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The Ophiolitic Mélange, a World-wide Problem on Tethyan Examples

By AUGUSTO GANSSER[1])

ABSTRACT

The ophiolitic mélange is defined as a olistostromal and tectonic mixture of ophiolitic material and sediments of oceanic origin with exotic blocks, reflecting areas which have subsequently disappeared. Being intimately related to ophiolitic belts they indicate important suturelines connected to plate boundaries. Ophiolitic mélanges occur mostly where continental type plates are subducted with obduction of oceanic material. These facts are discussed on examples from the Middle East and the Himalayas, where the mélanges are particularly well exposed.

1. General aspect

81 years ago, a famous trio of geologists, C. L. Griesbach, D. Diener and C. S. Middlemiss, sponsored by the Geological Survey of India, visited the Kiogar area at the border between Kumaon and Tibet in the Central Himalaya. In this fascinating, remote and barren area, lying between 5000 and 6000 m above sea level, they were puzzled by a most unexpected geology. Above competent folds in the well known Spiti sequence they observed a wild jumble of flysch-type sediments, together with foreign looking blocks from a few meters to several thousand meters in size, intricately mixed with basic and ultrabasic rocks. After a preliminary investigation of this area and a vivid discussion with his colleagues, well known for their great Himalayan experience, Diener came to the following conclusion (DIENER 1895, p. 604):

«Fünf Momente sind für die Klippen von Chitichun und am Balchdhura bezeichnend: 1. Die von der Hauptregion des Himalaya abweichende Schichtfolge; 2. die bogenförmige, diagonal auf das Streichen der Himalaya-Falten verlaufende Streichrichtung; 3. ihr Auftreten innerhalb eines muldenförmigen, mit Flysch und Spiti Shales erfüllten Gebietes; 4. ihre innige Verbindung mit Eruptivgesteinen; 5. das Fehlen jedweder Art von Strandbildungen in ihrer Umgebung.»

He could not agree to a direct comparison with the Klippen of the Swiss Alps and Carpatians, but accepted in principle Bertrand's and Schardt's ideas as «lambeaux de recouvrement». His main difficulty was the interpretation of the presence of large

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amount of basic rocks. Based on the available information he could not solve the problem as he stated at the end of his work (p. 606):

«Eine Lösung des tektonischen Problems der Klippen von Chitichun geben zu wollen, halte ich in Anbetracht der ungenügenden Kenntniss, die wir heute noch von der Ausdehnung jenes Phänomens besitzen, und bei dem Mangel einigermassen brauchbarer Nachrichten über den geologischen Bau der angrenzenden Theile von Tibet für verfrüht. Es mag genügen, hier auf jene Eigenthümlichkeiten hingewiesen zu haben, welche die tibetanische Klippenregion von allen bisher in Europa bekannten Klippenzügen unterscheiden und dieselbe zu einem der interessantesten und merkwürdigsten Theile des Himalaya stempeln, der wie kaum ein anderer noch auf lange Zeit hinaus ein dankbares Feld für weitere Forschungen abgeben wird.»

Though this discovery was of outstanding interest, eight years elapsed before new action had been taken in connection with this fascinating problem. Inspite of the scepticism of Dr. William King, then Director of the Geological Survey of India, A. von Krafft was ordered by the Survey to investigate this remote area during the summer season of 1900. During six weeks of intensive field work in the wider Kiogar area von Krafft gathered a wealth of most valuable information including rare fossil collections from various blocks, which, after a careful investigation by Diener, supported the foreign aspect of these faunas, unknown in this part of the Himalaya. Excellent panoramic sketches and photographs clearly outlined the contrast between lower and upper structural levels.

While DIENER (1895) compared the exotic Kiogar blocks to the Klippen of the Alps and the Carpathians, which at the time were newly discovered and thus of great general interest, VON KRAFFT (1902) saw no connection with Klippen and proposed as primary origin hughe volcanic explosions in Tibet through which the sediments were mixed with the basic volcanics. He admitted, however, that these arguments were not fully convincing on the still scanty available facts. His stimulating discussions of pro and contra of his ideas bring out many of the problems which crop up during the present discussions of mélange rocks. On page 169 he wrote:

"Those which assume structural causes would imply that the exotic blocks were brought into existence by the disturbances which lead to the upheaval of the Himalayas. This, however, is not the case. We have seen that the volcanics, which include the blocks, were folded together with the flysch. From this we can only conclude that the volcanics and consequently also the exotic blocks were preexistent to those disturbances, and any causal connection between the latter and the blocks is therefore impossible.

Nor is it at all conceivable that folding or faulting should have brought about those features, which were described in the above chapters. None of the theories alluded to would explain the presence of the volcanics and their intimate connection with the exotic blocks."

It is most unfortunate to science that von Krafft was not able to continue his fascinating studies. He died 1901 in Calcutta. Though von Krafft has not coined the word "mélange", his careful descriptions and discussions of a possible origin of the exotic rocks put him among the very first pioneers who stressed the importance of the mélange problem.

The first to mention ophiolitic rocks in southern Tibet north of the Kiogar region discussed above was Captain STRACHEY in 1851 (p. 308):

"A great outburst, in which are found hypersthene and bronzite, besides syenitic and ordinary greenstones, and various varieties of porphyry, occurs in the vicinity of the lakes which are found at the eastern extremity of the plateau. The greenstone is known to extend considerably to the west, and forms, at an elevation of about 17,600 feet, the summit of Balch, one of the Himalayan Passes into Tibet which I have crossed."

He stressed the structural difference between the granites of the Transhimalaya and the ophiolitic rocks (p. 309):

"The Granites appear to constitute lines of elevation, not of rupture; but there seems to be no specific action produced by them on the dip of the strata, which they appear to leave generally unchanged.

The Greenstones, on the other hand, usually follow lines of dislocation of the strata; being sometimes apparently contemporaneous, and at others intruded through rocks already consolidated."

SUESS, in his famous *Das Antlitz der Erde* (1901, p. 352 ff.), recognized the importance of the extraordinary findings of the Himalayan geologists and devoted some chapters to this problem. He realized the significance of thrust movements and of Eocene volcanics along the Indus:

«Vielleicht war hier im Eocän eine mit Vulcanen besetzte Disjunctiv-Linie vorhanden» (1901, p. 351).

He connected this line with the exotic area of Kiogar, and he stated (1909, p. 648):

«Diese Erfahrungen lehren, dass die Verfrachtung der tibetanischen Schollen und das Hervortreten der simischen Gesteine zur gleichen Zeit eingetreten sind»

and on the same page:

«Balchadura [the Kiogar area] stellt den Rand einer Bewegungsfläche erster Ordnung dar, an welcher sedimentäre Serien von abweichender Facies sich überlagern.»

It is significant, that this particular zone was later recognized as one of the most important subduction zones of modern geology.

The term "mélange" (autoclastic mélange) was introduced by GREENLY in 1919 when he described a complicated tectonic mixture in the Precambrian Mona complex of Anglesey island in Wales. From his careful descriptions it is evident that his autoclastic mélange has strictly tectonic implications with no relations to ophiolitic type rocks. The tectonic aspect of a mélange is still widely propagated (HSÜ 1968), but, as we will see, the question is much more complex and still most problematic.

The "mélange" has been revived in the Middle East, where excellent outcrops of this widespread phenomenon had eventually called the geologist's attention. BLUMENTHAL, when mapping in Central Anatolia, described a "Mésozoïque à facies tectonique brouillé" (1948). This same facies was mentioned by BAILEY & MCCALLIEN as Ankara Mélange (1950, 1953). They used the term mélange "out of respect for descriptions that Greenly and Matley have furnished of a similar tectonic mélange in Anglesey...". The detailed account of BAILEY & MCCALLIEN stressed the relation of exotic blocks to basic and ultrabasic rocks. They recognized Steinmann's "Trinity" after having discovered pillow lavas and stressed the world-wide occurrence of ophiolitic rocks, failed, however, to include the mélange formation into this general picture. Although not mentioning mélange in particular, KÜNDIG (1959) gave the following characteristics of these ophiolite occurrences (p. 469):

a) The great variety and mixture of hypabyssal, plutonic and volcanic rocks.
b) The occasional association – unexplained so far – of metamorphic (Glaucophane rocks) and non-metamorphic rocks.

c) An extremely complex, often chaotic imbricated structure frequently accompanied by overthrust sheets and nappes.
d) The apparent scarcity or absence of magmatic channels and feeders to supply the effusions and intrusions.
e) The scarcity or absence of thermal contacts with the embedding sediments; most contacts are apparently tectonic.
f) The difficulty of an age determination of the *mise en place* of the igneous rocks, owing to the chaotic relation with, and scarcity of fossils in, the accompanying sediments.

While discussing the ophiolites of Celebes the same author located ophiolites as follows (KÜNDIG 1956 *b*, p. 229):

"The consequence is that, with the appearance of ophiolites in an orogenic belt, i.e. with the transition from the shelf- or mio-geosynclinal- into the eu-geosynclinal zone, facies and thickness of sediments change abruptly.

As the transition zone coincides with the old trench-slope, which developed in a subsequent diastrophic phase into a thrust-line of the first order, it frequently occurs that the trough-contents, namely the eu-geosynclinal facies, with its masses of ophiolites, are thrust over the facies of the shelf edge. Such cases are known from Turkey, Kurdistan, Oman and in East-Celebes.

The trench-slope is, particularly during the ophiolitic extrusions at depth, an area of catastrophic events. It is not only the site of turbidity currents, but during the buckling down, vast tracts of the shelf edge mantle may glide down and accumulate as huge exotic masses (e.g. Mélange of BAILEY 1953) in a foreign environment."

When substituting miogeosyncline and eugeosyncline by continental and oceanic plates respectively, KÜNDIG'S statements fit modern ophiolitic concepts remarkably well.

That the world-wide occurrence of the mélange rocks together with ophiolites is not sufficiently recognized is underlined by the fact that the recent Penrose Conference, dealing with ophiolites, did not include mélange in its terminology (anon. 1972). This unfortunate situation calls for reaction, and it is the purpose of this article to stress the world-wide importance of the mélange formations and their intimate relation to the ophiolite suite and thus their direct involvement in modern geotectonic theories. It is for this reason that the name *ophiolitic mélange* is proposed in order to distinguish it from purely sedimentary mélange of the olistostrome type or purely tectonic mélange in the original meaning of GREENLY.

My personal interest in the "mélange" arose in 1936 when I visited the Central Himalayan border regions, already described by VON KRAFFT, and followed these enigmatic outcrops into the "root zone" of the Himalaya in southern Tibet. They were described as an "Exotic Bloc zone" (HEIM & GANSSER 1939) and later, based on the excellent occurrences of the Middle East, as "Colored Mélange" (GANSSER 1955).

In order to stress the global importance of ophiolites with their related mélanges, the Commission of Structural Geology of the International Union of Geological Sciences chose this subject as its main working theme. During a special Ophiolite Symposium, held in USSR in 1973 and sponsored by the Academy of Science of the USSR as well as the Commission on Structural Geology, the mélange problem was the main topic and could be discussed on the basis of excellent outcrops in the western Tien-Shan and Kyzyl-Kum area (Paleozoic ophiolites) as well as in the little Caucasus (Mesozoic ophiolites). In both areas the relation of ophiolitic mélange to major tectonics is well exposed, and this topic received an excellent review in a recent

Russian publication by the members of the Academy of Sciences of the USSR, Moscow (1973), entitled *Developmental stages of folded belts and the problem of ophiolites* (see also Geological Newsletter 1973, Vol. 3, p. 211). Their acceptance of major thrusting in relation to mélange formations as a world-wide occurrence is new and most stimulating.

2. Definition of ophiolitic mélange

From the great amount of data published recently on ophiolites and their relations to global tectonics, the importance of the ophiolitic mélange is increasingly evident, and also the confusion regarding its definition. Hsü (1968) discussed the rock unit "mélange" in great detail and has the merit of stressing the structural importance of this complex formation. The recognition of the mélange as a mappable unit has helped to clear up many a confused situation, where before much care was taken to unravel a hopeless tectonic picture by carefully mapping single exotic blocks.

Hsü's definition does not, however, stress the intimate relation to ophiolitic belts. The mélange, as originally defined by Greenly (1919), could be a tectonic feature only or also a purely sedimentary olistostrome complex. I would like to use the term *ophiolitic mélange* as the more widespread occurrence without, however, substituting the general term mélange by ophiolitic mélange. For this term I offer the following definition, which is based on many occurrences known to me personally or described in the literature. This definition is open to discussion, and I would welcome constructive criticism:

Factual and genetic characteristics of an ophiolitic mélange:

1. We recognize a mixture of rocks of the ophiolitic suite together with non-ophiolitic rocks often of unknown origin (exotic blocks).
2. The matrix of the mélange could be ophiolitic (frequently tectonically sheared serpentines) or sedimentary, the latter mostly of a flyschoid facies.
3. No contact metamorphism exists between components of a mélange, but metasomatic reactions can be locally important.
4. The base of a mélange is always a tectonic contact; the top is often marked by transgression of pelagic calcareous or flyschoid sediments.
5. The ophiolitic mélange results from a sedimentary (olistostromal) *and* tectonic mixture. (I would like to stress that such a mélange cannot have only a tectonic origin. This could not explain the intimate mixture of exotic blocks of very varied composition. See also Graciansky, in press.)
6. During emplacement recycling occurs, including olistostromal slumping, tectonization and further incorporation of oceanic crust. A part of the mixing is related to this episode.
7. The ophiolitic mélange is restricted to ophiolitic belts and outlines zones of major structural significance (plate boundaries).
8. The final emplacement of a mélange body can be by diapiric protrusion and then the original connections to members of the ophiolitic suite become completely disrupted.

9. It thus can occur also when the classical ophiolitic suite is incomplete or totally missing and may outline geotectonic belts in the same way as an ophiolite zone would do.
10. In zones with strong allochthonous character the mélange horizon is often overthrust by ultrabasic sheets (Himalaya, Oman, Zagros, Taurus, Papua ?).
11. The ophiolitic mélange must be distinguished from normal olistostromes (ELTER & TREVISAN 1973), the latter being interbedded into a normal sedimentary sequence. These differences are for instant clearly expressed in southeastern Turkey (Fig. 3), though in strongly tectonized regions this distinction is admittedly difficult.

The broad characteristics and the regional setting of some ophiolitic mélange formations from Asian examples are discussed in the following:

3. General discussion of ophiolitic mélange formations

a) The Oman mélanges

The ophiolitic belt of Oman forms the eastern border of the Arabian shield. From here, mélange formations have been known for over 45 years through the excellent work of LEES (1928). His ideas about the allochthonous position of the Hawasina beds (mélange) and the separate ultrabasic nappe (Semails) have been confirmed by recent investigations (REINHARDT 1969, ALLEMANN & PETERS 1972, GLENNIE et al. 1973), while some authors follow a more autochthonous interpretation with uplifts and related gravity slides (MORTON 1959, TSCHOPP 1967, WILSON 1969). Based on these new though still incomplete investigations, we suggest an underthrusting (subduction) of the Arabian (African) plate, resulting in overthrusting (obduction) of the Oman oceanic slab on of the Arabian shield (Fig. 1). A parautochthonous sedimentary shield cover is "overthrust" by the Hawasina unit, a mélange nappe which was overridden by the relatively undisturbed Semail unit, where the classical oceanic sequences from ultrabasics to pillow lavas is locally preserved below the upper Maestrichtian transgression. The locally steeply dipping metamorphic slivers observed in northern Oman between Hawasina and Semail thrust sheets are difficult to place (ALLEMANN & PETERS 1972).

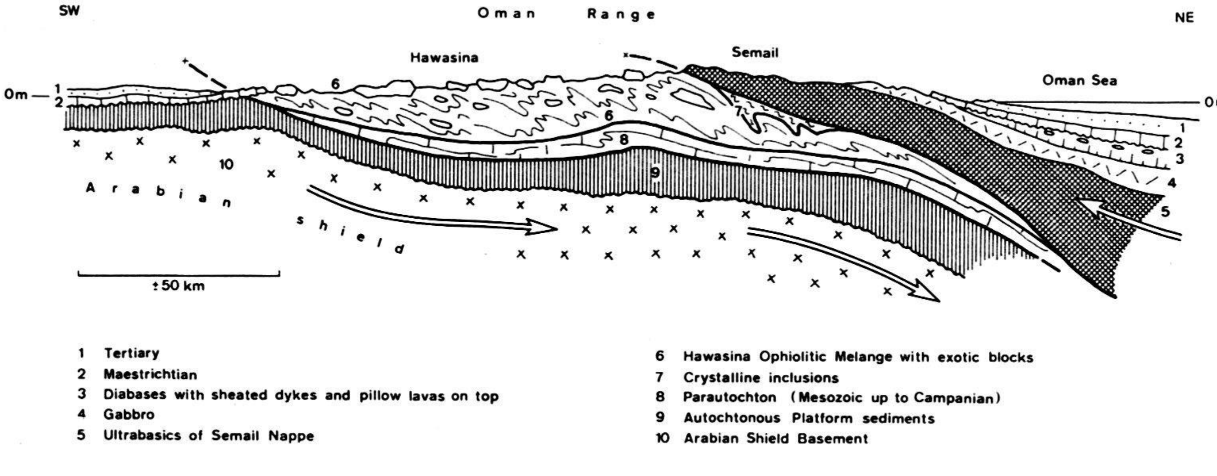


Fig. 1. Schematic section through Oman Mountains (compiled from various sources).

The youngest beds involved in the emplacement of the ophiolite nappes are Campanian to (?) lower Maestrichtian. In the Hawasina mélange matrix a planktonic Cenomanian to (?) lower Turonian fauna indicates the youngest age (ALLEMANN & PETERS 1972), while the exotics range from Ordovician to middle Cretaceous with a predominance of hughe Permian and Triassic blocks.

There is little doubt that the emplacement of the Oman ophiolitic nappes, including the mélange sheet, falls between lower Turonian and middle Maestrichtian times. Unlike other orogenic belts, the later movements in Oman were only of a small scale. Whereas the foreland features of Oman are relatively clear, the backland covered by the Oman sea is still highly enigmatic. An oceanic crust seems to be covered by a pile of 4000 m of mostly clastic sediments of Neogene age, the top of which lies over 3000 m below sea level (HINZ & CLOSS 1969). Similarly to the Beluchistan coast north of the Oman sea they mask the important pre-Maestrichtian structural history.

While Oman was little affected by post-Cretaceous movements, the history following the reactions of the northern Arabian (African) plate with its Eurasian counterpart is highly involed. This is witnessed by the mountain fronts bordering the shield from Turkey over Iran into Afghanistan–Pakistan, a zone exposing some of the world's most striking ophiolitic mélange occurrences (Fig. 2).

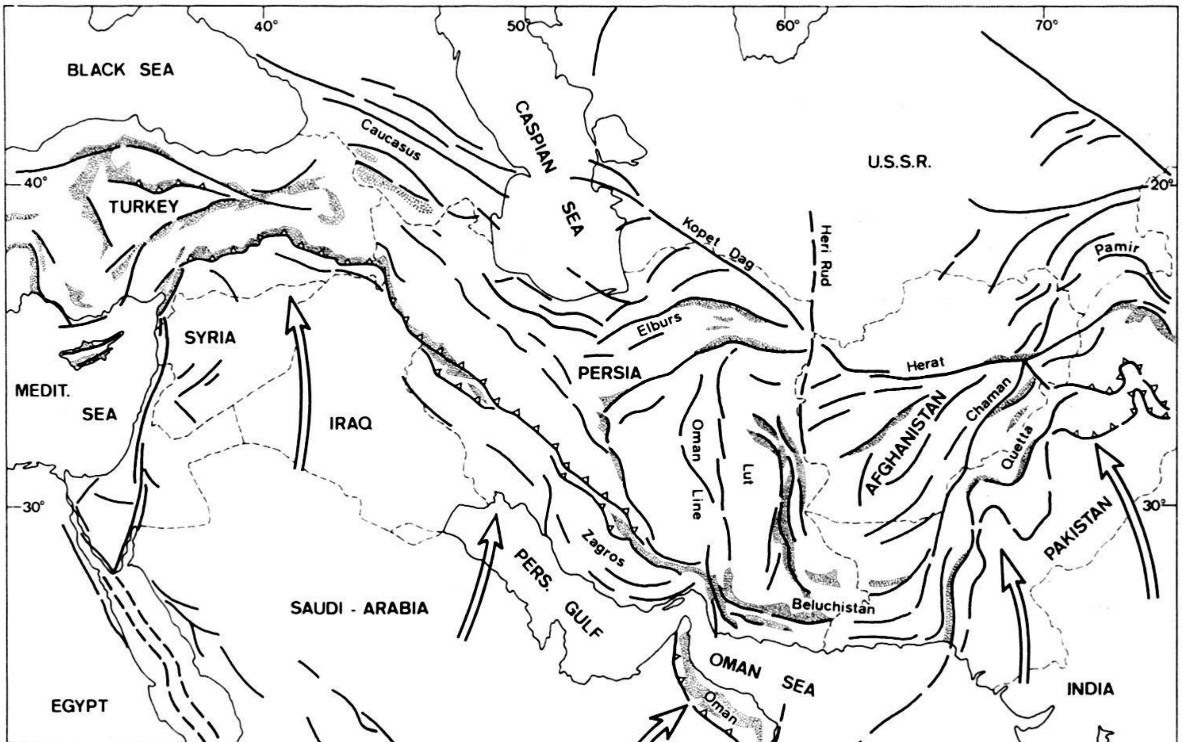


Fig. 2. The main structures of the Middle East.

b) The Anatolian mélanges including Cyprus

Turkey straddles the northern continuation of the western border of the Arabian shield, which contrasts strongly with Oman. This western edge coincides with the Levantine rift system, where Arabia has apparently moved in post-Cretaceous time relative to Africa over 150 km to the north (QUENNELL 1958, FREUND et al. 1968, 1970). Westwards from this structural north–south line conditions are strikingly different: The Mediterranean covers the actual African front and displays an oceanic ridge running in a west–east direction into Cyprus, which represents a part of this ridge rotated by 90°. The Kyrenia range in north Cyprus, with its large olistoliths, runs east–west and is thrust to the south forming a southernmost branch of the Taurids (DUCLOS 1964). This range occurs suspiciously near to our expanding oceanic ridge. Again quite unlike oceanic ridge conditions, south of the classical and well known Trodos mountains (MOORES & VINE 1971, VINE & MOORES 1972) and separated by them by a steep fault zone we find the Mammonia area (Paphos) with a classical ophiolitic mélange, which is transgressed by Maestrichtian marls. This area was studied in detail by LAPIERRE, who observed a pre-ophiolitic volcanism related to Triassic masses and separated this zone from the Trodos ophiolites (ROCCI & LAPIERRE 1969, LAPIERRE & PARROT 1972). Based on personal observations I prefer to regard the Trias with its volcanism as exotic blocks belonging to a Cretaceous Mammonia mélange. Only, and here comes the difficulty, a mélange should not border an oceanic ridge but should be expected at the consuming end of a plate. The last word on the eastern Mediterranean has certainly not yet been said (TURNER 1973).

To the east of the Levant lineament the active border of the northwestern Arabian shield is well exposed. In southeast Turkey, north of the Mardin area, the northwards drift of the shield produced an ophiolitic belt with classical mélange formations. The normal ophiolitic suite is here totally disrupted and mélanges predominate in the overthrust sheets, while erosion of the southwards advancing thrust produced olistostromal ophiolitic sedimentation over the stable plate. Here we observe the juxtaposition of mélange nappes in tectonic contact with secondary ophiolitic olistostromes (Fig. 3). In outcrops and particularly in well sections one sees the intercalation of ophiolitic material into turbidity sediments. These most interesting conditions, known already to KÜNDIG (1956), were described by RIGO DE RIGHI & CORTESINI (1964), without distinguishing ophiolitic nappes and ophiolitic olistostromes. The base of the mélange is again thrusted and the thrust plane has subsequently been folded. The mélange top is normally transgressed by Eocene, but in the higher ranges it was covered by the crystalline Bitlis thrust. A coherent ultrabasic thrust sheet is not developed and was probably sheared off by the higher crystalline thrust. Much of this material is now found in the olistostromes of the foreland (*Map Erzurum* with explanatory notes, 1963, Mad. Tetkik Arama Enst.).

This frontal ophiolite belt is not related to the famous "Ankara Mélange" of BAILEY & MCCALLIEN (1950, 1953). The latter occurs in a complicated, often steeply bordered, but mostly flat lying sheet and may have originated from the North-Anatolian fault zone. The presence of widespread and well exposed mélange zones along this important tectonic disturbance has been overlooked by most previous writers whose interest centered on the recent earthquake problems and possible strike slip movements. No convincing proof exists that along this line horizontal shifts of

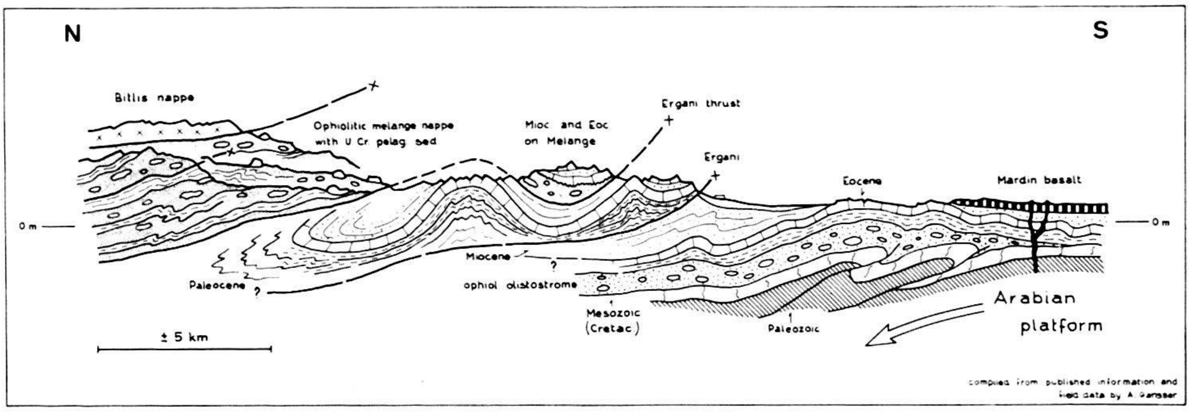


Fig. 3. Ophiolitic mélange nappe and ophiolitic olistostrome in southeast Turkey.

several 100 km accumulated (PAVONI 1961, AMBRASEYS & TCHALENKO 1969, NOWROOZI 1971, 1972). The presence of ophiolitic mélange suggests a rather large north–south compression which was active in pre-Eocene times along microcontinental margins, with obduction of ophiolitic material, of which the Ankara mélange may be a witness. In the more eastern sections of the North-Anatolian "fault zones" larger masses of serpentinized ultrabasics together with the mélange zones do occur (Fig. 4).

c) The Iranian and Afghan mélanges

They occur, similar to those of Anatolia, in two tectonically separate areas. While in Turkey the northern continuation of the western Arabian edge interferes as the Levant lineament, in Iran the eastern edge of the shield, the Oman range, interferes with its northern continuation, the still disputed *Oman line*. First propagated by FURON (1941) and later stressed by GANSSER (1955), estimates of its importance have fluctuated (STÖCKLIN 1968). Now, in connection with various plate boundaries, it has again aroused considerable interest (CRAWFORD 1972). This division is most striking if we compare the Zagros fold belt on the west of the Oman line to the Beluchistan ranges east of it. It is marked by a north–south striking fault zone or steep thrust zone with a considerable dextral displacement (GANSSER 1955; FALCON 1967, 1969; STÖCKLIN 1968).

The main north movement of the Arabian shield has been taken up by the *Zagros thrust* (TAKIN 1972). The underthrusting shield and a young (Pliocene) collision have obliterated a larger part of the previously present mélange rocks which were probably related to the subduction of Africa *and* Arabia previous to the opening of the Red sea (LAUGHTON 1966, 1970). At least two phases of post-Miocene movements can be recognized, one mainly thrusting and the other, still younger, with strike-slip elements (BRAUD & RICOU 1971) and vertical uplift.

Locally, ophiolitic mélange formations are still preserved along the western (Kermanshah region, see BRAUD 1970) and the eastern part of the Zagros thrust, the Neyriz area. In this latter area RICOU (1968, 1971) has revived the tectonic window hypothesis of GRAY (1949) by postulating 3 nappes which are piled on the Zagros foreland, all in front of the main Zagros thrust. He distinguishes above the upper Cretaceous foreland sediments a sedimentary nappe (Pichakun) ranging fromTrias to

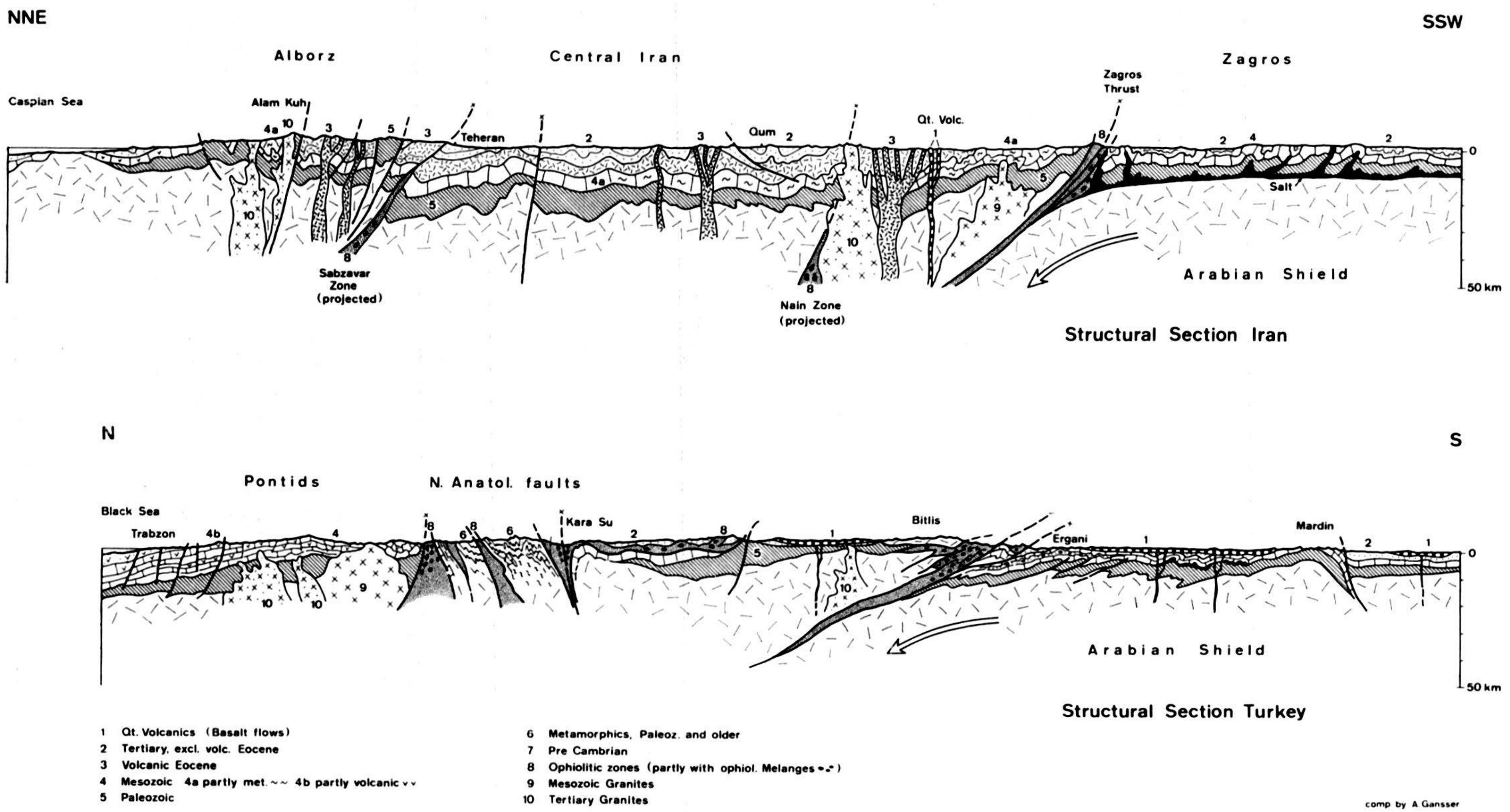


Fig. 4. Structural sections: Iran and Turkey.

middle Cretaceous, a mélange nappe with exotic blocks of metamorphic composition (marbles, amphibolites and biotite schists), Permian and Triassic limestones, radiolarites and Cretaceous pelagic limestones as well as basic lavas and serpentines, and on top a several km thick thrust-sheet of peridotites with gabbros. All nappes are transgressed by rudist limestones of Campano-Maestrichtian age, followed by Paleogene and Neogene sediments, themselves overridden by the young Zagros thrust (Fig. 5, Fig. 6). The various tectonic phases are well displayed. Here again, one may realize the effect of the Cretaceous drift of the African plus Arabian plate (pre-Maestrichtian Neyriz nappes) and the subsequent Arabian event in post-Miocene time (opening of the Red sea) which is responsible for the younger Zagros thrust. In spite of its pronounced structural complication, the Neyriz area displays a surprising similarity to Oman (a fact also stressed by RICOU 1971). Between the Cretaceous thrust sheets at Kermanshah and Neyriz, younger movements along the Central part of the Zagros thrust caused overriding of the older nappes. Similar conditions are known from the thrust-zone in Irak–Kurdistan between the Turkish and the Iranian ranges. Here amphibolite bodies together with serpentines suggest an incipient metamorphism, which also affected the upper Cretaceous flysch (GANSSER 1959). Mélange zones are not exposed and are again probably overridden or sheared off during the younger movements.

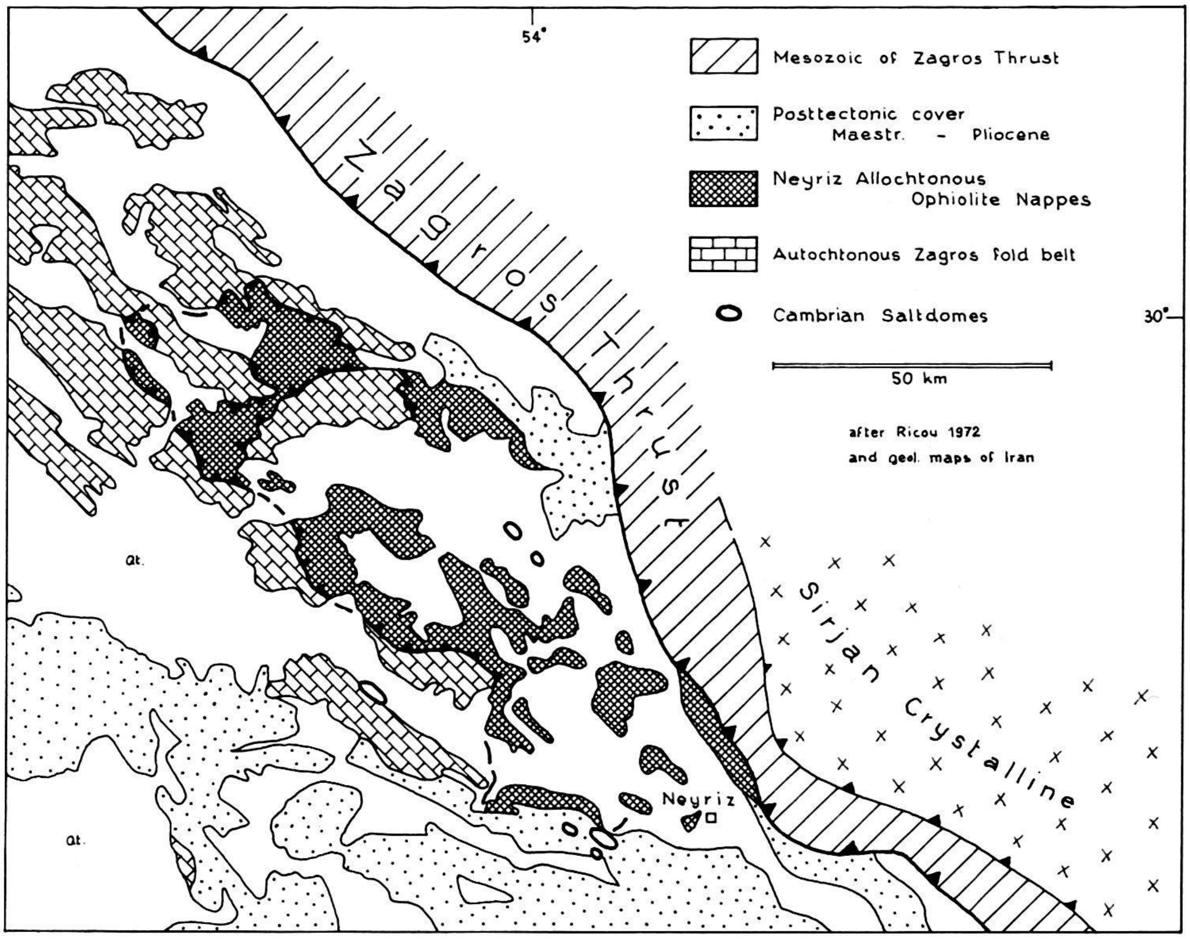


Fig. 5. Geological sketchmap of the Neyriz area.

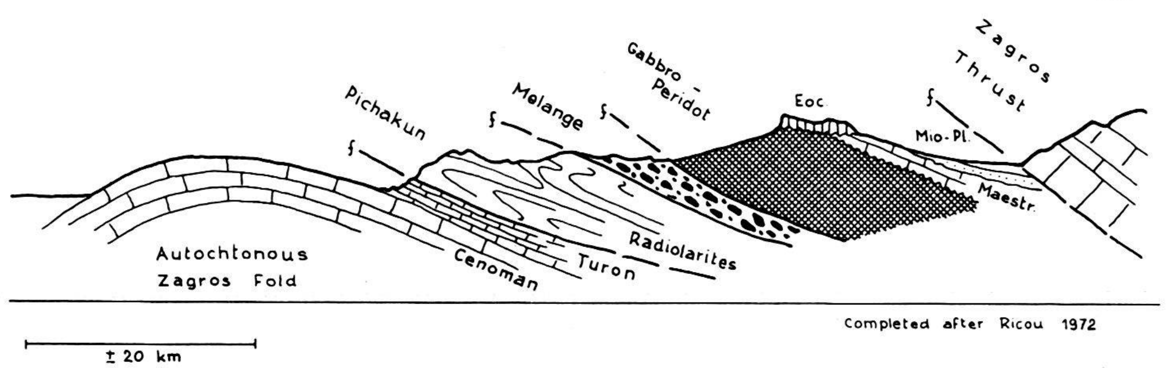


Fig. 6. Schematic section through the Neyriz nappes.

While the Zagros thrust has assimilated most of the north drift of the Arabian shield, in the wide and most complex area of Central Iran certain ophiolite mélange belts are surprisingly well preserved (Fig. 2). We find the best investigated area in the very center of Iran, in Nain (DAVOUDZADEH 1969). Here mélange belts are present

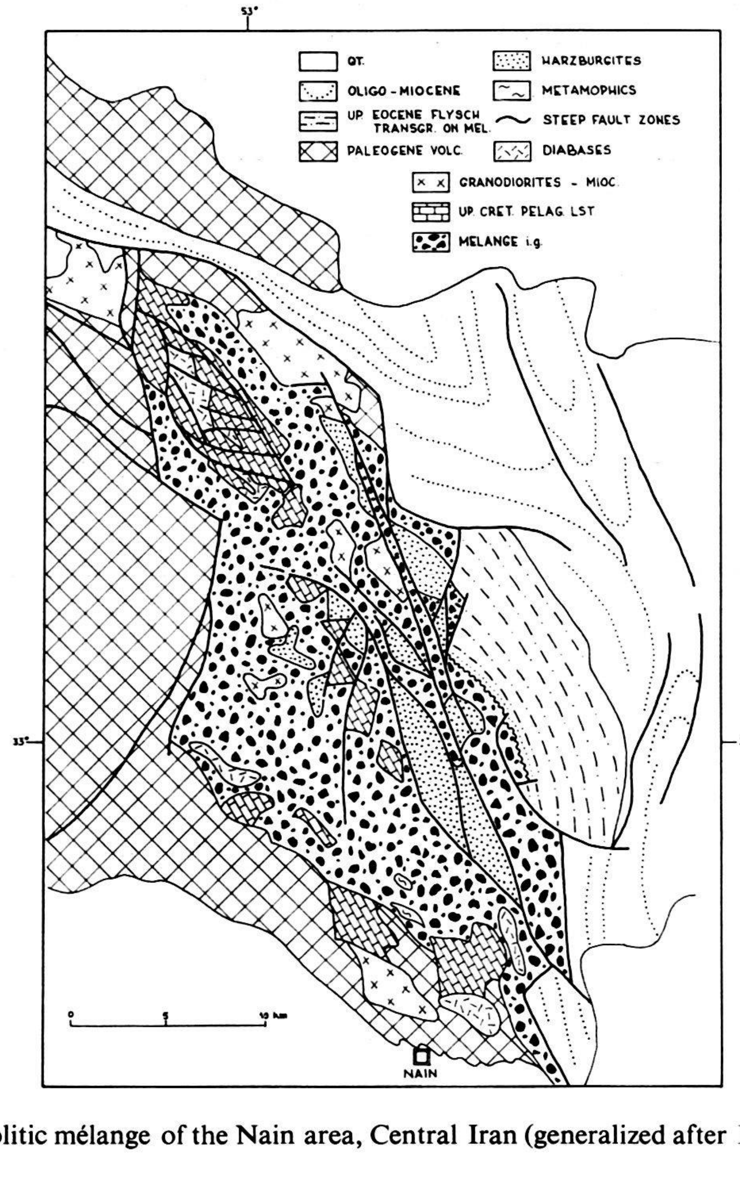


Fig. 7. The ophiolitic mélange of the Nain area, Central Iran (generalized after DAVOUZADEH 1969).

besides large homogeneous bodies of ultrabasics (Fig. 7). All contacts are steeply thrusted, but not overthrusted as they are in Neyriz, Oman or the Himalaya. Along a sharp south-east trending fault zone, reactivated in recent time (faulted alluvial fans), the Nain zone trends towards the mélange area of Neyriz already south of the Zagros thrust zone.

East of the Oman line the dominant geological feature is the *Lut block* (GANSSER 1969, STÖCKLIN et al. 1972), a classical microcontinent surrounded on its north, east and south side by more or less tectonized ophiolitic mélange zones. The northern area is at present being investigated by the University of Mashad, and mélange zones, mapped in detail, have provided a wealth of data (Davoudzadeh, personal information). Pink Globotruncana limestones and large patches of radiolarites are widely distributed, the latter apparently concentrated in the southern part of two belts (just north of the Doruneh fault zone). Rodingites in all possible stages of development are very frequent in the ultrabasic bodies (mostly harzburgites) while diabases are rather rare and top some of the higher mountains.

On the eastern edge of the Lut block ophiolitic mélanges form narrow bands which are limited by strike slip faults (FREUND 1970, GANSSER 1971, STÖCKLIN et al. 1972). They enter the northeastern part of the block as steep slices and may be associated with the large earthquakes within the northern Lut block (GANSSER 1969, AMBRASEYS & TCHALENKO 1969, NOWROOZI 1972). In spite of the strong tectonization within those slices, large masses of pillow lavas are locally preserved and show surprisingly little deformation.

The mélange zones increase towards the southeast of the Lut block within upper Cretaceous flysch. In the middle of one of those larger mélange areas erupted the still semi-active Taftan volcano (GANSSER 1971). This volcano, together with the Bazman volcanics, belongs to an east–west aligned volcanic belt separating the main Lut block from the Djaz Murian basin in the south. Along the southern border of this stable mass occur some of the largest ophiolitic belts in Iran which extend into the Makran region north of the Gulf of Oman. Unfortunately these remote areas are little known, and my information is mainly based on personal reconnaissance surveys (Fig. 8). Somewhat similar to the Nain region, though on a larger scale, massive basic (gabbro and diabase) and ultrabasic (serpentinized harzburgite) bodies are sharply separated from extensive mélange zones. The contacts are mostly steep,

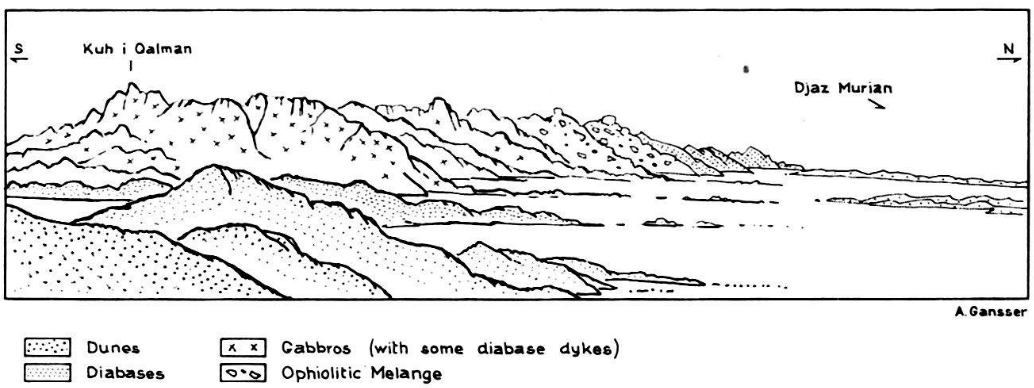


Fig. 8. The little known ophiolite belt south of Djaz Murian basin (view to west).

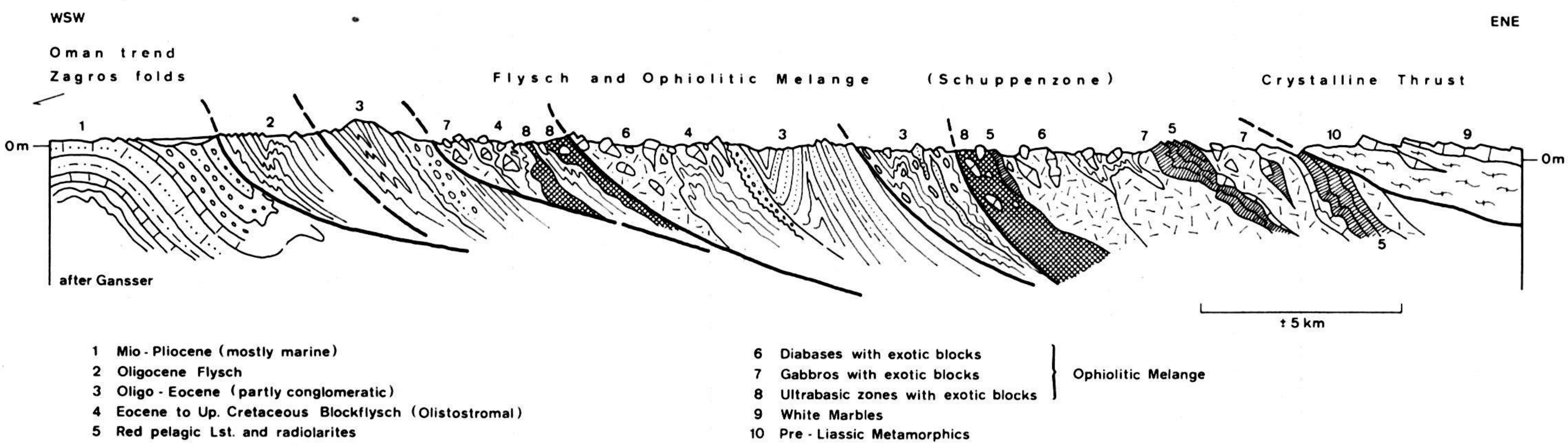


Fig. 9. Flysch/mélange section: north Minab, southeast Iran.

except for the western part, where one oberves westwards thrusting towards the eastern Zagros (Oman line) (Fig. 9).

This section is of considerable interest, since it displays a crystalline thrust sheet in the east which forms the highest unit. All tectonic contacts are steep at the surface but seem to flatten out at depth – a pattern of regional importance in this area. The crystalline thrust sheet consists of diaphthoretic chlorite-sericite schists and chloritic hornblende gneisses with intercalated small bands of gray marbles. They are topped by conspicuously white, sugary marbles, which are widespread as enclosures within the underlying mélange formations. In the Sargaz area the crystalline rocks are transgressed by flyschoid sediments which contain Liassic ammonites (unpublished report by Harrison 1936). In analogy to the Bitlis thrust sheet (Fig. 3) in southeastern Turkey, the pre-Liassic carbonates could also be Permian and not Precambrian as generally accepted. The lithological and even structural similarities are striking.

Within the mélange thrust sheets we find masses of diallage peridotites, serpentines with more or less developed ophicarbonates, diallage gabbros crisscrossed by gabbro-pegmatite dykes, various diabases and rarely pillow lavas. Apart from the ophiolitic components occur some reddish amygdaloid porphyries of a probable pre-ophiolitic age and sediments such as radiolarites, pink pelagic limestones, siliceous limestones together with white marbles, chlorite schists, epidote quartzites and hornblende-chlorite-schists of the type reminiscent of the crystalline thrust sheet. As youngest component occur *Globotruncana*-bearing pinkish argillaceous limestones.

All these blocks are again incorporated as olistostromal zones within the Eocene and lower Oligocene flysch. This fact is typical in the whole Beluchistan area and reminds again the conditions described in southeastern Turkey, only with more structural complications. In such areas the clear distinction between ophiolitic mélange formations and ophiolitic olistostromes is often difficult, and only a careful analysis of the youngest ages of matrix and blocks and of the structural relations can solve this problem. Most of these flysch sections show a highly compressed isoclinal folding. A younger east/west component with horizontal displacements is added to the structural complications. The flysch is transgressed unconformably by strongly deltaic clastic sediments which initiate the several kilometer thick Mio-Pliocene Makran group. The latter extends southeastwards to the Makran coast and beyond, and covers with its gentle folds a structurally highly complicated subsurface.

Since the Makran region is situated east of the Oman line, the effect of the underthrusting Arabian shield diminishes. In the gap between the Arabian and the Indian plate occur microcontinents such as the Lut block and the Sistan-Helmand blocks of central Afghanistan. A differential movement between these small but coherent masses seems evident and is well displayed around the Lut block with its well outlined fault zones. Along its eastern border they strongly affect the ophiolitic zones by shearing larger ultrabasic masses from the more mobile ophiolitic mélange formations. We again find similar movements in the major fault zones limiting central Afghanistan such as the Herat fault in the north and the Chaman fault in the southeast. Both these fault zones merge towards the east-northeast into the Kabul area and continue along the Panj Shir valley into the Hindukush. Between this triangular fault system all other structures are more and more compressed towards northeast, a narrowing effect, related to the stronger northwards drift of the northwestern Indian plate, as compared to the Arabian shield. The differential movement between the Arabian and Indian plates is mostly taken up by the large Chaman fault which separates two surprisingly different areas. While west of the fault zone the basement is covered by a complete Paleozoic and Mesozoic conformal section with some granitic intrusions, the eastern side displays large sedimentary gaps, a marked ophiolitic belt and a flysch facies of the uppermost Cretaceous and the Paleogene (DE LAPPARENT 1972). It is along this ophiolitic belt, south and southeast of Kabul, that well developed ophiolitic mélange zones are exposed, in sharp contact with the ultrabasic masses of the Logan Valley and along the Kabul river. They are transgressed by the basal conglomerates of the Eocene flysch, which locally contain ophiolitic olistostromes. These mélange formations along the Chaman fault and its secondary branches, well displayed in the Altimur region (MENNESSIER 1972), stress the importance of this structural trend and underline the striking facies changes related to it (Fig. 10).

The Quarternary volcanism, widespread in the west, disappears northeastwards, and its last occurrence was only recently discovered in the Dasht i Nawar region of central Afghanistan by BORDET (1972). No Quarternary or Recent volcanism is known within the orogenic belt around the northwards drifting Indian plate.

d) The Himalayan mélanges

The Chaman fault trend as well as the more eastern Quetta line, which separates the Indian platform sediments from the ophiolitic Beluchistan trend (GANSSER 1966), can be followed through the western Himalayan syntaxis into the Indus zone of the northern Himalayas, where the relation of ophiolitic mélange nappes to one of the best preserved plate boundaries is excellently exposed. Unfortunately this area is still very little known. We have now returned to our starting point, where 82 years ago the famous trio of geologists of the Indian Geological Survey were staring at a then not yet recognized ophiolitic mélange front.

Along the Indus zone, north of the Himalaya main range, we know so far three areas where the ophiolitic belt, which outlines the important suture line (plate boundary), has been studied. From west to east we distinguish the wider Ladak zone with the Dras volcanic belt (DE TERRA 1935, WADIA 1937), the ophiolites of the Rupshu area (BERTHELSEN 1951, 1953) and the Kiogar Kailas area (VON KRAFFT 1902, HEIM & GANSSER 1939, GANSSER 1964). It is in the latter region where we find, apart from the steep "root zone", a large extension of ophiolitic mélange nappes with a visible thrusting (or gliding) of over 80 km (Fig. 11). As far as we know this remote but highly interesting area has not been reinvestigated lately – at least no newly published information is available. However, reappraisals of previous findings in the light of modern global tectonics, paleomagnetic informations and comparisons with the well outlined ophiolitic mélange zones of the Middle East stress the intimate relations of the Himalayan mélanges to the zone of collision and subsequent obduction along the Indian and Eurasian (Tibetan) plate boundary (GANSSER 1966, 1973, DEWEY & BIRD 1970, CRAWFORD 1972, POWELL & CONAGHAN 1973, ATHAVALE 1973, CHANG CHEN-FA & ZENG SHI-LANG 1973). The divergence of opinion in the modern publications on this subject is understandable, since only a very few of these authors have seen the facts in the field.

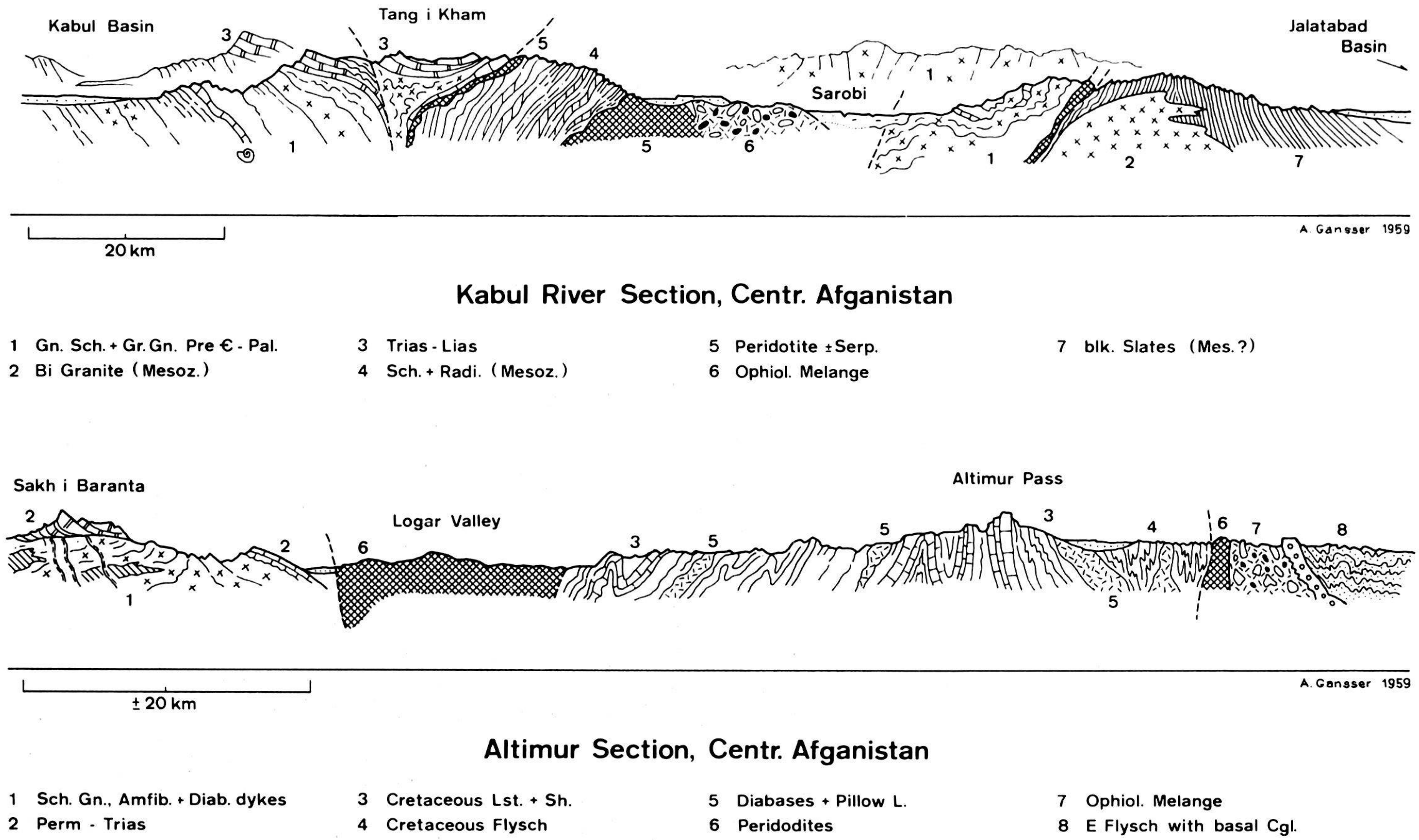


Fig. 10. Kabul River section and Altimur section (Central Afghanistan).

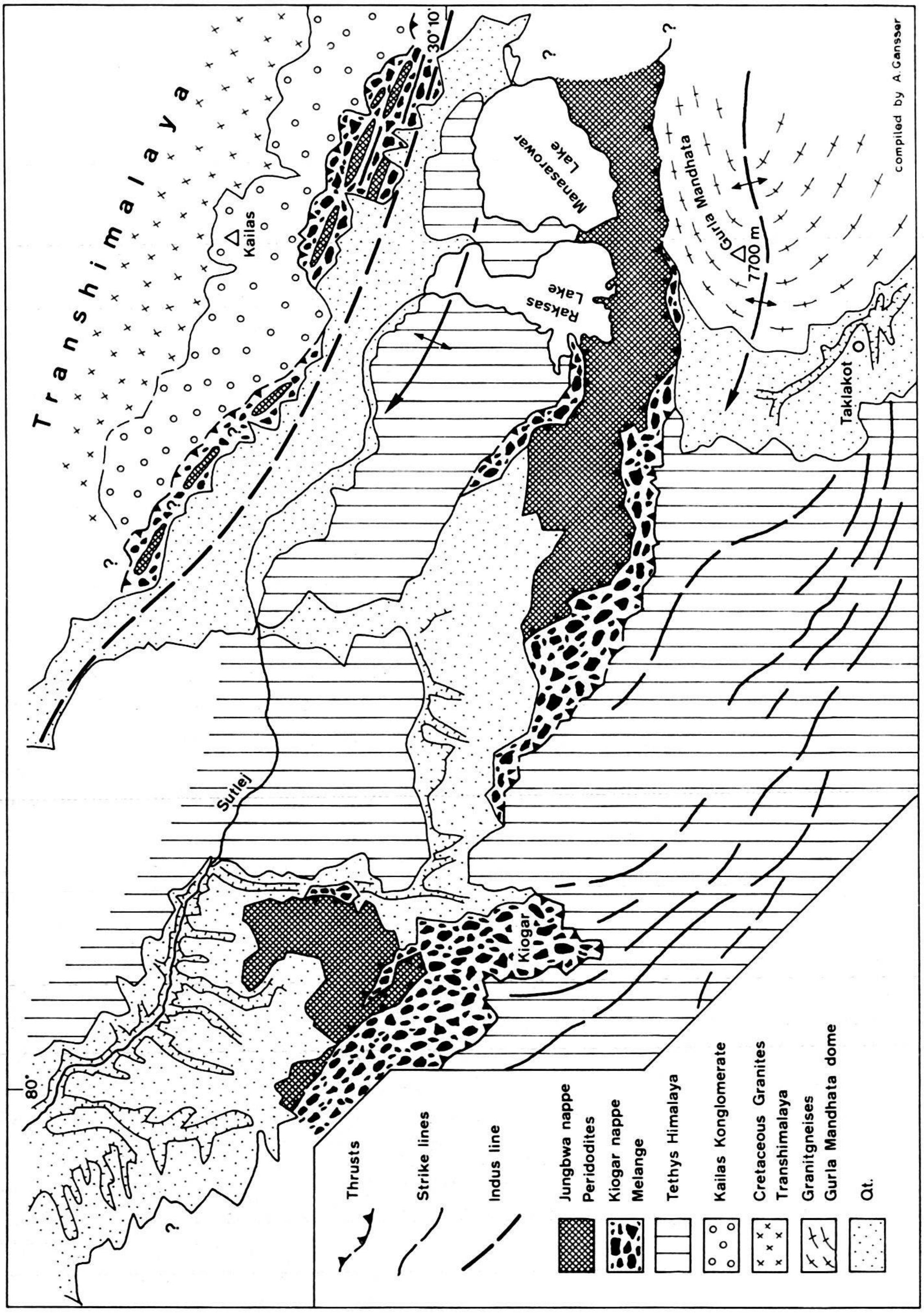


Fig. 11. The ophiolitic nappes in the Northern Central Himalaya (scale appr. 1 : 1 200 000).

Between the Indian/Tibetan border and the Transhimalaya south of the holy Kailas mountain we can recognize three major structural units: 1. *The Tethys Himalayan fold belt*, which in respect to the overlying ophiolitic nappes forms a neoautochthonous base. 2. An *ophiolitic mélange nappe*, which, following VON KRAFFT (1902), will be locally called the Kiogar nappe. 3. An *ultrabasic nappe*, which forms the highest structural element of the Himalaya, previously referred to as the Jungbwa unit, more recently as the Jungbwa nappe (GANSSER 1964). Each unit is limited by major thrusts, which again can be complicated by subsequent imbrications (Fig. 12).

The sediments of the *Tethys Himalaya* display a Jura type folding and include the middle Cretaceous Jumal sandstones. Following above the pelagic and ammonite-rich Spiti shales, the Jumal sandstones indicate the beginning of the first orogenetic Himalayan phase. The disturbance of the long conformable history of Tethys sedimentation, spanning the time from Eocambrian to the middle Cretaceous, is reflected by the incoming of detrital sediments which lead upwards into a flyschoid facies. These sediments were folded and subsequently sharply overthrust by the Kiogar ophiolitic mélange nappe, which cuts the already existing folds and postdates the Tethys folding phase.

The Kiogar ophiolitic mélange nappe exposes one of the best mélange sequences on our globe, well described on its southern margin by VON KRAFFT already in 1902 (Fig. 13). We also find some of the largest single units known, such as the Triassic Kiogar limestone covering as a single "block" an area of 20 km^2 with a thickness of up to half a km. For a detailed account of this area I refer to HEIM & GANSSER (1939, with a new edition 1974). Of special interest is the fact that the numerous sedimentary blocks display a facies unknown otherwise in normal outcrops in the Himalaya, and they witness a sedimentary basin of oceanic dimensions which has completely disappeared during the collision between the Indian and Tibetan plates. This is particularly true for the Permian, Triassic, Liassic and upper Jurassic blocks, while radiolarites and flysch blocks are not unlike some of the uppermost Cretaceous of the normal Tethyan sediments. Flysch-type sediments as well as highly sheared basic and ultrabasic rocks form the matrix of the mélange.

The most frequent sedimentary inclusions are Permian crinoidal limestones, which contain brachiopods, and various types of Triassic rocks. Amongst the latter huge algal limestone blocks and slabs contrast with pelagic limestones of Hallstätter type. VON KRAFFT discovered a Carnian limestone block from which 40 species of ammonites have been described (DIENER 1912). Curiously enough some of these Triassic blocks are embedded in red and greenish, more or less amygdaloid porphyrites, some even with free quartz, which are strictly related to the Trias and display sometimes intrusive contacts. They can also occur as single blocks within the flysch. It seems most likely that these volcanics are only slightly younger than the Triassic limestones and that they have no relation to the ophiolitic suite. We observe here a certain similarity with the porphyritic rocks related to Triassic limestones in the Mammonia region of southern Cyprus (see p. 486). Unknown in the "normal" Himalayan sediments are blocks of Liassic limestone containing ammonites and resembling the Adneth facies of Austria. Again of a most peculiar and otherwise unknown facies are oolitic limestones imbricated with a Kiogar block containing Calpionellas. This rather unexpected association is of particular interest, apart from the fact that Calpionellas seem to be unknown in the eastern Tethys. The Kiogar Calpionellas may actually represent the easternmost occurrence within the Tethys belt (personal information from Michel Durand-Delga).

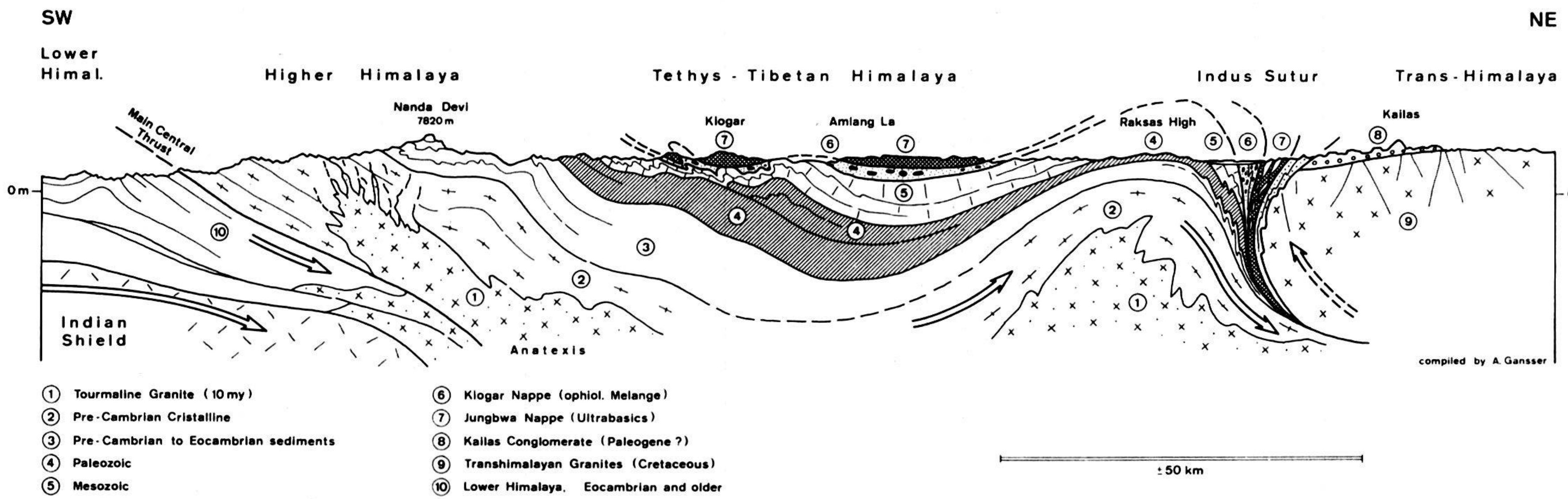
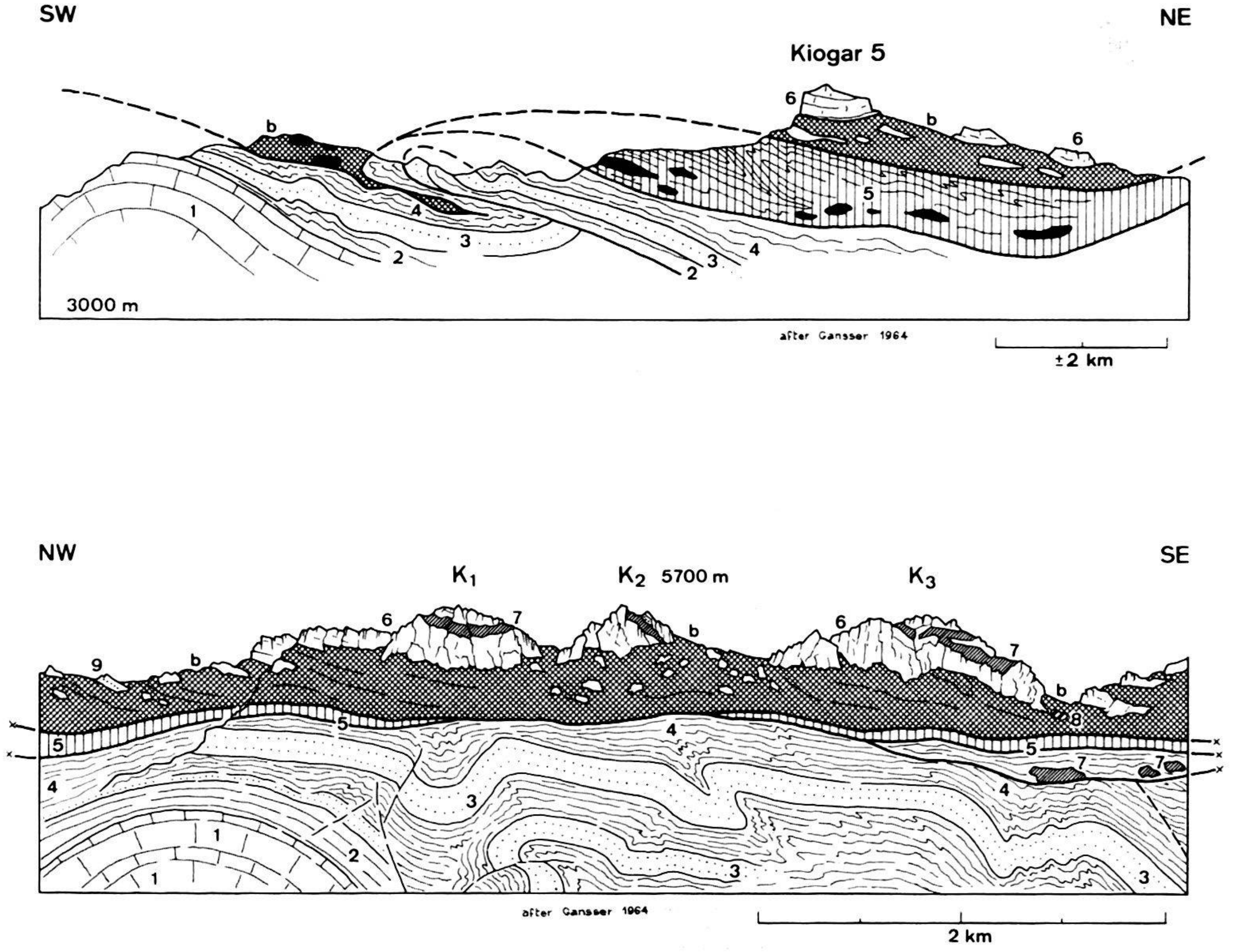


Fig. 12. Structural section: Noıthern Central Himalaya.



1 Kioto limestones (U. Triassic)
2 Spiti shales
3 Giumal sandstones
4 silty red and green shales covered by dark grey fucoid shales (Flysch)
5 siliceous sandstones with radiolarians (U. Cretac)
6 white Kiogar limestones (Trias ?)
7 oolitic limestones and calc shists with *Calpionella* (Up. Jur.)
8 Radiolarites
9 Tuffites
b basic and ultrabasic rocks with various exotic blocks from Permian to Cretaceous age

Fig. 13. The ophiolitic Kiogar thrustmass with exotic blocks, Northern Central Himalaya.

Of the younger sediments, radiolarites, siliceous shales and limestones and glauconitic sandstones have been noted. Apart from sediments the mélange exposes various types of basic and ultrabasic rocks within the flysch or replacing the latter as matrix but again appearing in some areas as blocks. Peridotites, serpentines, often with borders of ophicarbonate and diabase, are a frequent association. To complicate this geological jumble even more, we observe within some flysch horizons of the Amlang La region in southern Tibet layered intrusions of fine to medium grained augite monzonites with pigeonitic augite, alkalifeldspar, andesines and biotite. These curious rocks show thermal contacts with flysch limestones and form a post-flysch intrusion, probably of post-Cretaceous age. It may be younger and not related to the ophiolitic association.

The Kiogar ophiolitic mélange nappe is again overthrust by the highest structural unit of the whole Himalaya, the ultrabasic *Jungbwa nappe* (Fig. 14). There seems little

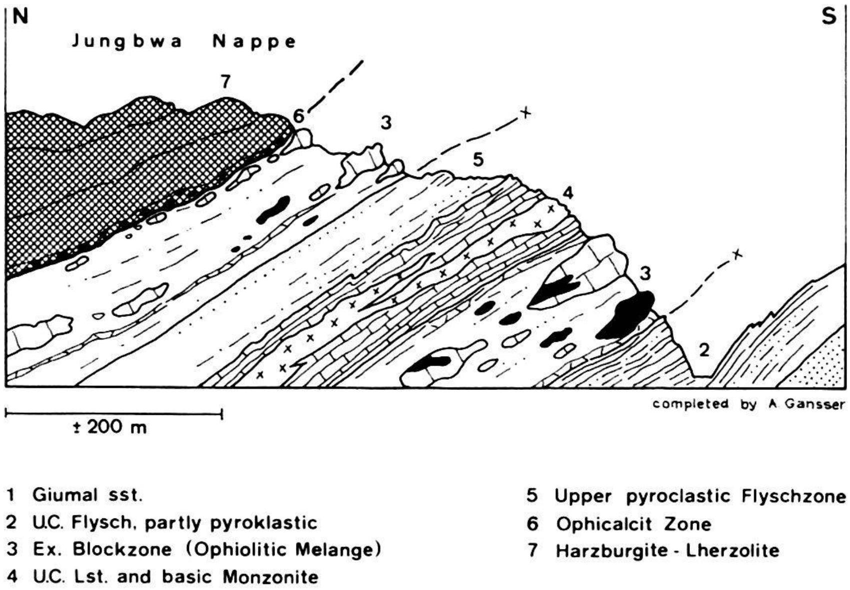


Fig. 14. Schematic profile: Southend of the ultrabasic Jungbwa nappe, Northern Central Himalaya.

doubt that here we witness the obduction and subsequent southward thrusting of a large mantle slab, squeezed out from the collision zone along the Indus line between the Indian and Tibetan plate. The visible extension of this sheet is about 3500 km^2 with a minimum thickness of 500 m, the upper part of this horizontal sheet having been eroded. Surprising is the widespread occurrence of harzburgites with only a local serpentinization in the form of antigorite. There is hardly any doubt that the composition of this basic sheet indicates an original high temperature and rather high pressure zone (under mantle conditions) and a much later "mise en place" in various not yet well recognized phases. The olivines (forsterite) are coarse-grained, with conspicuous kink bands, often parallel to the extinction. Less frequent are enstatite, approaching hypersthene and showing a strong lamellar segregation of monoclinic augites. The latter can also occur as single grains. Fe-Mg spinell as well as Cr spinell are locally enriched. In the Rupchu area to the northwest, BERTHELSEN (1953) reported from the same belt larger masses of chromite.

The base of the Jungbwa nappe consists of a highly sheared zone of ophicarbonates which even contain larger fragments of original peridotite. Metasomatic alterations against the flysch–mélange zone have partly obscured the original contacts.

Following the Kiogar and Jungbwa nappes northwards, one reaches the actual *Indus line*, where the same units can be recognized in a vertical position, but where everything has been highly squeezed and boudinaged, and where the ultrabasics occur as lenticular, serpentinized masses within mélange formations and slightly metamorphosed flysch-type deposits. Towards the Cretaceous biotite-hornblende granites of the Transhimalaya, this imbricated "root zone" is thrust northwards, partly on top of the Tertiary Kailas conglomerates which normally transgress the granites and are undisturbed apart from a local backfolding at the thrust contact (Fig. 12).

The relation of the Indus zone or line to the collision suture between the Indian and Tibetan plates is rather obvious, and the ophiolitic zone with more or less developed mélange horizons can be followed intermittently from the western Himalayan syntaxes over 900 km to the area under discussion in the northern Central Himalayas. One of the biggest open questions is the continuation of this major tectonic element to the east. That it continues with the same trend is indicated by the east–west striking topographical features, underlined by the suspiciously straight Tsangpo river system. A few observations corroborate this assumption. HAYDEN (1907) reported from the area south of Shigatse (southern Tibet) numerous basic intrusions in the form of diabases, noritic gabbros and serpentines within metamorphic Jurassic (Cretaceous) calcareous schists. He followed these basic rocks to the large Yamdrok Tso (lake) in the east. WIENERT (1947), in a little known publication, refers to his magnetic measurements during the botanical Schaefer expedition between Sikkim and Lhasa in 1938/39. Most surprising are the sudden large magnetic anomalies along the Tsangpo river ($+2600\ \gamma$, while just south of it, at Tsetang, the measurements drop to $-870\ \gamma$). Recently an ultrabasic belt along and paralleling the Tsangpo river was mentioned by Chinese geologists (CHANG CHEN-FA & ZENG SHI-LANG 1973). This information further supports an eastern extension of the ophiolitic belt of the northern Himalaya, the structural aspect of which is well exposed in the ERTS pictures covering this area. It may not take long before ophiolitic mélange formations are recognized also in this remote area, further corroborating the important suture zone related to the collision of the Indian and Eurasian plates.

4. Conclusions

The intimate relations of the ophiolitic mélange to the ophiolitic belts of world-wide distribution show us that most problems adherent to the ophiolites exist for the mélange formations. I stress the recognition of ophiolite belts as originally representing oceanic crust and mantel, a fact of prime importance when interpreting ophiolites in highly tectonized mountain ranges with nappe character (Alps, Himalaya) (DEWEY & BIRD 1970, 1971; MOORES 1970, 1973; GILLULY 1971; ROST 1971; VINE & MOORES 1972; ABBATE et al. 1972; GANSSER 1973; Academy of Science, Moscow 1973, I–III). The consumption of oceanic lithosphere in subduction zones along major mountain ranges is by now well known. While subduction is generally accepted, obduction (AVIAS 1967, COLEMAN 1971, MOORES 1973) brings us the same difficulty as the formation of ultrabasic nappes. Evidently most of the ophiolitic belts are now visible, because they are obducted and not subducted. This statement is particularly applicable to mélange formations, and we may go so far to state that an ophiolitic mélange may be explained through a mechanism related to obduction. A Cordilleran type orogenetic belt with the classical subduction of oceanic crust below a continental margin hardly produces mélange formations. They as well as the ophiolites are missing along 5000 km of Andean subduction (GANSSER 1972). Mélanges are weakly expressed along the northern Andes, but again developed under peculiar conditions along the central west coast of North America (HSÜ 1968, 1971). Substantially different conditions occur at the subduction of continental plates. Obduction of oceanic crust is here the rule, developed into conspicuous thrust-masses of ophiolitic rocks onto slabs of continental crust (COLEMAN 1971). Under these conditions mélange formations are particularly wide-spread, as we have seen in many Asian ophiolitic belts, since our best examples were from the Middle East ranges and the Himalaya, and recently ophiolitic mélange formations have been recognized in the Paleozoic Tien-Shan and the Mesozoic of the Lesser Caucasus (USSR Academy of Science's publication 1973). Further obducted ophiolites, where mélange formations may have been obliterated by thrusting, are reported from Papua (DAVIES 1968, DAVIES & SMITH 1971), though the mode of occurrence has recently been disputed (ROD 1974).

The subduction mechanism of continental plates (shield masses) and the obduction of ozeanic crust belonging to basins obliterated during a collision phase is still highly disputed. Flipping of a subduction zone is hardly the answer. The acceptance of the blue schist facies as valid indicator of underthrusting is widely generalized, but to exhume the blue schists from great depth is still a major tectonical problem (COLEMAN 1972). Blue schists mostly occur in mélange formations as exotic blocks, but they are rather atypical for such formations. It is not the place to enter into these controverses, but we may stress the fact that obducted mélange formations are mostly related to underthrust continental slabs which do not sink to greater depth but flatten out at approximately 40–60 km. Earthquake centers seem to confirm this in many places (COLEMAN 1971; NOWROOZI 1971, 1972; MOLNAR et al. 1973). This is particularly well documented in the subduction of the Indian plate and its thrust below the Tibetan mass. Earthquakes are widely spaced below the Tibetan plate at depths not exceeding 60 km. Below the Himalaya the calculated focal mechanism is consistant with thrusting along a plane dipping gently to the north (FITCH 1970).

The subduction of the Indian plate, now reflected in the Indus suture line, produced one of the best ophiolitic mélange formations known on our globe. We can only hope that this challenging area will receive in the future the intense geological investigation it deserves, after the first steps in this direction had been taken by VON KRAFFT 80 years ago.

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