investigations of paleo-latitude. The presence of radiolarian chert of Permian age in the Yangtze Block suggests a paleogeographic location near the Permian Equator, and this interpretation is confirmed by paleomagnetic investigations (McElhinny et al. 1981; Zhang 1984; Lin et al. 1985). The block may have advanced far northward before its collision with North China during the Triassic.

One more line of evidence is the isotopic dating of the ophiolite-eclogite blocks in the melange, which are fragments of oceanic crust metamorphosed during collision. Those in the Qinling–Dabie Mountains have been dated recently by Li et al. (1986), ranging from 210 to 243 m.y. They concluded, therefore, that the North China and the Yangtze Blocks finally collided after the end of the Paleozoic.

Although all lines of evidence favors the postulate of Triassic continental collision, the radiometric ages of Qinling metamorphic rocks older than 250 m.y. still demand an explanation. Several alternatives can be suggested.

1. The Qinling has a history of Caledonian collision, but the evidence has been mostly obliterated by the Mesozoic deformation. One might suggest, for example, that the northern belts of ophiolites in the Tianshui/Nanyang Zone, or a more northerly ophiolite belt buried somewhere under the Taihua rigid-basement nappes, marks the suturing of the continents collided during the mid-Paleozoic Orogeny.
2. The mid- and late-Paleozoic radiometric dates are indicative of metamorphism during the subduction phase of the Qinling deformation, which may have started as early as Devonian (Li et al. 1986).
3. The older radiometric dates reflect a partial equilibration of the radiogenic minerals during the Qinling metamorphism. Precambrian basement granites and gneisses, remo-

bilized during Mesozoic deformation, may yield isotope data indicative of dates intermediate between the old and new ages of crystallization.

We would not accept the first alternative, which finds little support in the sedimentary record of the Qinling Mountains, though it provides a most ready explanation of the Mid-Paleozoic radiometric dates of metamorphism.

What we prefer is the combination of the second and the third ones. That means, part of the older radiometric dates resulted from the remobilization of Precambrian basement of crystalline, and part of them stemmed from ante-collision subduction off the North China continent, which might have taken place probably since the Devonian. The northern boundary of the Paleozoic subduction zone was near the present Heigou Fault, but its southern boundary is hardly defined because it belongs to non-terminal suture (SENGÖR & HSU 1984) and has incorporated into the Indosinian collision suture zone. Such a working hypothesis is least contradictary to other lines of evidence.

Summary

The Qinling Mountains are interpreted as an orogenic belt of the collision type (Fig. 7). The Precambrian Taihua basement and its sedimentary cover of the North China facies are present in the rigid-basement nappes near the northern margin of Qinling. The Qinling Metamorphic Complex includes one or more belts or ophiolite melanges, the remobilized basement of underthrust crustal wedge, and metamorphosed ocean sediments. The melanges occur not only in the suture zone along the Tianshui/Nanyang trend, but also in klippen, as erosional remnants of ophiolite nappes overthrust onto Flysch and foreland fold belt. Turbidites, including mainly the sediments of accretionary wedge(s) on continental margin(s) of Paleotethys, form the Flysch Nappe south of the suture zone. The most southerly tectonic unit is the Foreland Fold Belt, where the passive-margin sediments of the Yangtze Block have been folded and overthrust southward onto the Yangtze Platform. Mesozoic intrusives of Qinling owe their origin to partial remelting of underthrust crustal wedges after Triassic continental collision.

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