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The major suture zone of the Qinling orogenic belt

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Abstract—The Qinling mountains are a typical composite continental orogenic belt which underwent various stages of evolution characterized by different tectonic regimes. Its late Proterozoic to early Mesozoic evolution was dominated by plate subduction and collision processes. The Shangdan fault zone marks the major suture which resulted from the plate subduction and collision and represents the basic division in both the superficial geology and the deep-seated crustal structure of the Qinling mountains. It is not a simple fault zone but an intricate geologic terrane, characterized by a prolonged and complicated history. It is referred to as Shangdan boundary fault terrane or Shangdan zone for short. The Shangdan zone consists chiefly of five parts: (1) fault systems as marked by various types of mylonite and cataclasite, (2) tectonic assemblages of Danfeng ophiolite blocks, (3) tectonic assemblages of obducted slices of a sedimentary prism, (4) granitic rocks related to orogenic processes of subduction and collision, and (5) basins controlled by late brittle faults. The evolution of the Shangdan zone can be traced through three major stages: the Caledonian period of subduction, the Indosinian period of collision and orogeny, and the Mesozoic–Cenozoic period of intra-plate deformation, among which the Indosinian period marks the most important stage in its development. In brief, the Shangdan zone is the major division between the ancient lithospheric plates in the Qinling belt and extends deep into the upper mantle.

INTRODUCTION

THE QINLING mountains are an important composite continental orogenic belt across the continent of east Asia and occurs between the North China craton and the Yangtze craton. According to its geological, geochemical and geophysical characteristics this tectonic belt consists principally of three zones, separated from one another by the nearly east–west Luonan–Luanchuan fault and the Shangdan fault. These are: (1) the North China craton southern marginal tectonic belt, (2) the northern Qinling tectonic belt, and (3) the southern Qinling belt (Fig. 1). The Qinling orogenic belt as a whole is characterized by its complex composition and structure due to a prolonged tectonic history. Different stages in its evolution involved different tectono-dynamical mechanisms. Plate movements appear to have begun from the late Proterozoic and prevailed until the early Mesozoic. While the southern Qinling tectonic belt originally pertained to a passive continental margin on the north of the Yangtze Plate, the northern Qinling and the North China craton southern marginal tectonic belt belonged to the North China Plate, the northern Qinling belt pertaining to an active continental margin on the south of the North China Plate. The main plate movements occurred in the Indosinian period when the North China Plate and the Yangtze Plate experienced continued relative motion involving lateral drift and rotation and finally settled down approximately where they now exist (Lin 1985). This plate motion results in subduction and collision along the Shangdan fault zone and gave rise to the fundamental structure of the present

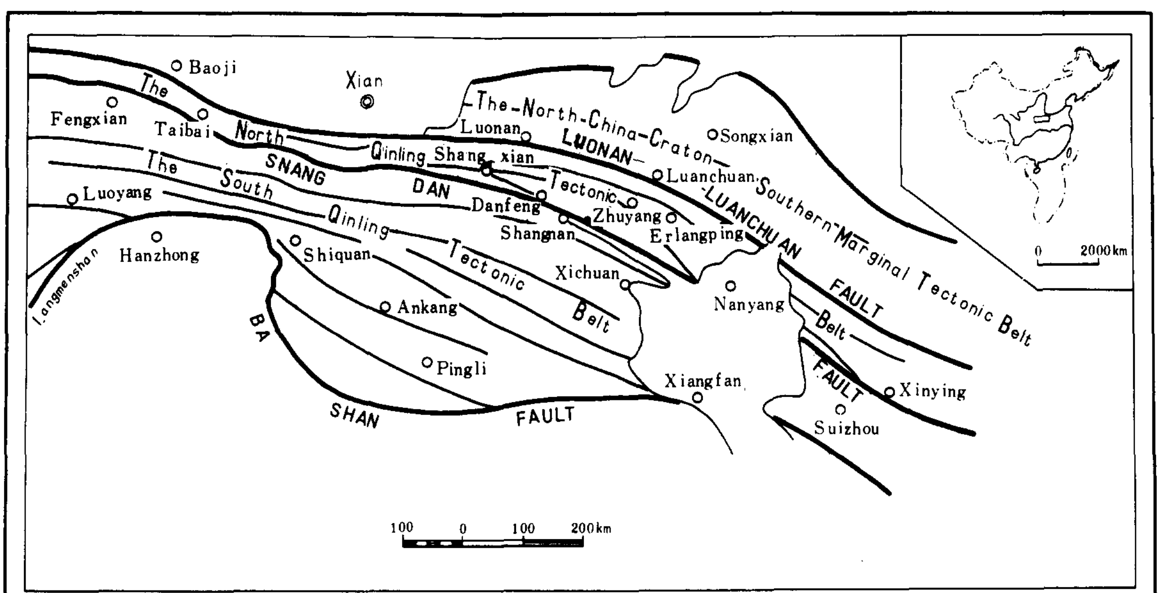

Fig. 1. Regional map of Qinling orogenic belt showing its major tectonic divisions.

Qinling orogenic belt. Obviously, the Shangdan fault zone has played a leading role in the prolonged evolution of the Qinling mountains. It not only marks the major suture zone of subduction and collision between the North China Plate and the Yangtze Plate but also represents a belt of great activity during the Mesozoic–Cenozoic period of intra-plate deformation. In fact, it is not a simple fault zone but an intricate tectonic border terrane dominated by the subduction and collision zone of the plate border and characterized by complicated structure and a prolonged history. By the term "tectonic border terrane" we refer to a linear geological terrane or tectonic unit which occurs as a dividing border between separate ancient plates or terranes and at the same time is a substantial feature itself with its own material composition, structure and history. The Shangdan fault zone is exactly a feature of this kind. It is therefore referred to as Shangdan boundary fault terrane, or Shangdan zone for short.

THE SHANGDAN ZONE

The present Shangdan boundary fault terrane is an end product produced as the result of prolonged and complex evolution. It occurs between the northern and the southern Qinling belt and extends approximately east–west for hundreds of kilometers, with a maximum width from north to south of only about 6–8 km. The northern and the southern Qinling orogenic belts differ markedly in that each has a distinctive late Proterozoic–early Mesozoic history and a different crustal structure due to its separate geological evolution associated with a separate plate, notwithstanding a common Mesozoic–Cenozoic history of intra-plate deformation.

Division in the superficial geology between the northern and the southern Qinling belt

The North China and Yangtze Plates have long been subjected to separate evolution. This difference is mainly reflected in their different stratigraphic associations. The southern Qinling belt is characterized by a double-layered crustal structure consisting of the basement and cover of the Yangtze craton. Late Proterozoic sediments and associated acid, intermediate and basic metavolcanics of the Yunxi and the Yaolinghe Groups and sediments of the Doushantuo and Dengying Formations ranging from flysch to cratonic facies are abundantly exposed in the southern Qinling belt but they never extend beyond the Shangdan zone. Sediments of the Lower and the Upper Palaeozoic and the Lower–Mid Triassic consistently show a pattern in which the shelf, slope, rise or even abyssal plain successively occur from south to north, suggesting the existence of an integrated sedimentary system of a passive continental margin off the north coast of the Yangtze continent. Despite the occurrence of a marginal fault trough in early Palaeozoic times, in which accumulated the rift-type deep water sediments of the Donghe Group and associated subalkalic subvolcanics and intrusives now occurring along a tract including Pingli and Shiquan, and some change and adjustment in depositional setting and facies pattern between the early Palaeozoic and the late Palaeozoic–early and middle Triassic, the above overall pattern of progressively deeper water sedimentary systems from south to north showed no conspicuous change with time (Fig. 2). This strongly suggests that the tectonic setting of a passive continental margin persisted on the north of the Yangtze Plate throughout the late Palaeozoic until the early Mesozoic Indo-China period. In the northern Qinling belt, entirely different rock assemblages occur. Underlying this area is a Precambrian crystalline basement consisting of the Qinling and Kuanping complex, which rather closely resembles that of the North China craton in view of their similarities in composition, structural features and geophysical characteristics. An especial characteristic of this belt is the occurrence of early Palaeozoic Danfend and Yunjiashan–Erlangping ophiolite complexes, back- and fore-arc turbiditic sequences, and a tract of extensive Palaeozoic calcalkaline granitic rocks. All these show that the northern Qinling mountains represent an active continental margin on the south of the North China Plate facing the contemporaneous passive continental margin of the Yangtze Plate to the south, which now occurs only as remnants, due to subduction, collision and Mesozoic–Cenozoic tectonic activity. It is obvious that the Shangdan fault and border terrane represents the zone of terminal collision and coalescence of these two continental marginal systems rafted on the converging plates, thus forming the major geological division between north and south. In terms of structural features, there are conspicuous differences as well as similarities between the northern and the southern Qinling tectonic belt. The differences lie in the fact that northern Qinling is characterized by consolidated basement blocks, such as the Qinling complex and a centre of pronounced concentrated deformation, metamorphism and magmatism marked by the Danfeng and Erlangping ophiolites, calcalkaline granitic plutons and back- and fore-arc type sedimentary systems and exhibiting complicated deformational features and tectonic associations formed by remnants of an active continental margin as the result of orogenic processes of subduction and collision. The southern Qinling, on the other hand, is characterized by deformation and tectonic assemblages characteristic of a passive continental margin formed on the preexisting tectonic foundations as the result of subduction and collision. The similarities in tectonics between the northern and southern Qinling arise from a common tectonic evolution commencing from the opening and spreading of an ancient Qinling ocean of restricted extent and terminating with its subduction and final closing and collision, and a common history of intra-plate deformation subsequent to the coalescence of the two plates, which is reflected in the occurrences of a series of southward overlapping thrust nappes at various structural levels across the whole Qinling mountains (Fig. 3).

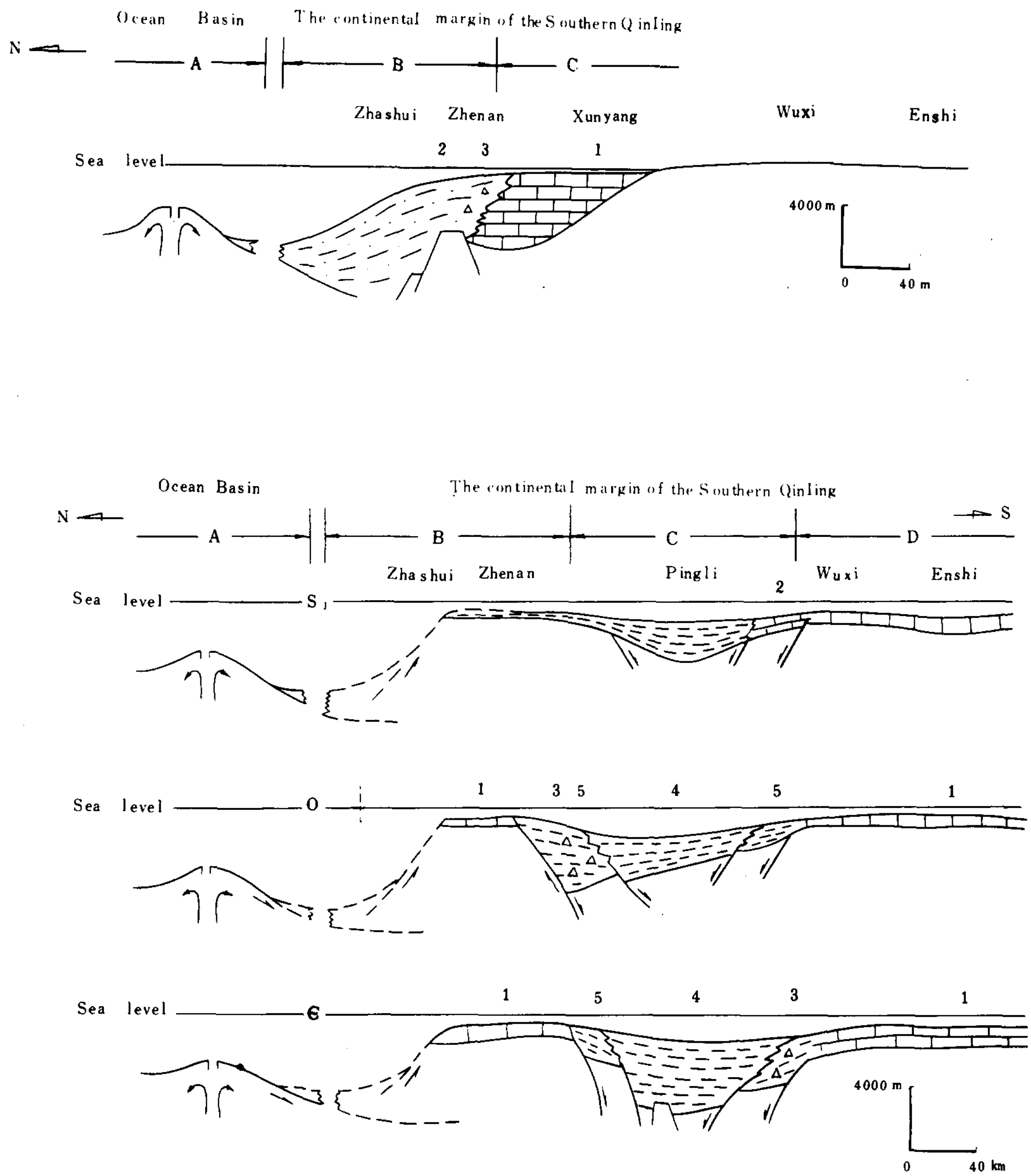

Fig. 2. Palaeogeographic map of southern Qinling belt showing sedimentary system on northern margin of Yangtze Plate. 1. Shallow water platform limestone, dolomite shale and sandstone; 2. Flysch; 3. Slump breccia; 4. Deep-water basin layered chert, carbonaceous shale, and phyllite; 5. Slope facies marlstone, turbiditic limestone and phyllite. A. Ocean basin (ophiolite area); B. Intervening platform; C. Trough; D. Marginal platform of the Yangtze block. A. Ocean (ophiolite area); B. Slope-rise; C. Shelf: 1. Shallow-water platform limestone, dolomite, sandstone and shale; 2. Flysch; 3. Slump breccia.

Division in deep-seated crustal structure between the northern and the southern Qinling

The Shangdan zone coincides with an offset in the magnetic anomaly pattern and a zone of high gravity anomaly variation across the Qinling belt. Extrapolated gravity and magnetic anomaly patterns for the 10–40 km upward continuation show similar features. Northern Qinling north of this zone exhibits gravity and magnetic anomalies rather similar to the North China craton, the anomalous magnetic field having considerably large positive intensity values, greatly different from that of

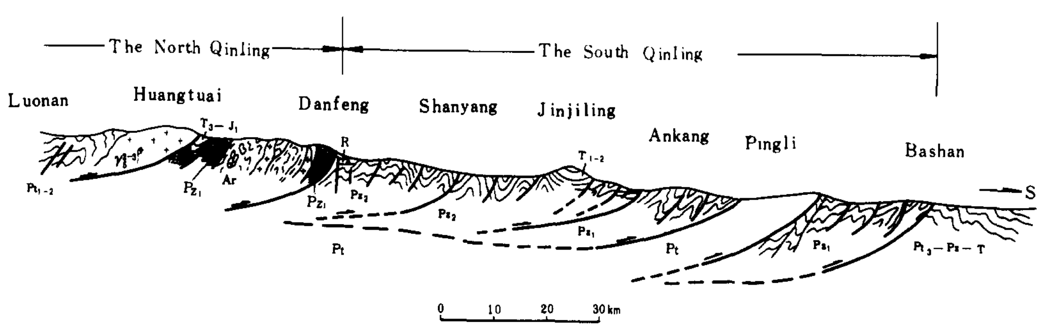

Fig. 3. Schematic tectonic cross-section across Qinling orogenic belt.

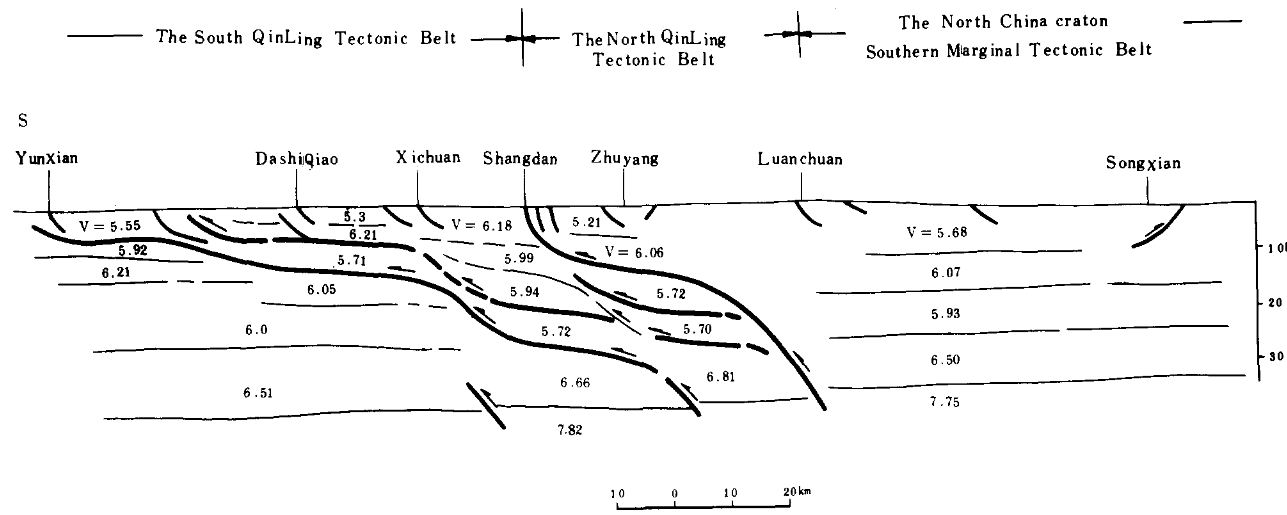

Fig. 4. Cross-section illustrating features of crustal structure of Qinling belt (modified from Zhu *et al.* 1987).

the southern Qinling (Zhu 1979, Zhou and Liu 1979). According to the unpublished data of Zhu Jieshou *et al.* seismic reflection profiles across the eastern segment of the Qinling range indicate that the northern and the southern Qinling as separated by the Shangdan zone have different seismic sections. As shown in Fig. 4, the Qinling belt can be divided into three parts according to crustal structure:

(1) the part north of the Luanchuan fault, i.e. the southern marginal portion of the North China craton, exhibits a relatively simple crustal structure with no conspicuous low velocity layer.

(2) The part south of Dashiqiao, which undoubtedly belongs to the Yangtze craton, only exhibits a low velocity layer at intermediate crustal levels (Ding 1987, Chen and Gao 1986).

(3) The remaining part between the above two divisions is the central portion of the Qinling belt proper which in contrast shows marked low velocity layers (5.72–5.70 km/sec), as notably exemplified by the area between the Shangdan zone and the Luanchuan fault which is characterized by several low velocity layers at depths in the lower part of the upper crust to the intermediate crust with thicknesses of about 10 km, probably representing ductile zone or zones of magmatic melting. In conjunction with the surface geology and other geophysical characteristics, we interpret the Shangdan zone as an upward steepening listric fault system which extends downward towards the north to merge into a low velocity zone at a depth of about 12 km which it follows for some distance, giving rise to a large scale decollement or detachment structure, and eventually penetrates at an oblique angle into the lower crust and the upper mantle. The northern crustal unit above this decollement belongs to the crustal structure of the North China craton, whereas the southern slab below it represents part of the Yangtze Plate. At the junction of the Yangtze with the North China Plate, however, is a large-scale subduction, collision, thrust and detachment zone with another large detachment layer at its base, beyond which is the crust with seismic structure characteristic of the Yangtze craton. In short, existing seismic data suggest an overall crustal structure of the Qinling belt in which the North China crust slab is thrust southwards over the northwards-subducted Yangtze crust, between which is a complex junction zone with intricate rock assemblages and intense deformation extending to great depth in the crust, the Shangdan zone being the collision zone proper.

As indicated by the above data, on the deep-seated crustal structure as well as the surficial geology, the Shangdan zone clearly represents an important dividing boundary in the Qinling orogenic belt. Moreover, its internal composition and character as discussed below will further demonstrate that it represents the very major suture zone of the subduction and collision boundary between Yangtze and North China.

COMPOSITION AND CHARACTER OF THE SHANGDAN ZONE

The Shangdan zone is characterized by complex composition and a prolonged history. It comprises a mixture of sediment fragments and rock blocks or slices of different ages, types and provenances, tectonically arranged in shear zone or thrust contact with one another. Although it has undergone multiple and superimposed deformation, its structure is still dominated by the major suture boundary between Yangtze and North China, forming an integrated boundary terrane. Specifically, it consists of: (1) a fault system composed dominantly of ductile shear zones of the Shangdan major boundary, (2) Danfeng ophiolite blocks tectonically set between thrusts, (3) a stacked obducted prism, (4) granitic plutons and dykes directly related to subduction and collision, and (5) red deposits within linear fault depressions controlled by late brittle faults.

Faults and shear zones of the Shangdan zone

The Shangdan zone is characterized by an intricate fault system consisting of faults and shear zones of varying nature, magnitude and scale formed at various structural levels during different periods of time which exhibit multiple deformation and superimposition accompanied by intense multiple dynamical metamorphism and composite implacement of linear intrusions. In terms of their pattern of occurrence, they are rather unevenly spaced across and extend continuously or intermittently along the strike. In brief, they comprise a labyrinthine fault system containing numerous individual long-lived, multiply-superposed shear surfaces in an intricate anastomosing pattern, which are revealed by various types of signatures, such as mylonite or cataclastic zones, aligned intrusions, dykes or mylonized linear intrusive bodies. Based on combined microscopic and mesoscopic studies in conjunction with large-scale mapping and detail field investigations, two major fault series are recognized, namely ductile or brittle–ductile series and brittle series, respectively. Also distinguished are four fault groups corresponding, respectively, to four major successive periods of tectonic activity, i.e. subduction, collision, thrusting and nappe formation, and strike–slip and block faulting, reflecting generation and evolution of the Shangdan zone in different tectonic regimes or settings during different stages in the development of the Qinling orogenic belt. The Shangdan zone is best and most characteristically exposed in the Danfeng–Shangnan segment and the segment of Shagou, Ningshan. In the vicinity of Danfeng, for instance, seven closely spaced shear zones or faults are recognized on the basis of large-scale mapping (Fig. 5).

1. *Late brittle faults and Cretaceous–Tertiary.* Late brittle faults in the Shangdan zone are mostly expressed by zones of fault breccias or other fractured rocks belonging to the cataclastic series. A conspicuous feature of these faults is their occurrence in a discontinuous, *en échelon* pattern with right-lateral displacement, along which are formed a series of Cretaceous–Tertiary fault basin, as exemplified, for instance, by the segments of, from west to east, Baishipu, Shagou in Ningshan, Shangxian–Danfeng, and Zhuxia where all the faults exhibit a history of fault movements involving earlier extensional faulting and associated downfaulting and later renewed faulting and thrusting cutting and displacing the basins and resulting in open flexures in the red beds (Zhang *et al.* 1986). It is apparent that the later brittle fault system first formed during later stages of the Yangshanian orogeny and has further undergone compressional movement in Tertiary times. Features of these late faults and basins in the Shangdan zone and other major faults in the northern Qinling belt are closely associated with more or less simultaneous strike–slip movements, suggesting that a genetic relationship to the strike–slip faults developed.

2. *Brittle–ductile shear zones.* Two types of brittle–ductile shear zones are recognized in the Shangdan zone: strike–slip shear zones and thrust zones. The former formed in a relatively later period and so are fully developed and well exposed, exhibiting mylonizd fault rocks and porphyroclastic mylonites with various types of features formed by ductile shear. Notably conspicuous is the widespread development of the penetrative mylonite schistosity of nearly horizontal stretching lineations and slickenside striations with dominant plunge 15°–20°, 110°–120°, indicating left-lateral movement (Mattauer *et al.* 1985, Xu 1986). At the same time, however, are often seen partly destroyed earlier stretching lineations and slickensides with the reverse sense of movement, i.e. right-lateral strike–slip movement, indicating that the direction of slip has changed from dextral to sinistral during the course of the fault movements. There exists a close relationship between these and the late brittle faults and red basins as discussed above, which are not isolated features throughout the whole Shangdan zone but are genetically associated with the strike–slip movement, their change in mode of activity from earlier extension to later compression and occurrence in *en échelon* arrangement being the inevitable consequence of the reversal of direction of the strike–slip movement from dextral to sinistral.

With regard to the brittle–ductile thrust shear zones, their major features are summarized as follows:

(1) most of them occur along the northern border of the Shangdan zone with the Qinling complex, extending with irregular breadths for long distances along strike (Fig. 5).

(2) They are marked by protomylonites, mylonites and aligned mylonitic granitic intrusions with north–south stretching lineations and other shear structures, indicating southward thrusting.

(3) Their development is accompanied by intense dynamical metamorphism of green-schist facies, giving rise to mylonite zones of green-schist facies.

Taking account of the fact that these shear zones are cut across by the above-mentioned strike–slip shear zones and that the mylonitic granites in them are largely Indosinian to Yanshanian in age, it is inferred that they appear to have formed during the early–mid episodes of the Yanshanian orogeny. Although they presently are inclined at a steep angle at the surface, geophysical data as presented above favour an interpretation that they are the major constituent parts of Mesozoic–Cenozoic thrust nappe structures in the northern Qinling belt, belonging to the group of brittle–ductile or ductile thrust shear zones.

3. *Ductile shear zones.* When the effects of later episodes of faulting are removed, the Shangdan zone conspicuously exhibit various mylonite zones formed at deeper levels. Based on large-scale mapping, isotopic data, as will be presented later, estimated strain magnitude and inferred depths at which the mylonites appear to have formed, and according to proportions of the matrix and grain size of porphyroclasts, or in terms of ratios of strain to recovery (Sibson 1977, Ramsay 1980, White 1980, Wise 1984, Zhong 1983, Song 1986, Zheng and Chang 1985), two types of mylonitic rocks can be distinguished: typical mylonite and mylonite gneiss. Typical mylonites include phylonites, ultramylonites, mylonite and augen mylonites. Original textures and structures are seldom retained within these rocks, which

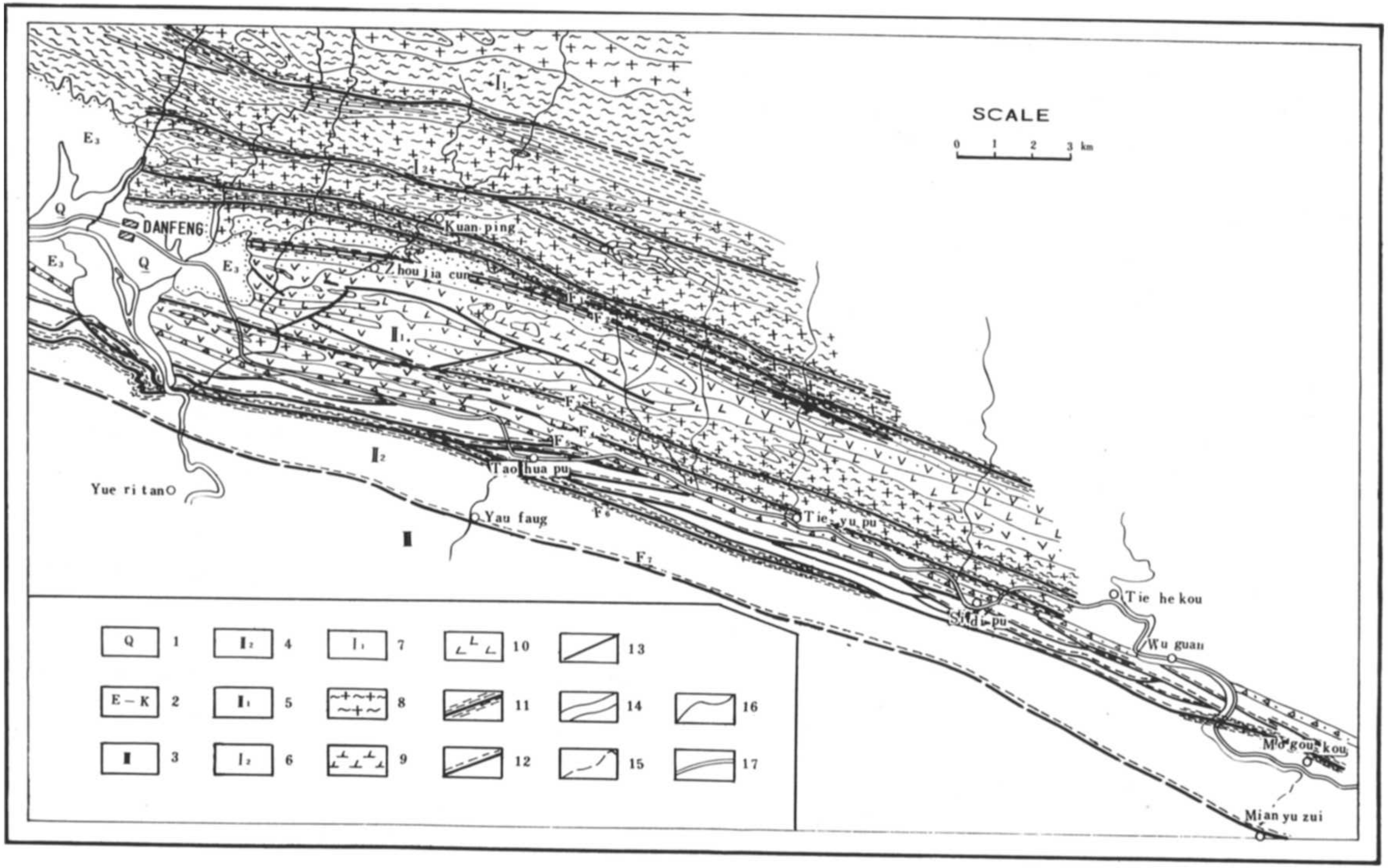

Fig. 5. Geological sketch-map of Danfeng segment of Shangdan zone in Qinling belt. 1. Quaternary; 2. Tertiary–Cretaceous; 3. Devonian Liuling Group; 4. Assemblage of obducted rock slices of sedimentary prism; 5. Assemblage of Danfeng ophiolite blocks; 6. Upper lithology of early Precambrian Qinling Complex; 7. Lower lithology of Qinling complex; 8. Granitic gneiss; 9. Granodiorite; 10. Pyroxenite or gabbro; 11. Shear zone; 12. Brittle–ductile fault; 13. Fault; 14. Brittle crush zone; 15. Assumed geological boundary; 16. Geological boundary; 17. Highway.

are fine-grained and have a matrix proportion larger than 50%, showing evidence of considerable recrystallization. Concomitant dynamic recrystallization and recovery appear to be the dominant processes involved in the formation of these rocks. Various kinds of ductile flow structure are developed, suggesting their formation at deep levels and at high temperatures and pressures and slow strain rates by extreme plastic deformation involving processes of plastic comminution, such as ductile flow, crystal creep and propagation. Mineral assemblages of the matrix provide a P–T estimate of 550°–600°C and above 5 kbar, implying their formation at depths of at least 15–20 km. As seen within the area covered by large-scale mapping, mylonites of this type largely occur in the Danfeng ophiolitic terranes and the fore-arc sedimentary prism of the Shangdan zone. In the ophiolites, mylonite zones occur as stacked high-angle thrust zones, which exhibit stretching lineations and A-type folds indicating southward thrusting, as illustrated by F_2, F_3 and F_5 in Fig. 5. In the sedimentary prism, however, what are found instead are an array of stacked northward obduction shear zones, as exemplified by F_6, F_7 in Fig. 5. These and other secondary parallel shear zones are the major features that signal emplacement of ophiolites and sedimentary slices by subduction and obduction, respectively, and reveal the occurrence in a pattern of tectonic slices, separated from one another by the thrust planes. This is also the case with other segments of the Shangdan zone such as Shagou and Baishipu. Combined preliminary results of seismic surveying and other geophysical data indicate that the Shangdan zone as a whole dips towards the north in a shovel-shaped form. It is therefore suggested that the shear zones formed by these extensively developed mylonites in the Shangdan zone comprise a complex tectonic assemblage dominated by a series of southward-directed thrusts, nappes and decollment or detachment structures and accompanied at the same by northward obductional thrust zones, resulting in an overall tectonic pattern in which the Yangtze Plate is subducted and consumed beneath the overriding North China Plate. Thus, these mylonites are interpreted as the major products of the Yangtze–North China Plate subduction and collision orogenies

The other group of mylonites in the Shangdan zone, i.e. mylonite gneisses, occur only as remnants engulfed in the above-mentioned mylonites. Most of these rocks are augen mylonites gneisses and gneiss tectonites falling into blastomylonite, which resemble regional metamorphic rocks but can still be recognized according to the presence of relic prophyroclasts in the rock and evidence of rotational shearing in the matrix. They reflect an earlier episode of ductile shearing in the Shangdan zone, probably representing relics of incipient products of plate subduction.

Danfeng ophiolitic assemblage

The Danfeng ophiolite complex is the dominant constituent part of the Shangdan zone, being of particular geological significance. It comprised a low-grade metamorphic complex of mafic and ultramafic rocks and flysch-type sediments, which occurs as a linear tract extending intermittently along the southern flank of the Qinling complex. In view of the diversity and complication of ophiolites and associated tectonic settings in continental orogens and the uncertainty of some geological and geochemical methods and criteria, a careful assessment has been carried out on these rocks from the viewpoint of the broad meaning of ophiolite as an assemblage of mafic–ultramafic rocks in continental orogens, and on the basis of their own particular characteristics and multi-disciplinary studies including field investigation, structural analysis, petrological and geochemical studies as well as comparison with typical ophiolites in the world, suggesting that the Danfeng ophiolites largely fall into the arc-marginal sea type (Miyashiro 1973, 1975, Coleman 1977, 1984, Moores 1982, Tang and Lu 1986). Their dominant characteristics are as follows:

(1) they are composed dominantly of massive basalts, pillowed tholeiites and layered gabbroic complexes, with intercalations of sheeted diabase dykes and minor ultramafic rocks as well as abundant fore-arc flysch-type turbidites but lacking any real oceanic sediments having essential characteristics of typical ophiolites. Consisting of blocks of different provenances in tectonic contact with one another, the assemblage is incompletely developed and shows no evident stratigraphic sequence. According to rock associations, it is suggested that they largely formed in arc-settings near the continental margin (Figs 6 and 7).

(2) Most of the various types of basic volcanic rock in the Danfeng ophiolites exhibit uniform characteristics in terms of their major and trace element contents and are characterized by the association of rocks of tholeiitic and calc-alkaline series, falling into the CA + TH type (Figs 8, 9 and 10). In terms of REE distributions, they mostly show enriched REE patterns, excluding a few exceptions that are marked by flat patterns (Fig. 11). Initial Sr^{87}/Sr^{86} ratios range from 0.703 to 0.708. These and other major geochemical characteristics are of the arc-marginal sea type, markedly different from those of ridge ophiolites. There is considerable variation both across and along the Danfeng ophiolite tract. Some basic volcanics occurring west of Shagou belong to the tholeiite and alkali basalt series and exhibit medium- to high-pressure metamorphism, whereas calc-alkaline rocks are more abundant in the vicinity of Baishipu. This suggests that the Shangdan zone comprises a complex tectonic assemblage of ophiolites of various types and origins formed in different tectonic settings.

(3) The ophiolite blocks of the Danfeng ophiolite assemblage are separated from one another by faults or ductile shear zones of various scales, forming a terrane of tectonically juxtaposed rock blocks, suggesting that they represent tectonically emplaced rock bodies of different provenances. In fact, they represent remnants of dominantly arc-type ophiolites emplaced during the

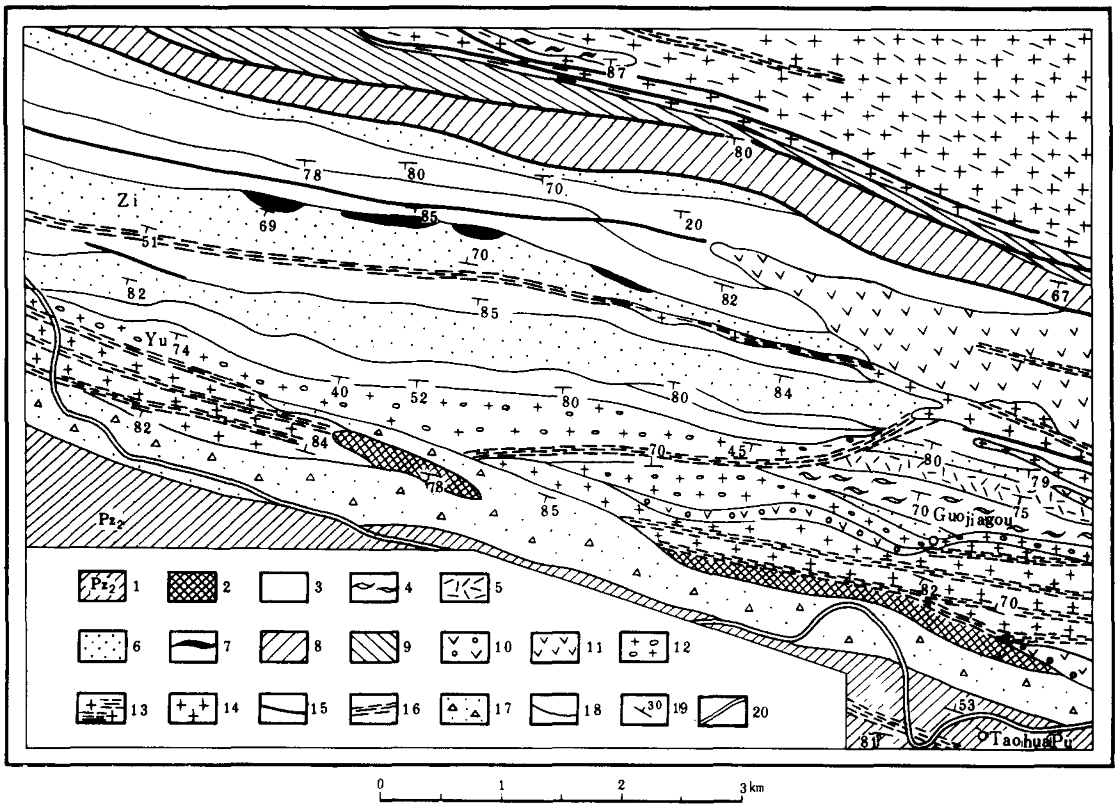

Fig. 6. Geological sketch-map of Danfeng ophiolite terrane of Taohuapu area in Qinling belt. 1. Devonian Liuling Group, 2–12, Danfeng ophiolites. 2. Garnet hornblende schist; 3. Massive mafic lava; 4. Pillowed lava; 5. Dyke swarm; 6. Mafic lava intercalated with slate and thin-bedded limestone; 7. Pyroxenite; 8. Turbidite; 9. Pelitic turbidite; 10. Gabbro complex; 11. Gabbro; 12. Quartzo-feldsparthic mylonite gneiss; 13. Mylonitized granite; 14. Granite; 15. Shear zone; 16. Brittle fault; 17. Fault; 18. Geological boundary; 19. Attitude; 20. Highway.

Yangtze–North China Plate subduction and collision orogenies with complete consumption of the intervening Qinling oceanic crust, which form the most significant signatures of the present suture zone in the Qinling orogenic belt.

(4) Isotopic dates from the volcanics of the Danfeng ophiolites as presented below fall into the Caledonian period, whereas its tectonic emplacement dates back to the Indosinian period.

(5) In the northern Qinling belt occurs another ophiolite zone roughly parallel to the Danfeng ophiolite zone, known as Yunjiashan–Erlangping ophiolite, which appears to represent the back-arc marginal sea type of ophiolite based on combined geological and geochemical data and correlation (Zhang 1986). This and the Danfeng ophiolites both belong to the southern continental margin of the North China craton and might have formed contemporaneously. However, a distinction

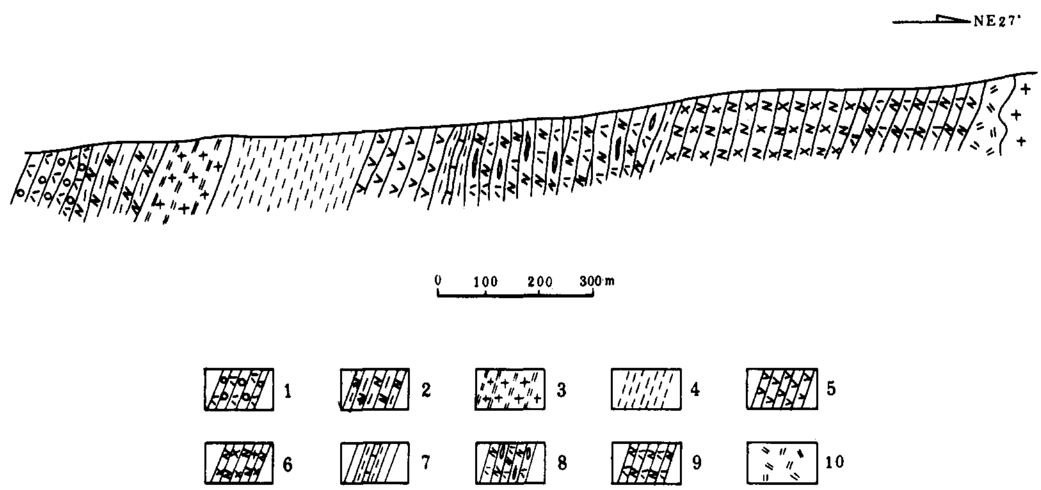

Fig. 7. Diagrammatic cross section of Danfeng ophiolite terrane through Guojiagou in Qinling belt. 1. Garnet hornblende schist; 2. Chlorite plagioclase amphibolite; 3. Mylonitized granite; 4. Mylonite; 5. Amphibolite; 6. Mafic dyke swarm; 7. Slate with thin beds of limestone; 8. Pillowed lava (amphibolite); 9. Massive lava (amphibolite); 10. Gabbro.

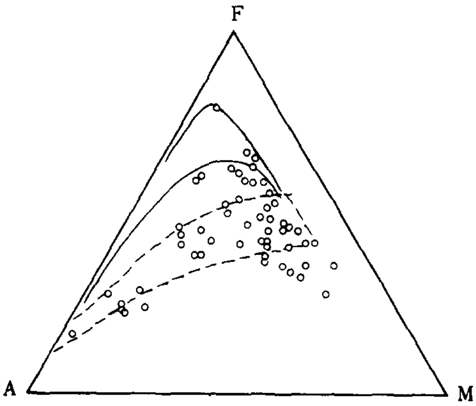

Fig. 8. AFM diagram for mafic rocks from Danfeng ophiolite.

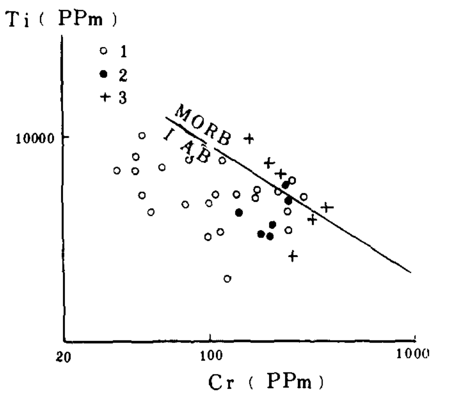

Fig. 9. Ti–Cr variation diagram for Danfeng ophiolites.

should be drawn between the two since they represent different ophiolite types corresponding to different tectonic settings.

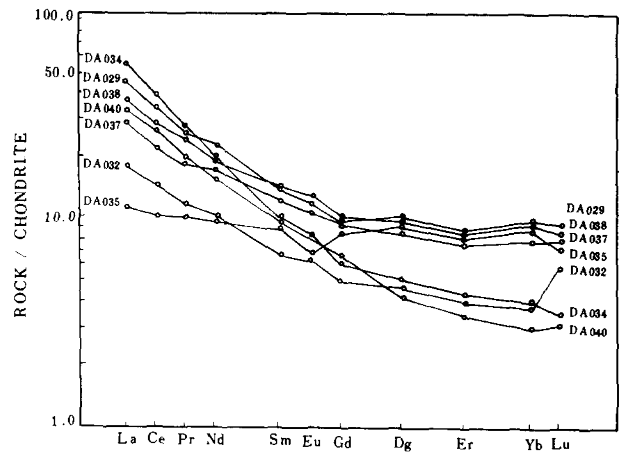

Fig. 11. REE patterns in mafic volcanics from Danfeng ophiolites.

Stacked obductional thrust slices of the fore-arc sedimentary prism

On the southern side of the Shangdan zone occurs a distinct narrow terrane which has always been assigned to the adjacent Liuling Group of Mid–Upper Devonian age to the south. However, its lithological association, parent rock formations, clastic source and deformational features suggest a clear distinction from the Liuling Group. Moreover, the boundary between the two is marked by a large shear zone with evidence of intense ductile shearing and crumpling. The sequence consists chiefly of three distinct lithologies: (1) graywackes interbedded with tuffs and, locally, with intermediate-acid volcanics; (2) tuffs and carbonite rocks with minor conglomerates; and (3) tuffs interbedded

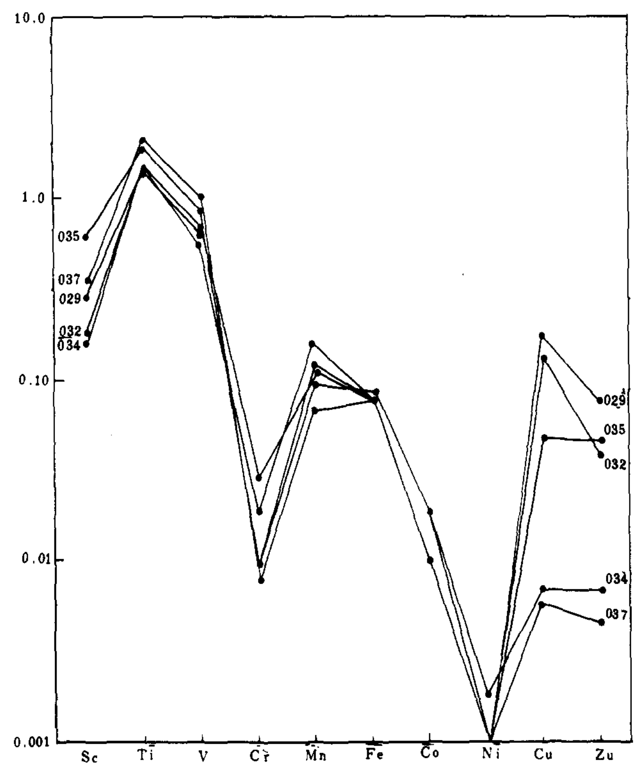

Fig. 10. Normalized trace element distribution patterns in mafic rocks from Danfeng ophiolites.

with acid, intermediate to basic volcanics and graywackes (Fig. 12); thus graywackes, tuffs and volcanics forming its distinctive parts. The sediment supply appears to have come from the southern margin of the North China Plate. It is another distinctive characteristic of these rocks that they exhibit strong deformation, notably characterized by a series of ductile shear zones of different scales separating several discrete rock slices which are overriding over one another towards the north, forming a tectonic assemblage of stacked obductional thrust slices. The composition and sediment source of this assemblage suggest that it might represent a sedimentary prism associated with the continental margin of the North China Plate. Therefore it should be distinguished as a separate, distinct unit from the Liuling Group. In contrast, the Liuling Group proper is underlain by the basement of the northern margin of the Yangtze Plate. It comprises a succession, of turbidites dominated by considerably mature quartz sandstones and pelitic rocks and interbedded with contourists as well as some shallow-water deposits in various local places. In general it forms a deep water facies associated with the shelf front and lacks characteristic lithic graywackes of active continental margins (Dickinson 1974, Heezen 1968). Presumably it represents the northern extreme part of the passive continental marginal sedimentary system of the Yangtze Plate. The sediment supply comes from sources to the west and south (Zhang *et al.* 1986). Deformation is relatively simple, characterized by a pattern of southward-directed composite folds and faults. In conclusion, the Liuling Group proper and the sedimentary prism recognized from it originally pertained to different plate margins but have been brought together during the Yangtze–North China Plate subduction and collision orogenies, the sedimentary prism is associated with the continental margin of the North China Plate, which has tectonically emplaced along the Shangdan zone of plate convergence by ductile deformation or thrusting, forming an assemblage of shallow-level obductional tectonic slices, which become the southern constituent part of the Shangdan zone.

Granitic rocks related to subduction and collision orogenies

Granitic rocks are widely exposed in the Shangdan zone. Their major characteristics are as follows:

(1) they occur as elongated, aligned linear masses extending along ductile shear zones or faults of the Shangdan zone.

(2) Individual intrusions are generally formed by a complex of various rock types such as granite, granodiorite and monzogranite, so that they represent composite, multiple intrusions, which sometimes contain many remnants of metamorphic rocks. Geochemical characteristics show marked variations among individual intrusions. In general, thay are characterized by fairly high Si and K contents and notably enriched trace elements, such as Rb and Ba, and contain abundant accessory minerals such as magnetite, zircon and sphene. Dissolution and metasomatic textures are commonly developed in these rocks. Examples of such intrusions are the Kuanping and Tieyupu grano-complex, Danfeng (Fig. 5), the Shahe intrusion, Shangxian, and the Baliping intrusion, Shagou.

(3) Apart from the occurrence in these intrusions of structures formed by plastic flow or brittle fracturing during their emplacement, a more conspicuous feature that characterizes them is that they exhibit strong mylonitization, forming various types of mylonite, some intrusions even forming tectonic blocks themselves.

(4) Automorphic zircons from a granitic mylonite yield a U–Pb date of 211 ± 8 Ma (in cooperation with A. Kröner), also obtained are other dates such as 189 Ma and 231 Ma (Pb) (Yan 1985). The majority of these dates fall into the span of the Indosinian period. Based on their pattern of occurrence, structural relationships and igneous rock association, most of these intrusions are interpreted as S-type granitic rocks formed and tectonically emplaced along the Shangdan suture zone during the Indosinian collision orogeny, thus forming one of the most important signatures of the Shangdan suture zone in the Qinling orogenic belt.

AGE AND EVOLUTION OF THE SHANGDAN ZONE

As a geologically most significant dividing boundary in the Qinling belt, the Shangdan zone must have initiated in the earliest stage in the development of the Qinling belt. When and how the Qinling orogenic belt initiated and in what tectonic regimes it evolved in its early stages of development are questions of current controversy and inquiry. Our studies suggest that the Qinling orogenic belt represents a composite continental orogen that has evolved in different tectonic regimes during different stages in its development. Its initial stages of development are characterized by initiation and evolution of a Proterozoic rift system on the basis of an early Precambrian pre-existing sialic crust and subsequent ensialic orogeny. Towards the end of the late Protrozoic the continent broke up and an ancient Qinling ocean of limited areal extent came into existence. The Qinling, then entered on a distinctive tectonic evolution, characterized by dominantly modern-style plate tectonics. Beginning in the Upper Proterozoic, a depositional system in an integrated tectonic and paleogeographic arrangement on a northern passive margin of the Yangtze Plate persists in the southern Qinling throughout the Palaeozoic until the Lower Mesozoic. Meanwhile, the northern Qinling begins to acquire the characteristics of an active margin along the southern coast of the northern China continent by the Caledonian stage. Existing geological and geochemical data combined with isotopic dates and some scanty paleomagnetic data (Lin 1985) suggest that terminal collision of the two continents occurs dominantly in the Indo-China period followed by intense Mesozoic–Cenozoic

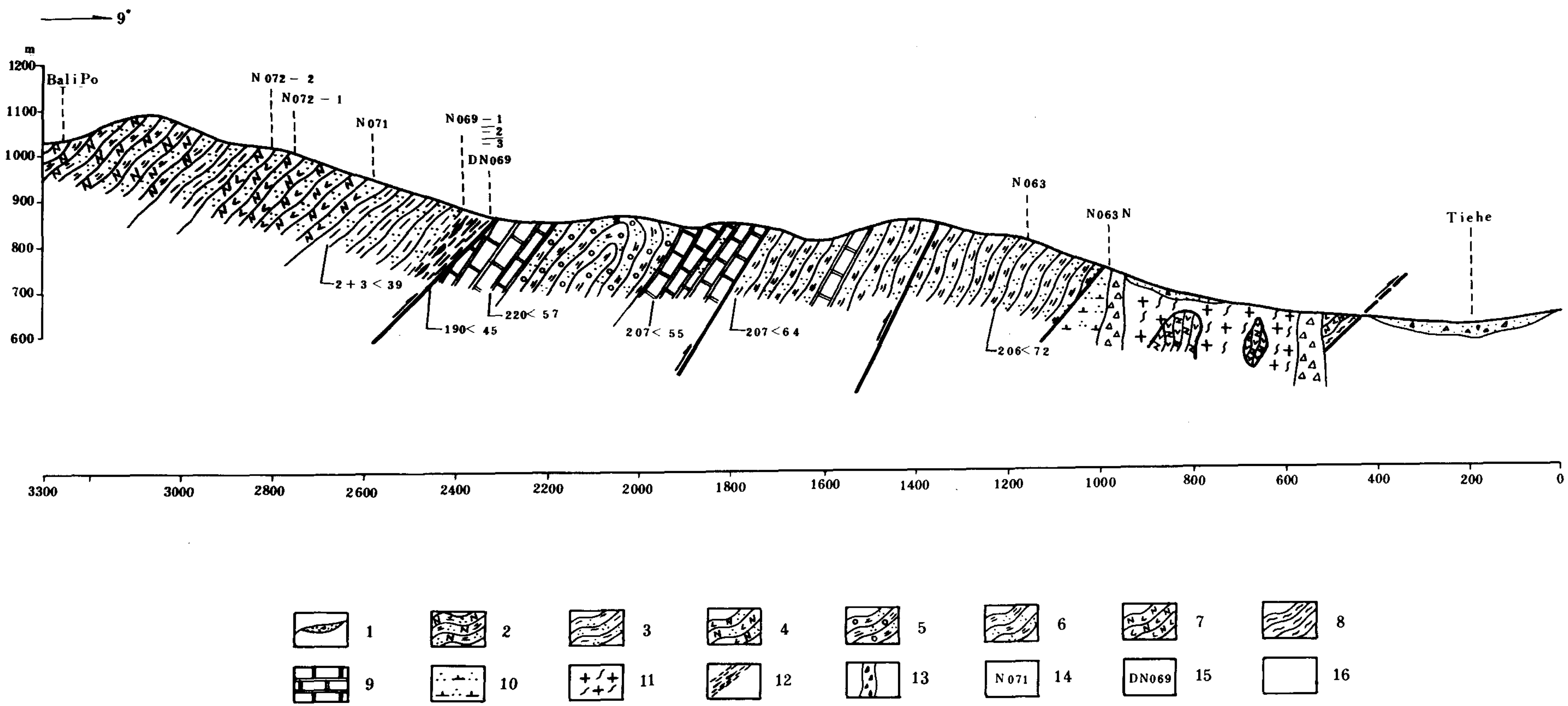

Fig. 12. Diagrammatic cross section of sedimentary prism of Shangdan zone in Danfeng area in Qinling belt. 1. Quaternary; 2. Sericite feldspar quartz schist; 3. Mica quartz schist; 4. Garnet-bearing sericite quartz schist; 6. Sericite quartz schist; 7. Amphibolite; 8. Chlorite schist; 9. Marble; 10. Quartz diorite; 11. Schistose granite; 12. Mylonite; 13. Cataclastic rock; 14. Number of sample; 15. Oriented specimen.

intra-plate deformation. During this prolonged geological evolution of the Qinling orogenic belt, the Shangdan zone has always been an important geological boundary and has undergone a complex tectonic history involving multiple deformations. Based on geological and geochemical characteristics and relationships of the above-mentioned five major constituent parts of the Shangan zone in conjunction with isotopic studies, regional geology and existing geophysical data on the Qinling crustal structure, the Shangdan boundary fault terrane appears to have undergone three major stages of development as follows:

Early Palaeozoic plate subduction

A Sm–Nd date of 402 ± 17.4 Ma is obtained from a norite gabbro in the Danfeng ophiolites while the tholeiitic rocks yield a Rb–Sr whole-rock isochron of 447 ± 41.5 Ma. These appear to reflect the formation date of the ophiolites. At the same time, in an arc system underlain by early Precambrian basement rocks of the Qinling complex on the northern side of the Shangdan zone occur abundant Caledonian calc-alkaline granitic rocks which yield dates of 382 Ma (Rb–Sr) and 340–420 Ma (K–Ar) (Yan 1985). Both of these indicate the coexistence of an early Palaeozoic Qinling ocean and a continental margin on the southern side of the North China Plate and also suggest initiation of an active margin on this preexisting foundation as a result of its development. By this time the Shangdan zone had become a subduction zone along which the Yangtze Plate was subducted and the oceanic crust consumed beneath the North China Plate. However, neither distinct ridge ophiolite complex nor accretionary prism containing typical deep-sea sediments have ever been found, suggesting complete consumption of the oceanic crust of limited size with only some products that are closely related to subduction preserved. It is these assemblages that record Caledonian subduction of the Yangtze Plate underneath the North China Plate (Figs. 13 and 14).

Indo-China collisional orogeny

The subduction that commenced in early Palaeozoic times has continued into the Indosinian period, which is characterized by dominantly continent–continent collision orogeny of the Yangtze and North China Plates. As the major collisional boundary, the Shangdan zone forms a large scale distinctive ductile shear zone consisting of large thrust sheets and nappes. The matrix of a mylonite from this zone yields a Rb–Sr whole-rock isochron date of 219 Ma, which falls right into the Indosinian period. The Danfeng ophiolites in the Shangdan zone formed in early Palaeozoic time, as previously discussed, yet the time of their tectonic emplacement in the Shangdan zone is signalled by the formation of shear zones. Likewise, emplacement of voluminous collision-related granitic rocks in the Shangdan zone occurs chiefly during the Indosinian period, as is evidence by a U–Pb zircon date of 211 ± 8 Ma (Fig. 14) obtained from these rocks. In addition, the assemblage of stacked obducted rock slices of the sedimentary prism formed by tectonic emplacement in the Shangdan zone during this period. All this indicates that the Shangdan boundary fault terrane,

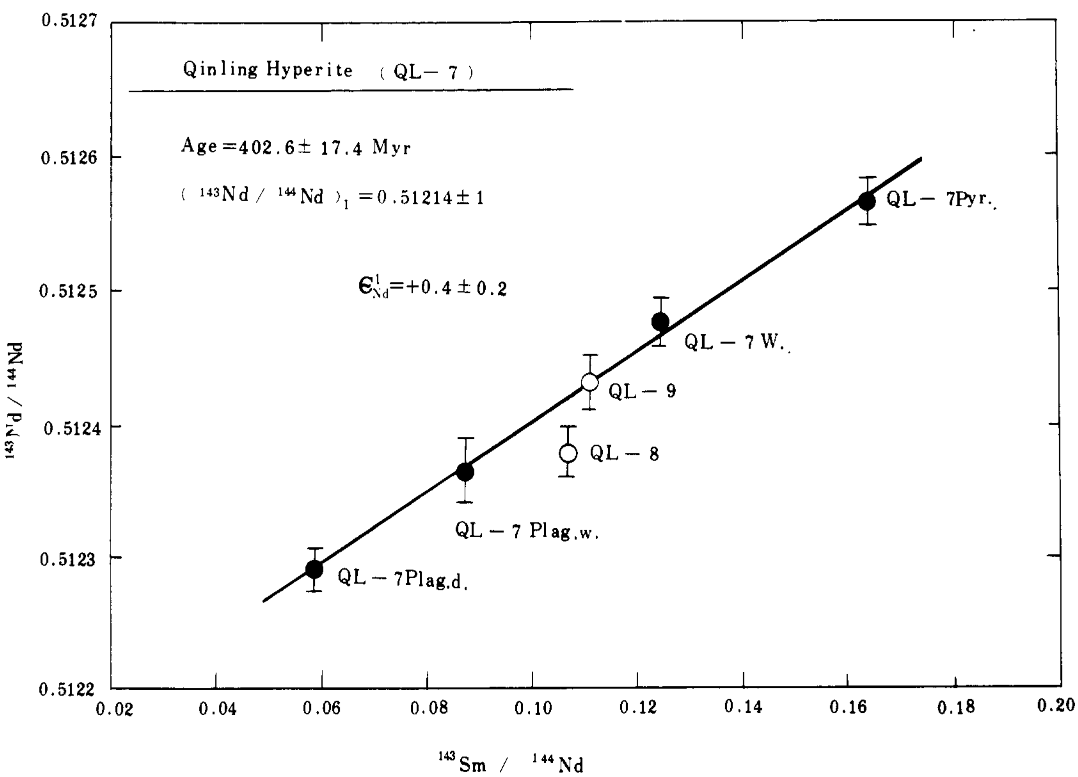

Fig. 13. Whole rock Sm-Nd isochron for norite gabbro from Danfeng ophiolite, Lajimiao, Shangxian.

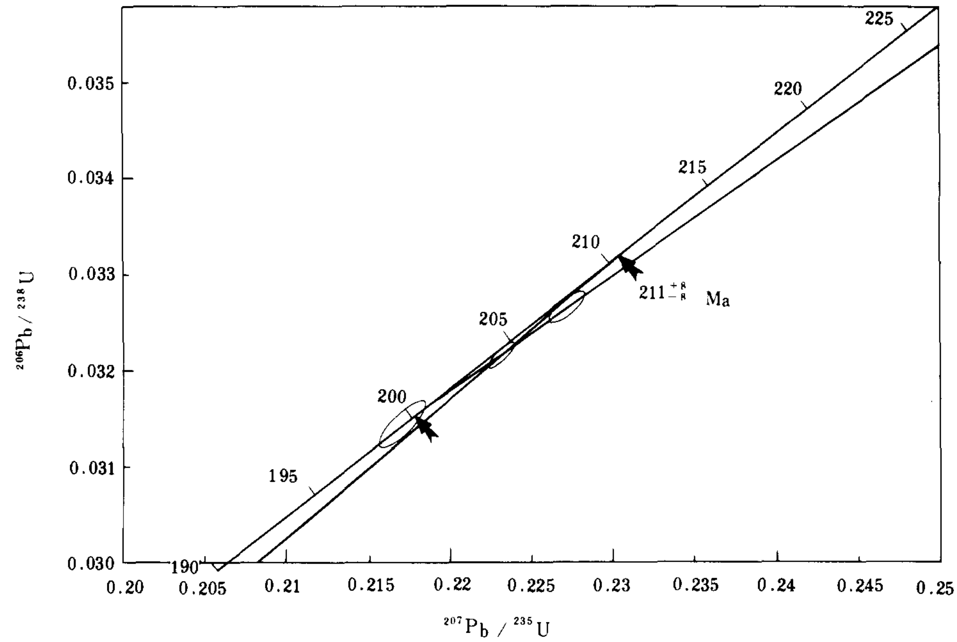

Fig. 14. U–Pb concordia relationship of zircon from mylonized granite in ductile shear zone of Shangdan zone.

as the major plate suture zone in the Qinling continental orogenic belt, has by now reached its terminal episode and climax of development. The Danfeng ophiolites are chiefly of the arc type, tectonically mixed with some other types of ophiolite block but with no ridge-derived ophiolite, suggesting complete consumption of the typical Qinling oceanic crust, leaving no off-scraped materials and at the same time indicating a complex evolution. The ophiolites are formed by arc- or continental margin-related ultramafic and mafic magmas which appear to have been produced dominantly during the course of the plate subduction by hot melts rising from the descending oceanic slab at depths to the base of the overriding plate and partially melting the lithospheric mantle, which are emplaced onto the arc of the continental margin forming the original ophiolites. During the collision orogeny, these became rearranged and mixed together in various tectonic styles in response to large-scale crustal shortening, eventually forming the present Danfeng ophiolite zone. The sedimentary prism in the Shangdan zone appears to have originally formed at the time of subduction in a fore-arc basin that occurred approximately at the same time as, or shortly later than, the Danfeng ophiolites, which it probably partially covered. During the subsequent subduction and collision and later thrusting, it was emplaced by obduction and overthrusting of a series of tectonic slices onto the arc area, eventually juxtaposed into place against the Danfeng ophiolite zone on the northern side. With regard to the granitic rocks, they are thought to have been produced and emplaced at crustal depths by melting of continental crust in the tectono-thermal dynamical regime during the subduction and collision orogenies of the two plates. To conclude, as the collision orogeny terminates towards the end of the Indosinian period, the development of the Shangdan zone with its dominant constituent parts and assemblages tectonically juxtaposed in their present arrangement may have been virtually completed, resulting in the eventual formation of the major zone of convergence and suturing of the Yangtze and North China Plates (Fig. 15).

Mesozoic–Cenozoic intra-plate deformation

Extensive Yanshanian igneous activity and associated mineralization are observed in the Shangdan zone and over a vast region north of it, including the northern Qinling mountains and even the marginal area of the

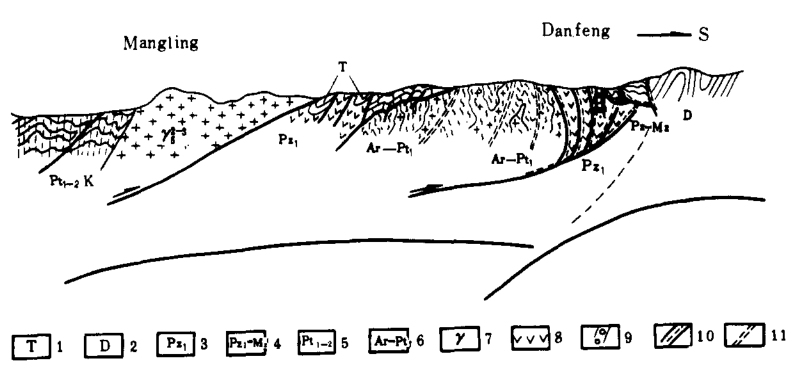

Fig. 15. Schematic cross-section of Shangdan zone.

North China craton (200–0.5 Ma, U–Pb, Rb–Sr, Sm–Nd and K–Ar). Another feature of the late history of the Shangdan zone is the occurrence of brittle–ductile shear zones and incessant strike–slip shearing and brittle faulting which controls the development of the Cretaceous–Tertiary basins and offsets the red beds deposited in them. All this suggests that the Qinling orogenic belt is still characterized by tectonic instability after its incorporation into a unified China Plate during the Indosinian collisional orogeny, as is reflected by continued northward subduction at deep depths and large scale shortening in the upper crust as well as tectonic activity in response to the subduction and collision of the Indian Plate with the Eurasia Plate and the subduction of the Pacific Plate beneath the China Plate. Under these combined regional tectonic conditions, intense intra-plate deformation occurs in the Qinling mountains during the Mesozoic–Cenozoic Yanshan and Himalayan periods, resulting in an intraplate orogeny which involves subduction and interthrusting and stacking of continental crust accompanied by large scale magma production along the major detachment surface at deep–moderate crustal depths and emplacement of plutonic rocks and associated mineral migration and ore concentration, as well as strike–slip and block faulting in response to isostatic adjustments caused by regional tectonic stresses. This orogeny in the Qinling belt is of no less importance than the subductional and collisional orogenies and has contributed to eventual formation of the present grand and majestic Qinling mountains. During this intracontinental orogeny the Shangdan zone has always been the center of tectonic activity, marked by renewed thrusting, strike–slip and block faulting, truncating as well as following the pre-existing structures, leading to superimposition of intra-plate deformation on the plate suture zone and eventually forming the overall structural features of the present Shangdan zone.

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