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The Ophiolite-Radiolarite Belt of the North-Oman Mountains

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ABSTRACT

The article deals with the orogenic history of the northern Oman mountains and is based essentially on recent investigations in the Sheikhdom of Al Fujairah. This area occupies a key-position within the Oman mountains together with the Jebel Akhdar-Sayh Hatat areas.

The stratigraphy of the main structural units: Autochthonous Arabian Platform Sediments – Parautochthonous Ruus al Jibal Unit–Hawasina Complex–Metamorphic Series–Semail Ophiolites –Neoautochthonous Sediments is discussed.

New data are presented on some of the Mesozoic sediments of the Ruus al Jibal unit. As to the Hawasina Complex, part of the radiolarites can be dated with authigenic micrite intercalations. Ages of Upper Tithonian, Lowermost Cretaceous and Cenomanian–Lower Turonian are established with planktonic microfossils, confirmed by the radiometric age determination of intercalated tuffs in the case of an Upper Cretaceous sample. The metamorphism of the monometamorphic series is dated as Upper Turonian–Lower Santonian (86 $\pm$ 5 m.y.). These series represent metamorphosed radiolarite-shale sequences. For the Semail Ophiolites it can be shown, that its well preserved original succession from peridotites–layered zone–gabbros–dolerites to pillow lavas has been dislocated westward as a nappe unit for over 100 km, truncating with a strong tectonic unconformity the underlying metamorphic and Hawasina series. Neoautochthonous, postorogenic marine sediments are of Upper Maastrichtian-Tertiary age, resting transgressively on Hawasina series and Semail peridotites.

The structural style of the Oman mountains is briefly demonstrated: The Ruus al Jibal unit represents a parautochthonous sedimentary sheet from the eastern margin of the Arabian platform. The Hawasina Complex is composed of strongly imbricated sheets of a deep-water radiolarite-shale-turbidite-volcanic series embodying numerous shallow-water olistholites. This Hawasina sheet-pile was generated chiefly by gravity gliding of both incompetent matrix rocks and competent olistholite carbonates into a westward migrating depression. The depression with its accumulated and contemporaneously evacuating content moved successively in front of the advancing Oman trench. The beginning of the movement mirrored at surface, is determined as about Albian. The climax of the diastrophism is dated as (Upper Campanian?)–Lower Maastrichtian.

The Metamorphic Series are in thrust contact with the nonmetamorphic Hawasina rocks as well as with the Semail Ophiolites.

Finally, emphasis is placed on the reconstruction of the structural history of the Oman mountain system based on the stratigraphic and petrographic data at hand.

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REGIONAL GEOLOGIC SETTING

The following main structural units can be distinguished in the mountain area of Northern Oman:

F. Neoautochthonous Sediments
E. Semail Ophiolites
D. Metamorphic Series
C. Hawasina Complex
B. Ruus al Jibal Unit
A. Autochthonous Sediments of the Arabian Shield

A. Autochthonous sedimentary Cover of the Precambrian Crystalline

Basement of the Arabian Shield

Basement igneous rocks are not exposed in the Oman mountains.

Precambrian to Infracambrian sediments of more than 1800 m thickness are reported as deepest exposed outcrops in the Jebel Akhdar and Sayh Hatat windows underneath the nappe structures of the Hawasina Complex and the Semail Ophiolites.

Infracambrian evaporites (Hormuz Salt Formation) with much rock salt causing swells, domes and piercing plugs are widespread on the Arabian platform but not in the Oman mountain area. Their areal extension is delineated to the north by the Zagros thrust zone and to the east by the western front of the Oman mountains.

Paleozoic to Campanian sediments of over 2000 m thickness are found in the Jebel Akhdar and Sayh Hatat windows. The Permian to Campanian part forms a mildly folded carbonate sheet unconformably overlying the strongly folded and more or less metamorphosed pre-Permian substratum.

B. Para-autochthonous Ruus al Jibal Unit

It comprises about 4000 m of Permian-Campanian carbonates of a facies identical with the autochthonous Arabian platform sediments. Structurally, it represents a folded and faulted thrust sheet. The frontal limb of the Ruus al Jibal thrust panel overrides a thin portion of Hawasina beds. In turn, it is overridden by the main mass of the Hawasina Complex. This superposition is well exposed in the Hagil window east of, and in outcrops along the coast north of, Ras al Khaimah. As a whole, the unit is an upthrusting near-edge slice of Arabian platform sediments.

C. Hawasina Complex

It represents a well-defined gravity nappe of several thousand m thickness, composed of a great number of thin to thick (up to many hundreds of meters) sheets of deep-water sediments, chiefly radiolarites, turbidites, calcilutites, pillow lavas and tuffs. These sediments serve as a "matrix", within which small to mountain-size olistholites of marine shallow-water sediments are floating. The matrix can be dated by micrite intercalations within radiolarites as Upper Cenomanian–Turonian, Aptian–Albian and Berriasian. The olistholites reveal all ages from Ordovician to Senonian. In a few places, tectonic slivers from the base of the overlying metamorphites or the Semail Ophiolites are imbricated with the top sheets of the Hawasina Complex.

D. Metamorphic Series

Monometamorphic and polymetamorphic complexes can be distinguished.

The *monometamorphic* series comprise mainly quartzites with all transitions to phyllites, abundant pillow lavas, tuffites, gabbros and basalts. These rocks represent metamorphosed radiolarites, shales, intrusives and extrusives. Carbonates are extremely rare and are found as 1–2 m thick marble beds. The maximum Rb-Sr whole-rock age is 200 m.y.

The *polymetamorphites* are mainly diopside quartzites, muscovite quartzites and banded amphibolites. The mineral association is characteristic of the upper amphibolites facies. No suitable rocks for absolute age determination could be found. A biotite formed during the second metamorphism in the greenshist facies gave a K-Ar cooling age of 83 $\pm$ 5 m.y.

Both the metamorphic series are in fault or thrust contact with under- and overlying units in all cases observed.

The polymetamorphites are almost free of carbonate rocks. In several cases, the metamorphites are imbricated with upper sheets of Hawasina radiolarites and shales.

E. Semail Ophiolites

This unit forms a several km thick nappe which covers a large portion of the Oman mountain area for a length of over 500 km. The horizontal displacement of the nappe, which retains the detailed stages of magma generation, is about 100–150 km. Throughout the area, a uniform rock succession is observed with gradual transitions from peridotites (bottom) – layered zone – gabbros – dolerites – pillow lavas (top). This ophiolite sequence overlies the Hawasina Complex or the Metamorphic Series with a sharp thrust contact. The succession represents a continuous irreversible generation from a mantle magma with a final subaquatic effusive stage which is now exposed as the youngest member of the whole sequence and which is never covered by any pre-orogenic sediment.

The time of the ophiolite nappe displacement can be traced precisely. The nappe succession of the Oman mountains, especially the Hawasina nappe complex and the overlying ophiolite nappe are, on both flanks of the mountains, transgressively overlapped by postorogenic, undisturbed Upper Maastrichtian fossiliferous shallow-water carbonates. On the other hand, the youngest of the well-dated sediments buried below the overthrusting Semail ophiolite nappe are of Campanian (–?Lower Maastrichtian) age.

F. Neoautochthonous Sediments

Slightly folded post-orogenic marine carbonates of Upper Maastrichtian age (often with transgressive coarse basal conglomerates) overlie with a sharp angular unconformity the whole Oman nappe complex which was completed by that time. In certain localities, the Upper Maastrichtian shallow water carbonates overlie either

Hawasina sediments or Semail Ophiolites. The overlap is well exposed on both sides of the Oman mountains.

The Maastrichtian carbonates in turn are overlain by a thick marine Paleocene-Miocene sequence on the western side, and a Paleocene-Pleistocene section on the eastern side, of the Oman mountains. No marine Tertiary or Quaternary sediments are found within the mountain area of North-Oman nor does any Tertiary crop out along the mountain flanks in the northern tip of the peninsula (Fujairah to Ras al Khaimah).

Along the clearly defined western mountain front from Al Khari to Al Khatt, Pleistocene (–?Pliocene) birbirites, siliceous dolomites and especially younger river deposits cover the eroded and weathered mountain flank.

Within the mountain area, thick Pleistocene river deposits form several terraces.

Along the eastern coast, shallow marine Pleistocene sediments are uplifted regionally to terraces which may rise several tens of m above sea level.

STRATIGRAPHY

Sediments of the stable Arabian Platform

Pre-Permian

In the North-Oman mountains, three regions expose sediments of the Arabian platform: Jebel Akhdar and Sayh Hatat in the south, and Ruus al Jibal in the north.

Igneous rocks of the Precambrian basement are not exposed.

The oldest sediments known – on which little work has been done so far – are Precambrian sediments exposed in the deeply incised domal uplifts of J. Akhdar and Sayh Hatat. Tschopp (1967) gives the following summary of the pre-Permian succession:

Jebel Akhdar	*Sayh Hatat*
Transgressive Permian dolomites, locally with basal conglomerate	
Quartz sandstones and siltstones, black laminated chert layers	Quartz sandstones with shale partings, slightly metamorphosed
Dolomites, mainly with algal stromatolites at the top	Dolomites
Siltstone-sandstone succession with thin limestone bands	
Marine sandstones and tidal flat limestones	
Conglomerates with basement rock boulders	Epimetamorphic green phyllites, chlorite and sericite shists

Tschopp (1967) mentions for the pre-Permian section a total thickness of more than 1800 m. A possible Precambrian to Lower Ordovician age is assumed.

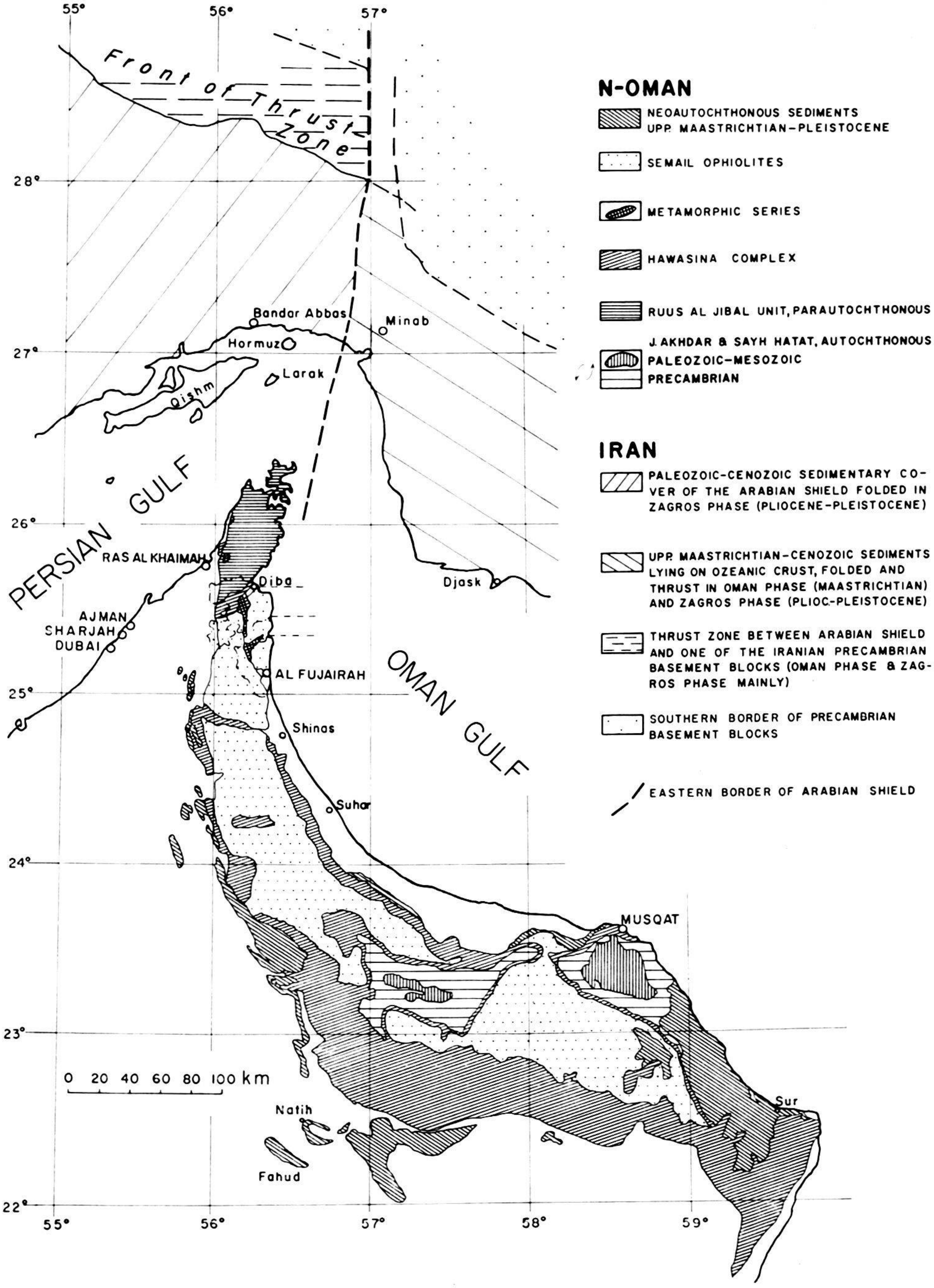

Fig. 1. Geological sketch-map of North-Oman and neighbouring areas.

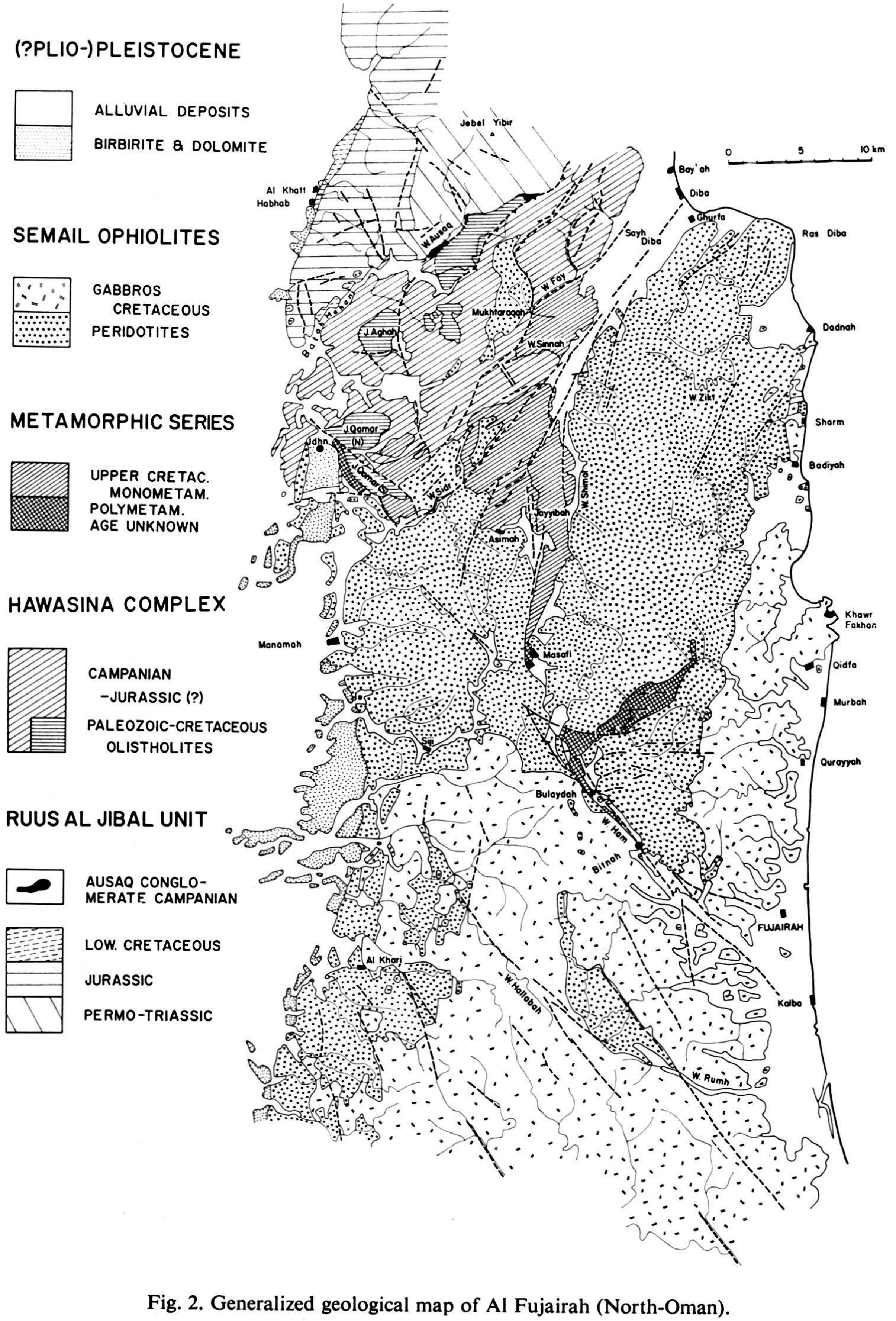

Fig. 2. Generalized geological map of Al Fujairah (North-Oman).

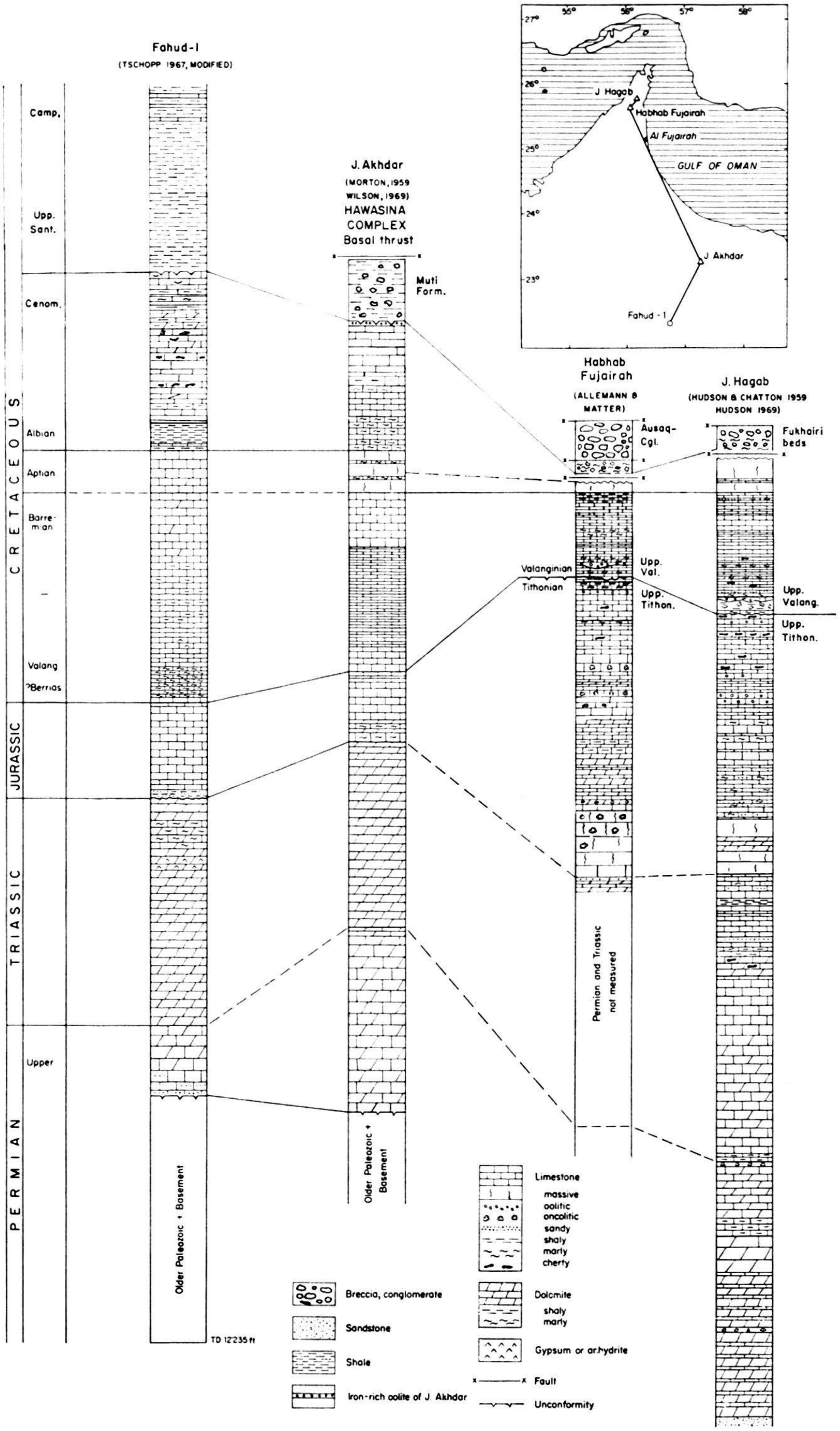

Fig. 3. Composite stratigraphic columnar sections of Arabian platform sediments in Oman.

A widespread evaporite layer, including much salt, covers the Arabian platform of the Persian Gulf and Oman areas with the exception of its easterly margin which is buried below the nappes of the Oman mountains. No salt is found in the Jebel Akhdar and Say Hatat windows.

Permian-Triassic

Sediments of this age are almost exclusively represented by carbonates.

Ruus al Jibal

Permian-Triassic carbonates (Fig. 3) constitute a large portion and occupy the stratigraphically deepest exposed part of the Ruus al Jibal unit. Valuable information on this unit has been given by HUDSON (1960). The Jebel Hagab section in the central region of the unit can be regarded as representative. It comprises a partly fossiliferous dolomite-limestone succession of over 2000 m thickness, subdivided into several formations by HUDSON (1960). For the interesting details, we refer to his paper.

At the very base of the Hagab succession, a few meters of sandstones are found below the Permian dolomites. A thrust cuts out a possible older section. Southwest of the Jebel Jibir, in the gorge of Wadi Kharas, more than 100 m of thickbedded limestones with head-size corals and algae occur, which are thought to underly the basal part exposed in the Jebel Hagab section. Above the main mass of the Permo-Triassic sediments, formed by dolomites and limestones, the upper 300 m of the Triassic section are characterized by sandstone, marl and shale laminae. Within a few tens of meters, these beds pass conformably into overlying thick-bedded limestones which, in the upper half, carry Liassic fossils. There is no determinable break from Triassic to Liassic sedimentation.

Jebel Akhdar and Sayh Hatat

A sharp unconformity, locally with conglomerates, marks the transgressive base of the Permo-Triassic section (Fig. 3). No details are published on the carbonate section. TSCHOPP (1967) mentions only dark dolomites with a varying thickness of 200 to 700 m for the Permian section and a 1600 m maximum thickness of Triassic dolomites in Sayh Hatat. The lithology and these thicknesses, however, do not match those given by MORTON (1959, Fig. 3) for the Sayh Hatat area where the Triassic is represented by about 100 m of limestone. More data are necessary for a precise correlation with the Ruus al Jibal equivalents.

It is noteworthy to mention that HUDSON, BROWNE and CHATTON (1954) and MORTON (1959) directly compare the Permo-Triassic section of the Jebel Qamar, one of the larger olistholites within the Hawasina Complex, with the Ruus al Jibal and J. Akhdar sections.

Jurassic-Cretaceous

Ruus al Jibal (Fig. 4, 5)

HUDSON and CHATTON (1959) have published an excellent paper on the Jurassic-Cretaceous Musandam Limestone of the Ruus al Jibal unit. In fact it is based on one section of the Jebel Hagab region east of Ras al Khaimah. This standard section

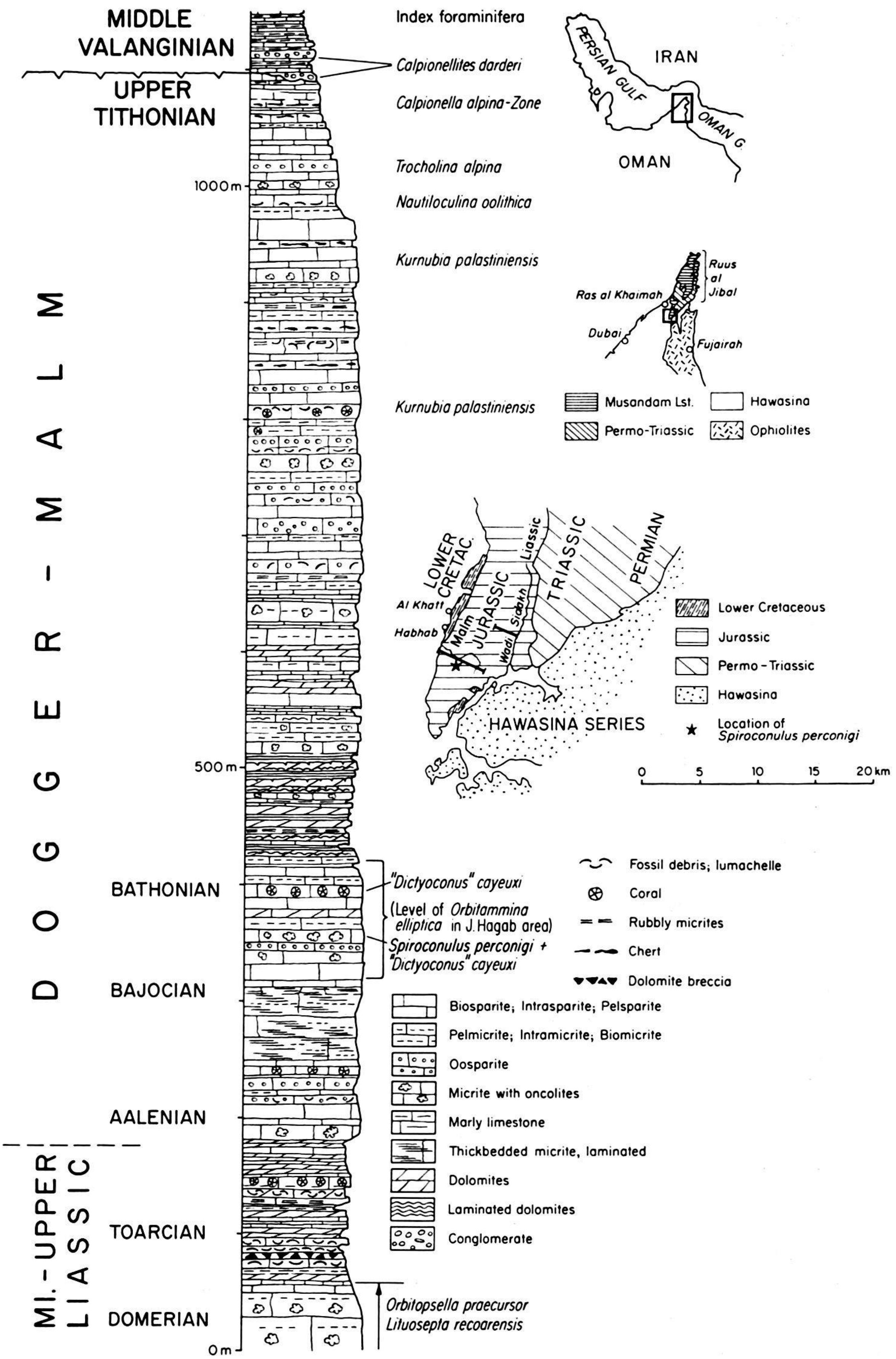

Fig. 4. Generalized Upper Liassic-Valanginian section of the Musandam Limestone in Al Fujairah (North-Oman).

covering exclusively carbonates of almost 1500 m thickness has been compared with corresponding sediments of Dukhan, Central Arabia and SW Iran.

In the course of recent investigations covering mainly the Sheikhdom of Al Fujairah, an additional section of some 30 km S of J. Hagab has been examined. The results agree well with those of HUDSON and CHATTON (1959), the main difference lying in the much greater number of dolomite beds in Fujairah. The generalized Jurassic section is shown on Figure 4; more details on the Cretaceous part are seen on Figure 5.

The section studied in the present work displays Liassic-Lower Tithonian shallow marine carbonates with an environmental range from subtidal limestones to supratidal dolomites with algal mats and mud cracks. The bathymetric variation of the deeper to the tidal flat sediments lies within tens of meters.

With the Upper Tithonian, a fast transition to radiolarian-Nannoconii-calpionellid pelmicrites takes place, reflecting more open marine conditons and an increase in depth. This regime, occupying the whole northeastern marginal strip of the Arabian platform (Ruus al Jibal unit), is interrupted by a sharp unconformity in Valanginian time. Locally, a strong angular unconformity cuts down to the Tithonian and coarse conglomerates may be found in Al Fujairah. In two cases (Batah Mahani and Habhab, (Fig. 5), the age of the time break is well defined paleontologically.

At Batah Mahani, Upper Jurassic *Kurnubia*-biosparites are unconformably overlain by radiolarian-Nannoconii-micrites which carry *Capionellites darderi*, a worldwide index form of Middle-Upper Valanginian. Two breccia-conglomerate intercalations and conglomeratic marls within the micrites include boulders of different Upper Jurassic limestones and extremely rare dolomites (?Middle-Upper Jurassic). Important are limestone boulders of Upper Tithonian-Lower Berriasian micrites covering the *Calpionella alpina* and *Calpionella elliptica* subzones. Intraclasts within these beds reveal *Calpionellites darderi*.

At Habhab, a very slight angular unconformity separates micrites with chert nodules of the *C. alpina* subzone (Upper Tithonian–Base Berriasian) from micrites without chert (Middle Valanginian). Again, from the two breccia-conglomerates which interrupt the calcilutite section, the lower one is of Middle-Upper Valanginian; the upper one possibly of Hauterivian age.

These breccia-conglomerates, which may reach 8 m thickness and carry boulders of up to head size, are identical with the ones found in the Ashhab Limestone of the Hagab area (HUDSON and CHATTON 1959, p. 86 and Fig. 5), for which an age of ?Sequanian–Tithonian was assumed. The two breccia-conglomerate beds in the Hagab section are up to 13 m thick and carry somewhat coarser limestone boulders than in Fujairah.

The suggested "?Sequanian-Tithonian" unconformity at the base of the Ashhab Limestone is, in fact, identical with the well-developed Middle-Upper Valanginian angular unconformity in Al Fujairah.

The Valanginian-?Hauterivian conglomerate beds are again topped by thin bedded radiolarian-Nannoconii-micrites. They persist up to massive shallow-water limestones of Barremian-Aptian-Lower Albian age which mark the youngest beds exposed in the Lower Cretaceous carbonate section of the Ruus al Jibal unit in Al Fujairah and Jebel Hagab.

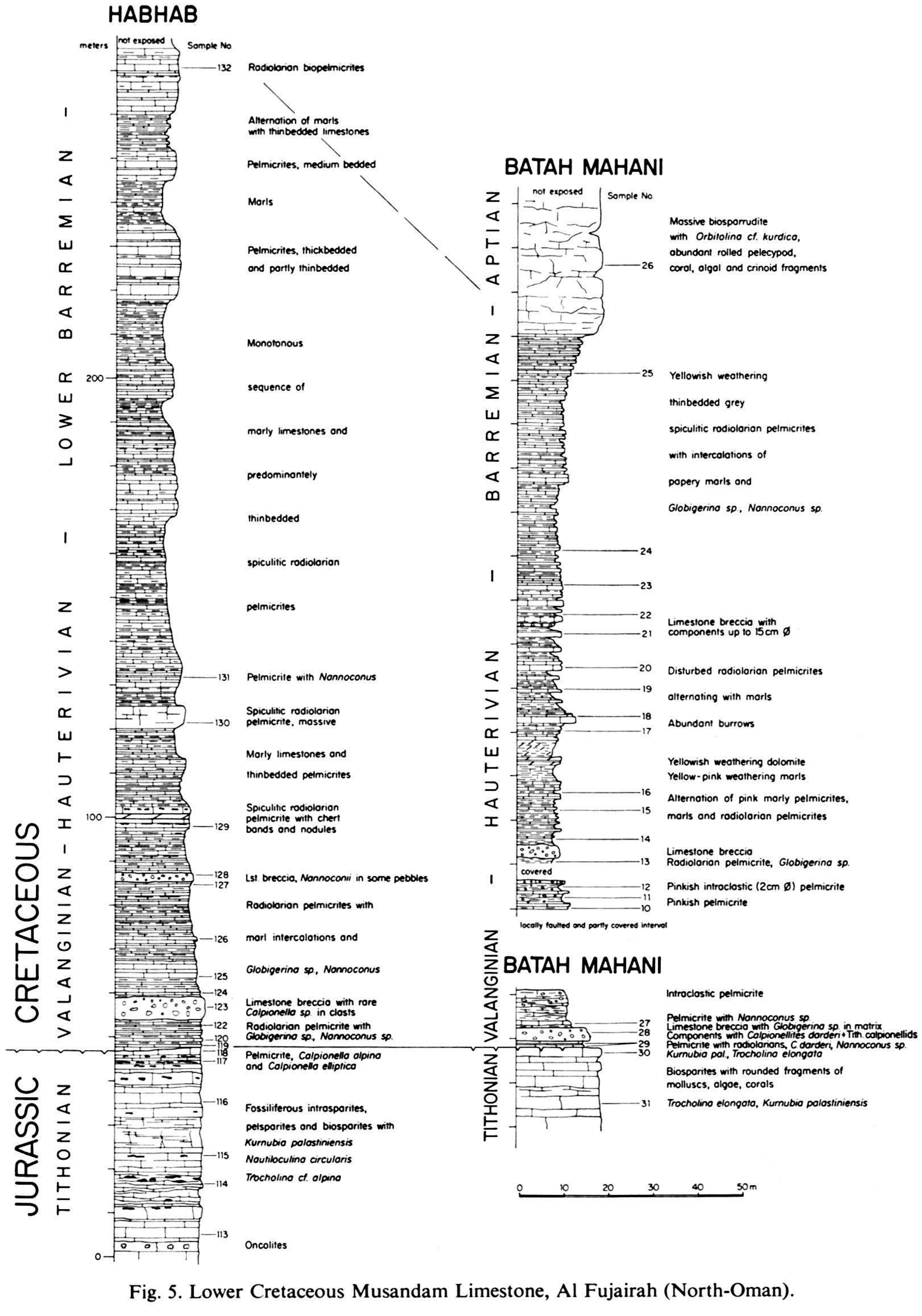

Fig. 5. Lower Cretaceous Musandam Limestone, Al Fujairah (North-Oman).

Campanian pelagic marls and conglomerates of Wadi Ausaq (Fig. 3): Between the Permo-Triassic carbonates of the Ruus al Jibal unit and the overthrust radiolarite-shale series of the Hawasina Complex in Wadi Ausaq, about 15 m of Campanian pelagic marls and limestones with abundant planktonic foraminifera occur in a few places. Nearby (contact not exposed), more than 50 m of very coarse conglomerates are locally present.

Finer conglomerates appear intercalated between the thin-bedded dominantly pink pelagic carbonates. The tectonic disturbances along the thrust contact conceal the original relationship to a great degree and a normal stratigraphic contact with the former substratum has not been found. Locally, the marl and conglomerate beds can be followed with interruptions for several km.

The Ausaq conglomerates and pelagic marls are, jugding by their description, very similar to the time-equivalent Fukhairi beds of the Hagil window (see HUDSON et al. 1954). The main difference concerns the spectrum of the boulders. The boulders of the Ausaq conglomerate, of up to cubicmetre-size, are chiefly limestones and some chert from the nearby Permian facies. Typical Jurassic and Cretaceous boulders have not been encountered. The boulders of the Fukhairi beds, however, carry besides limestones and chert, also serpentinite, igneous rocks and spilite. This palette of components is of importance for genetic relationships (p. 695). As a whole, the Ruus al Jibal unit reveals a continuous marine carbonate section of Permian to Aptian age, with a short break in sedimentation during Valanginian time. The Campanian Ausaq and Fukhairi beds, deposited in small basins in front of upthrusting parautochthonous Ruus al Jibal sheets, are synorogenic sediments.

Jebel Akhdar and Sayh Hatat

No details have been published on the Jurassic-Cretaceous stratigraphy of this area. The results of the very brief accounts given by MORTON (1959), TSCHOPP (1967), and WILSON (1969) are plotted on Figure 3.

Despite some differing statements on age, facies and thickness, there is no doubt that the Jurassic-Cretaceous of these areas are part of the Arabian platform sediments, comparable with the age-equivalent Ruus al Jibal section.

With respect to the specific problem of a genetic relationship between the large Oman mountain units, it is of utmost importance to determine the latest pre-orogenic autochthonous sediments. The climax of the orogenic movements is easily dated: it occurred before the undisturbed neoautochthonous Upper Maastrichtian limestone transgression onto different units of the completed Oman mountain building. The question is, therefore: what are the latest autochthonous, pre-paroxysmal sediments?

All authors agree that the continuous autochthonous Musandam carbonate sedimentation ends with the Wasia group in Upper Cenomanian time. It is overlain by a ferruginous oolite bed along the southern Jebel Akhdar area which is also thought to be of possible Cenomanian age.

This iron oolite is followed by a sedimentary gap covering Turonian-Lower Santonian time. The break (nondeposition?) can be recognized in the mountains as well as the desert foreland area (e.g. Fahud). Above this sharp break, the Muti shale formation is found, obviously following the roof plane of the Musandam carbonates. Above its glauconitic base, several conglomerate intercalations with cobbles predom-

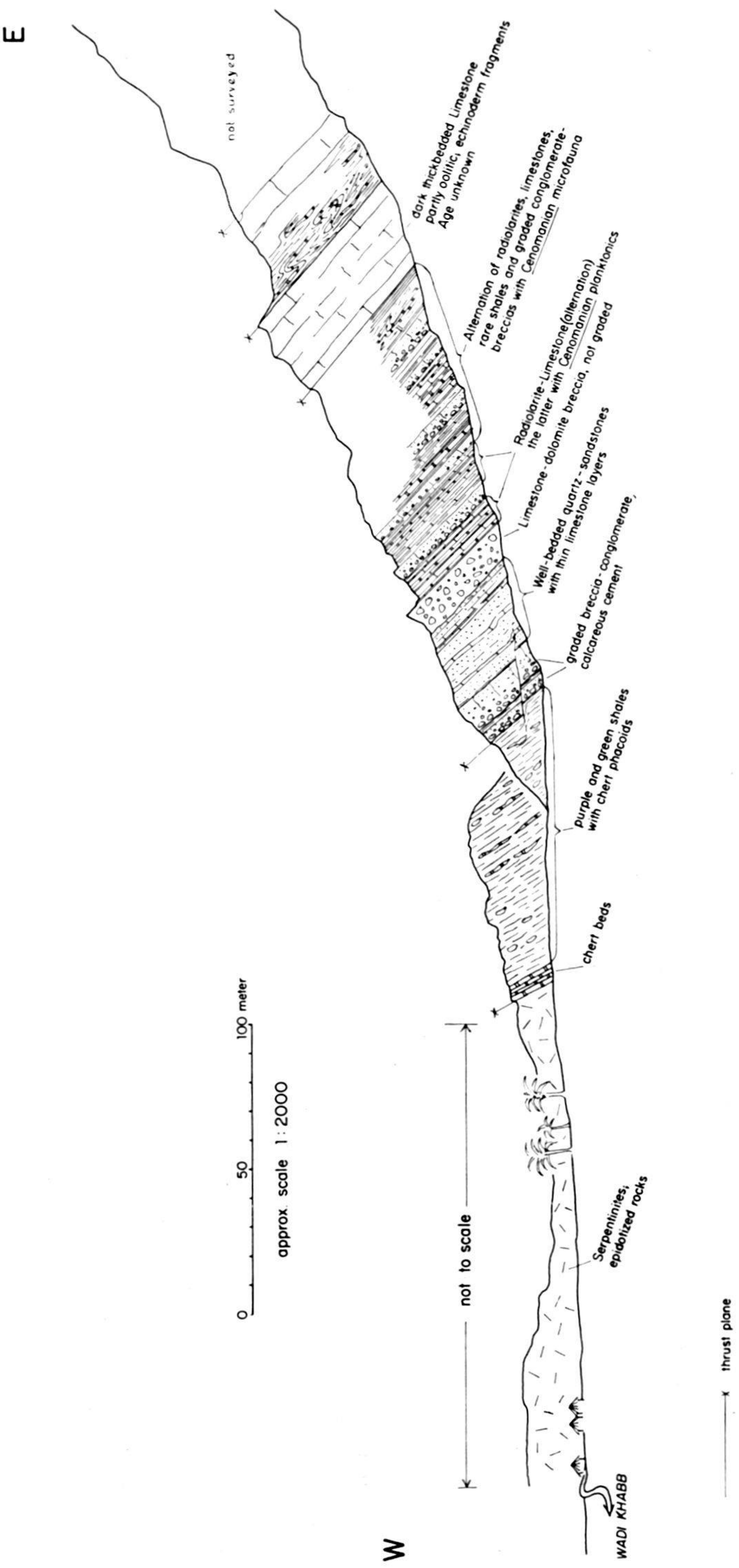

Fig. 6. Section through Hawasina series in Wadi Shakh (Al Fujairah).

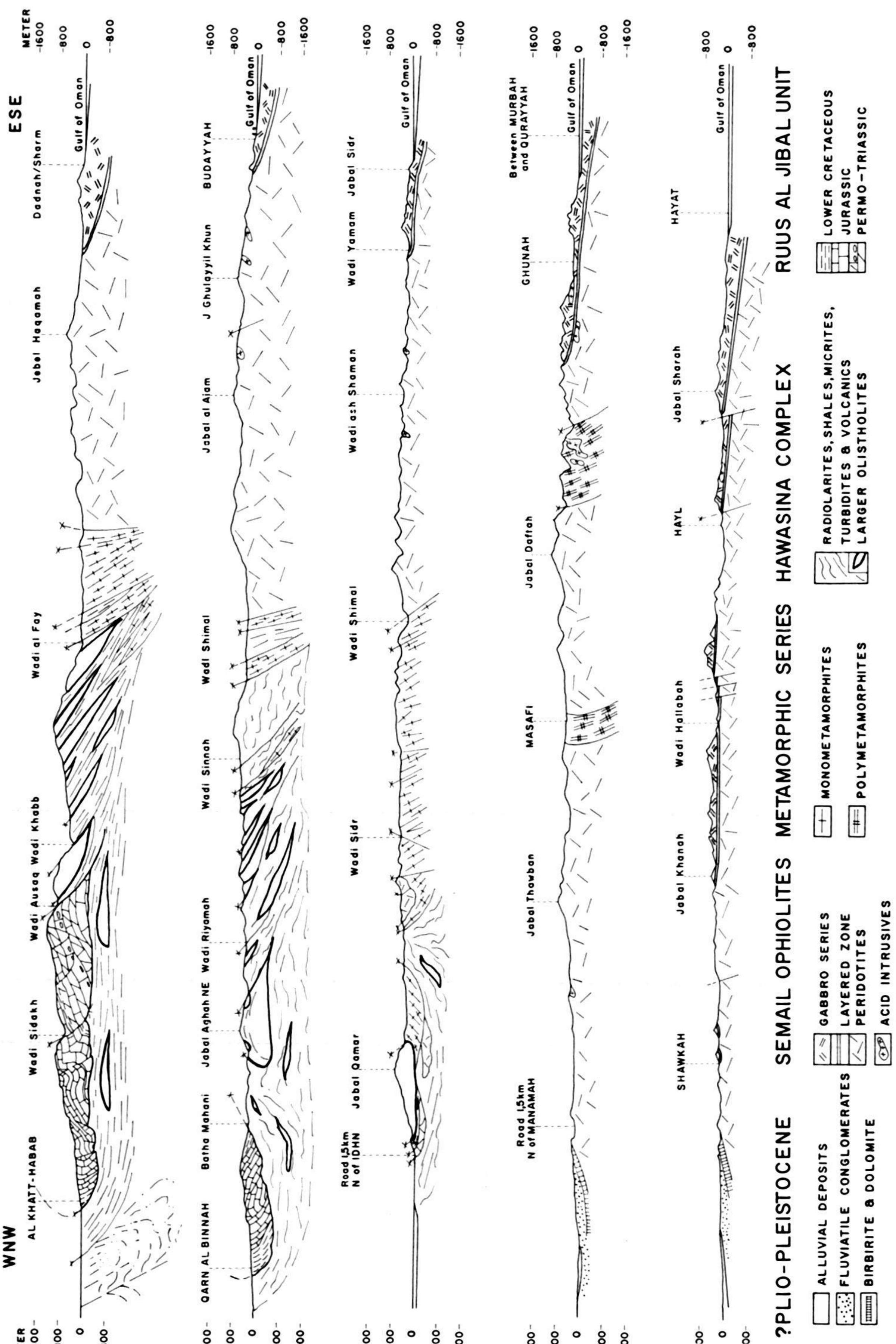

Fig. 7. Geological cross-sections through North-Oman mountains in Al Fujairah.

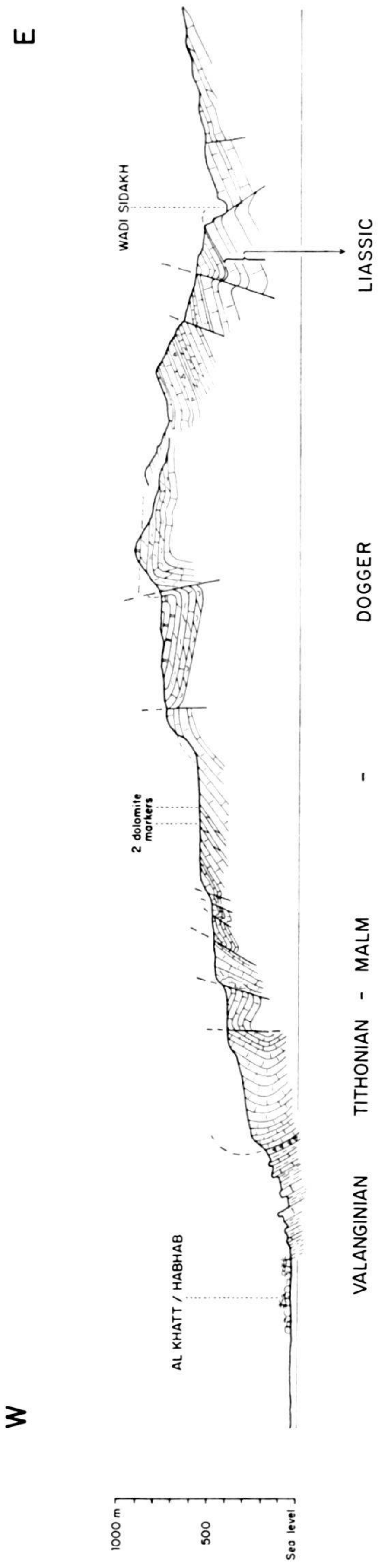

Fig. 8. Geological cross-section through frontal part of Ruus al Jibal unit (Al Fujairah).

inantly from the underlying Cenomanian limestone formation, are encountered within the shales. The pelagic shale with globotruncanids is of Upper Santonian-Campanian age. This conglomeratic Muti shale passes southward in a direction of the desert foreland into the nonclastic, age-equivalent Aruma shale formation. Hence, the Muti formation is the Campanian part of the autochthonous Arabian platform sediments of the Akhdar-Sayh Hatat areas. The Muti formation was mentioned by TSCHOPP (1967) and described by WILSON (1969). It seems to be – in this case we follow WILSON – an autochthonous formation overlying the ferruginous oolite with a stratigraphically normal contact. However, in contrast to Wilson, we think it to be the youngest formation of the ± autochthonous J. Akhdar-Sayh Hatat sedimentary Arabian platform sequence. It is separated from the Hawasina nappe complex (Mi'aidin Limestone at the base) by a major thrust plane.

Unlike the tectonically undisturbed autochthonous Muti formation, its analogue in the north, the Ausaq and Fukhairi beds, are slightly sheared off from their parautochthonous Ruus al Jibal substratum. All three formations are the latest pre-orogenic sediments laid down on the Arabian platform edge of the westward migrating Campanian (-? Lower Maastrichtian) foredeep, in front of the advancing parautochthonous and higher nappes of the Hawasina Complex. In J. Akhdar–Sayh Hatat and Wadi Ausaq, the cobbles of the intercalated conglomerates are derived from the Musandam substratum, whereas in the Fukhairi beds of the Hagil window, they also come from Hawasina rocks.

Hawasina Complex

It is one of the principal structural units of North-Oman (Fig. 6, 7). This complex unit displays a large number of intensely imbricated, more or less isoclinal sheets, slivers or flat recumbent folds which are – locally – often extremely folded on a small scale. When it is also tectonized, part of the succession may become a highly contorted chaotic mass with competent beds scattered as blocks floating in a mixture of incompetent beds. The chaotic "colored mélange" may then resemble a tremendous boulder bed with a colorful matrix. A normal succession of monoclinal sheets may grade laterally within a few kilometers into such a chaotic mélange mass.

Most of the competent larger blocks, lenticular masses and, in certain cases enormous sheets with a lateral extension of several kilometers reveal uniform lithological units of limestones, dolomites and rare clastics. These bodies, which consist in most cases of shallow marine sediments, are olistholites ("exotics" of other authors). In contrast, the great mass of imbricated or contorted incompetent units are open-sea to deep-water sedimentary sequences representing the "matrix" of the Hawasina Complex. The dominant rock types are radiolarites, shales, calcilutites, turbidites and submarine volcanics. Smaller or larger matrix units comprise one or a multiple alternation of several rock types in varying amounts. The matrix rocks are the authigenic filling of deeper basin parts. The olistholites are not their contemporaneous shallow-water equivalents but lithified older shallow water units situated at the edge of the basin, the majority being displaced into the basin by gravity gliding.

Matrix

It consists of the following characteristic rock units:

Few to over 100 m – thick sheets or intensely folded and contorted sequences of red, scarcely green *radiolarites and shales*. Found throughout the Hawasina Complex. Radiolaria are the only indigenous fossils.

Radiolarite-calcilutite alternations are observed in varying proportions of cm- to several m-thick intercalations of calcilutites. In cases, graded fine breccias may occur at irregular intervals. In two cases, Nannoconii and calpionellids of three zones (within an Upper Tithonian-Middle Berriasian range) were found isolated and in small intraclasts of pelmicrite rock samples. The thickness of these series may reach 2–300 m.

Red radiolarite-shale-turbidite series: consist mainly of an alternation of red radiolarites and dark shales with abundant brown-weathering well-graded breccias and calcarenites. The intervals of corresponding grain size in turbidites commonly carry reworked Orbitolinas of Upper Barremian-Lower Albian age and radiolitid fragments of Albian-Cenomanian age. The original thickness of these series may exceed 100 m.

Radiolarite-micrite-turbidite series are composed chiefly of alternating red and green radiolarites and micrites, regularly interrupted by turbidites of up to 10 m thickness. Components are mainly limestones, dolomites and cherts. Isolated, but often broken Cenomanian larger foraminifera and Cenomanian planktonics are encountered in the matrix of turbidites. Rare planktonic foraminifera of Upper Cenomanian-Lower Turonian age are found in micrites which alternate with radiolarites. This unit may reach 300 m thickness.

Thick-bedded (bedding up to 10 m) slightly graded *calcarenites*. Often strongly oolitic (ooids displaced!). Convolute lamination and crossbedding is common. Thin, sandy limestones are often laminated. Rare carbonaceous material may occur in thin-bedded intervals. No index fossils were found. The series may surpass 200 m thickness.

Up to 200 m thick sheets of *tuffaceous sequences*. Tuffs, partly with large bombs, ash- and lapilli-layers, pillow-lavas, pillow breccias and serpentinite layers constitute the bulk of these units. These rock types are seen in divers alternation with subordinate radiolarites, shales, calcilutites and turbidites. Index fossils were not found.

Olistholites

Their thickness ranges from meters to several hundred meters; their lateral extension from hundreds to several thousand meters.

The oldest olistholite sediment has been reported from Jebel Qamar (HUDSON et al. 1954), where Ordovician grits and shales contain *Cruziana* and trilobites. A pre-Permian age of some smaller olistholites of quartz-sandstones and of some limestone units is possible, but not proved.

The main bulk of the Hawasina olistholites consists of Permian and Triassic limestones and dolomites. Larger olistholites are mountain forming, such as Jebel Qamar, Jebel Kawr and others. Numerous small "exotics" may be of the same age, but most of them have not yet been studied.

Few Jurassic olistholites have been dated. A thin Bathonian clastic limestone and a Lower Tithonian calcarenite yielded microfossils. From field evidence, however, it is not clear whether the Middle Jurassic sample which is derived from a highly imbricated zone, is in fact an olistholite or belongs to the matrix rocks. The second possibility then arises as to whether the fauna could be contemporaneous or derived from older rocks. The age-restricted fauna (Bathonian) does not favour reworking, yet, it does not exclude it.

Jurassic components are common in Upper Cretaceous turbidites. This indicates that, at least locally, Jurassic carbonates existed within the Hawasina basin. The largest and probably most important olistholite of Jurassic-?Lower Cretaceous age is Jebel Agah. The litho- and biofacies of this thick, poorly-fossiliferous, laminated, marly micrite sequence with chert bands points to an outer slope environment. It differs very markedly from the age-equivalent interval of the subtidal Musandam Limestone (Ruus al Jibal unit).

From the olistholites studied, none has been dated younger than Jurassic with the exception of Jebel Agah (but most of them, however, have not been studied in detail!). Berriasian caliponellid-lithoclasts are rather common and especially Upper Barremian-Lower Albian reworked, isolated Orbitolinas and Orbitolina-limestones are frequent components in many turbidites of the Hawasina Complex. They are evidence for a widespread Lower Cretaceous marine regime at least for several strips within the westerly half of the Hawasina belt.

With one exception, Upper Cretaceous olistholites are unknown. The large Jebel Agah olistholite displays some occurrences of authigenic Upper Cretaceous sediments in normal stratigraphic, transgressive contact with the Upper Jurassic-Lower Cretaceous olistholite core. Preserved in several depressions of this core, underneath the overthrust Aptian radiolarite-shale-turbidite series, are found: Light grey and purple micrites with abundant Upper Albian-Lower Cenomanian planktonics which transgressively overlap the eroded surface of the olistholite core. In other instances, bright red and grey pelagic marls and thin limestones with coarse conglomerates near the base carry – including the matrix of the conglomerates – rich Coniacian-Santonian planktonics. This distinctly younger transgression can be observed in several places. The pebbles of the conglomerates are composed of different, yet predominant, Upper Barremian-Aptian Orbitolina limestones.

The transgressive J. Agah conglomerates and pelagic carbonates differ from the Ausaq conglomerates and marls, because a transgressive overstep is preserved in contact with the substratum; the fundamental difference in composition of boulders; the higher ages of the J. Agah pelagic marls and its higher tectonic position. Jebel Agah is an olistholite undoubtedly engulfed within the Hawasina Complex. The excellently preserved microfaunas in two different transgressive deposits are of genetic importance for part of the Hawasina Complex (see Plate I).

Igneous and volcanic rocks within the Hawasina series

Abundant pillow lavas, composed of augite-basalts with analcite and calcite filled viscles occur within many levels of the Hawasina Complex. Pillow-lavas grade laterally and vertically into tuffs, the components of which vary in size from bombs to single augite crystals. These components consist of euhedral zoned brown hornblende phenocrysts in a groundmass of euhedral brown hornblende needles, biotite and magnetite with interstitial plagioclase and chlorite. They are partly subaquatic and partly subaeric with a carbonate matrix. Within the tuffs occur hornblende basalt sills occur with xenoliths of granitic and dioritic composition (pieces of basement?). Occasionally, flows of red andesite are encountered. K-Ar data an a biotite from a tuff has given an age of 92 $\pm$ 6 m.y. The crystallinity of the illites from the sediments with which the extrusives are intercalated, indicate an anchizone metamorphism, far below the greenshist metamorphism of the monometamorphic series.

Minor serpentinite masses are imbricated between the Hawasina sediments. These chrysotile and lizardite serpentinites are surrounded by a mylonitic rock, composed of actinolite, quartz and plagioclase, or very seldom of wollastonite and diopside, pointing to a local high temperature metamorphism along the overthrust plane. Gabbro dikes within the ultrabasics are partly rodingitized with the formation of prehnite, chlorite, hydrogrossularite, idocrase and colourless diopside.

Sedimentary Environment

The predominant matrix rocks such as radiolarites, shales, micrites, turbidites and volcanics occur at all levels of the Hawasina Complex. No reliable zonation of the depositional area results, therefore, from the superposition of these rock types.

Within the matrix rocks, no fossils of shallow-marine origin occur except for the re-sedimented ones in turbidites. The authigenic fossils are restricted to radiolaria, sponge spicules, nannofossils, calpionellids and rare planktonic foraminifera in micrites. In the case of the Upper Cretaceous micrites, as well as the caliponellid-bearing pelmicrites which are both found as intercalations within radiolarite of the sequences, these mudstones might well be regarded as distal parts of the finest-grained turbidites. The lime mud could then be an allothigenic, but penecontemporaneous sediment. However, the samples examined sofar revealed no micrograding. Whether authigenic or allothigenic, this question may influence only the conclusion on the bathymetric interval. In any case, the depositional interval of the radiolarite-mudstone alternation is determined as about the carbonate compensation depth. The allothigenic fauna appears in components of turbidites as well as in olistholites. In turbidites, macrofossil debris and microfossils are redeposited according to their grain size. The youngest fossils found in turbidites are exclusively isolated forms which most probably represent part of the contemporaneous fauna. Older faunal elements are found isolated or in rock fragments.

The macro- and microfaunas enclosed in olistholites are typical shallow-water forms of Ordovician to Lower Cretaceous, but predominantly of Permo-Triassic age. The only exception is a thin sheet of Berriasian calpionellid limestones deposited in somewhat deeper water of a low energy environment. The transgressive overlapping pelagic micrites on the Jebel Agah olistholite with their abundant planktonic foraminifera also signify a low energy environment. However, they are from shallower depth of an outer neritic environment and in no way comparable with the depositional environment of the matrix rocks.

Olistholites and the part of the re-sedimented components of the turbidites are of shallow-water origin. Turbidites may contain rock-fragments of variable origin. Well-rounded boulders and the presence of carbonaceous material (rare) in some of the turbidites, as well as transgressive conglomerates on eroded rock surfaces, indicate at least local terrestrial erosion e.g. the presence of neighbouring land. In most instances, however, the normal finer turbidites consist of rather angular rock components which are derived chiefly from sedimentary rocks desintegrated to rock fragments in subaquatic conditions. Rock sequences in form of gravity slides may have been displaced into deep-water basins at different times although preferentially between the Cenomanian and Maastrichtian.

Comparisons of age-equivalent sediments show that several Cretaceous basins existed within the Hawasina belt, separated by highs which – at least partially – reached positions above sea level.

Age

The age of the Hawasina Complex is based on the fossils of the matrix, on the fossil content of the turbidite components and the olistholites.

Fossils in matrix rocks: The finding of Middle Jurassic foraminifera in a turbidite matrix in the absence of any younger form might be regarded as resedimented more-or-less contemporaneous fauna. However, micrite intercalations within radiolarite series yielded *Nannoconus steinmanni* and calpionellids from three zones (Upper *Crassicollaria* zone-Lower *Calpionellopsis simplex* zone) for samples in two locations of Al Fujairah (Muqhtaraqeh region). Unfortunately, in most instances, recrystallization of the micrites has led to a grain size coarser than the nannofossils.

Hudson et al. (1954) report *Calpionella alpina* in calcite-mudstones which occur together with radiolarites in the Hagil-plain, some 30 km north of Al Fujairah.

In both cases Upper Tithonian-Berriasian pelagic mudstone sedimentation is confirmed within the Hawasina basin even if the microfauna is slightly reworked and not strictly contemporaneous (three calpionellid zones within one sample; possibility of distal carbonate mud-turbidites within the radiolarite basin).

With regard to the age of the micrite-radiolarite alternations, other findings in Al Fujairah are of interest. Upper Cenomanian-Lower Turonian micrites are intercalated in green and red radiolarites and single layers of a few cm- to m-thick sequences of thinbedded micrites occur. This alternation is interrupted by turbidites of up to 10 m thickness with boulders of up to cubic metre-size. This series of radiolarite–micrite–turbidites, one of the typical subunits of the Hawasina Complex in Al Fujairah, may reach 300 m. In most cases, it is more or less disturbed tectonically. In Wadi Shakh, however, the bedding of the whole sequence is unusually undisturbed (Fig. 6).

The thin micrite intercalations contain a rare but diagnostic planktonic microfauna with thin delicate tests of ?Upper Cenomanian-Lower Turonian age (*Rotalipora* sp., *Praeglobotruncana* sp., *P. stephani*, *Hedbergella* sp., *Whiteinella* sp., *Heterohelix*).

The intercalated turbidites contain limestone boulders, rarely fossiliferous, of different ages; Jurassic to Aptian could be determined. In the turbidite matrix occur isolated benthonic larger foraminifera (*Praealveoline cretacea*, *Ovalveolina* sp.) and planktonics (*Rotalipora apenninica*). These forms are of Cenomanian-?Lower Turonian age. No younger form has been found in this series. They may be regarded as approximately contemporaneous or slightly older than the micrite fauna. The mixture of nonlithified platform and slope sediment with clastic material of older rocks requires displacement into the radiolarite basin by turbidites.

Olistholites are of Ordovician to Lower Cretaceous age, with the exception of Jebel Agah which reveals transgressive pelagic Upper Albian-Lower Cenomanian sediments at one locality and Coniacian-Santonian ones at several other localities on the Jurassic-Lower Cretaceous olistholite core.

The largest (mountain-size) olistholites are composed chiefly of Permo-Triassic carbonates (see HUDSON et al. 1954; WILSON 1969).

With respect to a possible zonation of the Hawasina belt, it needs to be emphasized that the monometamorphics are a former radiolarite-shale series with extremely rare carbonates. The cooling age of the metamorphism could be dated as 86 $\pm$ 5 m.y., e.g. Upper Turonian–Lowermost Santonian. Since the metamorphics tectonically overlie the Hawasina complex, the position of this former radiolarite basin was east of the one occupied by the nonmetamorphic Hawasina sediments.

Zonation

The superposition of the subunits which build up the Hawasina Complex and the Metamorphics allows the following lateral zonation of the Hawasina basin from E to W:

1. Carbonate-free radiolarite-shale belt. Age of sediments unknown, assumed to be Jurassic-Lower Cretaceous. Metamorphosed in Upper Cretaceous time.
2. Belt of reduced carbonate content in radiolarites. Not metamorphosed. Micrite intercalations dated so far are Upper Tithonian–Berriasian.
3. Radiolarite-shale-turbidite belt with Carbonate platform highs delivering turbidites into radiolarite basins. Oldest turbidite dated carries isolated uniform Middle Jurassic shallow water foraminifera (but reworking cannot be excluded beyond doubt). Most of these series carry, in particular, Barremian–Aptian–Lower Albian Orbitolinas and macrofossil fragments. Rock fragments in turbidites are of Permo-Triassic-Lower Cretaceous age. No fauna younger than Albian has hitherto been encountered.
4. Radiolarite-micrite-turbidite belt. Thick turbidites derive from rising platform highs, micrites alternate with radiolarites. Micrites carry planktonics of ?Upper Cenomanian-Lower Turonian age. Matrix of turbidites with Cenomanian-?Lower Turonian benthonics and planktonics.
5. Olistholite belt (of Jurassic Lower Cretaceous slope carbonates) with transgressive Upper Albian pelagic and transgressive Coniacian-Santonian pelagic sediments (e.g. J. Agah).
6. Belt of pelagic Campanian carbonates and coarse conglomerates. This basin strip is placed on the edge of the Arabian platform, in the intermediate zone between the Hawasina belt and the rising part of the Musandam platform (Ruus al Jibal unit) which, together with the advancing Hawasina front, deliver the material of the coarse conglomerates.
7. Belt of Flysch-like deposits in an Upper Maastrichtian-?Paleocene foredeep along the western front of the North-Oman mountains (Al Fujairah–Ras al Khaimah). Several thousand m-thick clastic-pelagic series are encountered (subsurface).

Within the above succession, volcanic rocks occur mostly in zones 1–4.

Comparison with the Jebel Akhdar and Sayh Hatat areas

The succession of Precambrian core–Permian-Cenomanian carbonates–Hawasina series–Semail ophiolites is regarded by several authors as a single normal stratigraphic Precambrian-Maastrichtian sequence (Morton 1959; Tschopp 1967; Wilson 1969). Since these authors agree with respect to the principal questions, we only quote Wilson (1969), who discusses the pertinent points at some length. Wilson's interesting conclusion results in an evolutionary scheme of the Oman mountain building which is claimed to be based mainly on paleontological and sedimentological data.

The principal questions which play a key-role in his theory are the following: Evidence for the vertical "normal stratigraphic" succession of the Precambrian section–Musandam Limestone–Mutih formation–Mi'aidin Limestone–Hawasina radiolarites–Semail ophiolites is given by the Mi'aidin section in the Jebel Akhdar region. Of special interest is the boundary problem between the Mutih formation and the Mi'aidin Limestone.

There is good evidence and full agreement among all authors for the Upper Santonian-Campanian Mutih formation resting transgressively on the iron oolite capping the Cenomanian Wasia formation. Obviously, it is an age-equivalent unit of the Aruma-Shale in the desert foreland which also unconformably overlies Cenomanian beds. Most probably it is also the equivalent of the Ausaq pelagic marls and conglomerates in Al Fujairah, as well as the Fukhairi beds in the Hagab area. Both are Campanian formations. They are, however, tectonically truncated from the Musandam substratum.

There is neither fact nor argument against a stratigraphical contact between the Musandam Limestone and the Campanian Mutih formation. The Mutih formation is the youngest stratigraphic unit of the autochthonous Arabian platform sedimentary cover in the Jebel Akhdar area.

Some of Wilson's principal arguments, which are based almost exclusively on the key section of the Wadi Mi'aidin, are:

1. There is a normal sedimentary transition between the Muti formation and the overlying 500 m thick Mi'aidin Limestone unit.
2. A sedimentary transition also exists between the Mi'aidin Limestone and the higher radiolarian chert beds.
3. Within the Mi'aidin Limestone, Wilson describes:
   - a monogenetic reworked Orbitolina microfauna in turbidites at base of the formation;
   - a Lower to Middle Jurassic (by checking his faunal list p. 638) microfauna reworked in turbidites above the Orbitolina-bearing beds;
   - a Limestone-cobble with a Permian *Neoschwagerina* and another one probably with a Cenomanian *Praealveolina cretacea*. For these findings, the stratigraphic level within the Mi'aidin Limestone is not indicated.
4. The microfaunas reworked into turbidites are claimed to represent an inversed sequence, the younger forms being at base.
5. The microfaunas are said to derive from older rocks only, by washing action of turbidites. Turbidity currents – in general – are mentioned as a "powerful erosional force". The age of the Mi'aidin Limestone (p. 638) "must clearly be younger than the youngest of the derived fauna which it contains" (Cenomanian *Praealveolina*).
6. No indigeneous fauna has been found in the Hawasina Group by Wilson. The age of the Hawasina Complex and the Semail Ophiolites therefore is given by the Campanian Muti formation at the base and by the Upper Maastrichtian limestones which transgressively are laid down, after an erosional period, onto the completed nappe structures of the Oman mountains. Thus, during the time interval Upper Campanian–Lower Maastrichtian the following had to occur: the generation of the Mi'aidin Limestone, Hawasina radiolarites, turbidites and volcanics; the emplacement of

the olistholites, and the generation of the Semail Ophiolites as well as the emplacement of all these units to the final superposition.

7. "One might expect contemporaneous pelagic or shallow-water fauna to have been swept in from the basin shelf, together with the reworked faunas from older rocks" but "there is no evidence of washed-in, datable, contemporaneous macrofauna or microfauna" (p. 641).

Our comments to these points of Wilson's are briefly:

1. As to the question of stratigraphic or tectonic contact between the Muti formation and the Mi'aidin Limestone, we may quote Wilson (p. 640): "The basal contact of the Wadi Mi'aidin Limestone on the Muti shale could form a slide plane, but there is no concrete evidence that the Wadi Mi'aidin Limestone has had significant horizontal displacement:...".
2. Sedimentary transitions of this kind are also found in Al Fujairah (Wadi Shakh). In addition, the planktonics found there are never younger than Cenomanian–Lower Turonian. Indigeneous fauna younger than Cenomanian are also missing in the Mi'aidin Limestone – radiolarite section.
3. Orbitolina at base of the Mi'aidin Limestone:
   Mr. Wilson was kind enough to have the critical thin sections examined by specialists. All forms found are exclusively "*Dictyoconus cayeuxi* LUCAS and *Spiroconulus perconigi* n.gen. n.sp. (ALLEMANN and SCHROEDER [in press]) both of Middle Jurassic age. Due to the importance of this sample, the thin sections were examined by W. Maync (Bern), L. Hottinger (Basel) and R. Schroeder (Frankfurt) who confirmed without exception the determination as uniform Middle Jurassic fauna, with "*D*" *cayeuxi*.
4. According to the above determination, there is no reverse faunal sequence from base to top of the Mi'aidin Limestone turbidites. Further, the available data indicate that no normal faunal succession exists.
5. We experienced elsewhere the fact, and are far from denying it, that even well-preserved isolated microfossil specimens of different (or, in cases, the same) age, may be found reworked in turbidites (although not washed out of the rock by turbidity action proper). In case of some Hawasina turbidites in Al Fujairah, however, the pelagic microfauna found in micrite intercalations of radiolarites are of about the same age as the youngest, isolated planktonics and benthonics of the intercalated turbidites (?Upper Cenomanian–Lower Turonian against Cenomanian–?Lower Turonian).
6. Indigeneous microfaunas in different micrite intercalations of radiolarite sequences in Al Fujairah reveal different radiolarite ages of at least Upper Jurassic–Lower Turonian.
7. see 6 and the chapter on the Hawasina Complex.

We therefore conclude:

The youngest part of the Wadi Mi'aidin Limestone section – whether it is a single or a composite unit – is of about Cenomanian age. No younger fauna has been found so far. This unit overlies the Campanian Muti shale with a thrust contact. The Muti formation has to be regarded as youngest unit of the autochthonous Arabian platform sedimentary cover.

The Campanian Muti shale is overlain by the complexly imbricated Hawasina series of different age and lithology. Only radiolarite-turbidite units which are older than Lower Turonian overlie the Muti shale. The autochthonous Campanian section is overthrust by older Hawasina units.

If we reconstruct the lateral succession of the different sedimentary strips in the Hawasina basin according to their tectonic superposition, the older, radiolarite-rich series are found in the east, the more carbonatic and successively younger ones are more westward in direction toward the Arabian platform (Plate I).

Metamorphic rock series

HUDSON, BROWN and CHATTON (1954), MORTON (1959) and GREENWOOD and LONEY (1968) interpreted the metamorphic series as transformed equivalents of the

Hawasina beds. TSCHOPP (1967) and WILSON (1969) take into consideration a possible correlation of the metamorphic rocks with the Precambrian Sayh Hatat metamorphics. According to Morton, the Semail magma metamorphosed the underlying Hawasina series, this being indicated by an increase in the grade of metamorphism of the Hawasina series towards the Semail peridotite. The contact of the Hawasina and the metamorphic series, however, is a thrust contact. Morton's statements may have found their source in the fact that between the Semail ophiolite nappe and the Hawasina series, slabs of metamorphic rock series have been tectonically incorporated.

During our present survey it became evident that the metamorphic rocks had to be subdivided into two completely different series: 1. the monometamorphites, metamorphosed solely in greenschist facies, and 2. the polymetamorphites, which underwent an early metamorphism in the amphibolite facies and a later one in the greenschist facies. In between these metamorphisms a magmatic phase occurred.

Monometamorphic series

Most abundant are quartzitic rocks. They range from almost pure quartzites, quartzite schists, quartz-sericite schists, quartz-biotite shists to phyllites. A Rb-Sr total-rock age of a quartz-phyllite has given a maximum sedimentation age of 200 m.y., which makes this series and the Hawasina series equivalent in age. Also metamorphosed pillow-lavas, hyaloclastites (with relics of brown glass shards), gabbros, basalts (containing crossite) tuffites with associated stilpnomelane-quartzites are abundant. Serpentinite with chrysotile and brucite as main constituents is sometimes encountered. Less important are laminated calcareous quartzites, interlayered with chlorite-epidote schists, which were probably derived from calcareous and dolomitic shales.

The rocks show a strong, tight, isoclinal folding with an axial plane schistosity more or less parallel to the original bedding. During a second phase, large folds with some major anticlinal and recumbant structures originated.

The mineral assemblages are characteristic for the quartz-albite-epidote-biotite subfacies of the greenschist facies. The age of this metamorphism is given as 85 ± 5 m.y. by an K-Ar dating of a muscovite from a muscovite-spessartite-quartz noddy vein.

Polymetamorphic series

The polymetamorphic series are mainly composed of diopside quartzites, muscovite quartzites and banded amphibolites composed of labradorite and brown-green hornblende. Also some massive garnet amphibolite occurs. Occasionally spectacular banded calc-silicate marbles composed of diopside, grossularite, wollastonite, orthoclase and calcite are encountered. Also, a large mass of hypersthene quartzite containing poikiloblastic hypersthene in crystals up to 100 cm, discordant in the banded diopside quartzites and amphibolites, was found. The mineral assemblages: woll + diop + calc $\pm$ K-spar; diop + gross + qz $\pm$ sphene; diop + woll + calc + gross; gross + diop + K-spar + calc; K-spar + diop + qz $\pm$ sphene; Kf + phlog + calcite and qz + hyp are characteristic for a metamorphism in the upper amphibolite facies. It is difficult to estimate the H_2O/CO_2 ratio of the original fluid phase, as no invariant assemblages were detected. The presence of grossularite indicates, according to the experimental data of STORRE (1970), an appreciable amount of H_2O.

As no suitable rocks were sampled, the absolute age of this series is not known. They are possibly equivalent to the Precambrian clastic series of Jebal Akhdar and Sayh Hatat (TSCHOPP 1950). During a younger metamorphism in greenschist facies the rocks were partly transformed into mineral assemblages with actinolite, epidote, chlorite, albite and biotite and deformed into steep isoclinal folds. A K-Ar dating on a biotite has given 83 $\pm$ 5 m.y. as cooling age for this later metamorphism. Between the two metamorphic phases, irregular, fine-grained garnet granite veins and mineralized quartz veins were intruded.

Semail Ophiolites

The extrusive and intrusive basic and ultrabasic rocks in the Oman mountains, together with some granite dikes and granodiorite intrusions, have been referred to by LEES (1928) as the "Semail Igneous Series". These rocks constitute most of the Oman mountains south of a line running from Diba to Wadi Saram.

The northern part of the Oman mountains consists mainly of ultrabasic and basic igneous rocks.

In the southern part, on the territory of Muscat–Oman, a considerable amount of the Semail ophiolite suite is represented by dolerites and basic effusives (REINHARDT 1969). The approximate thicknesses of these zones are: Peridotite complex 4–5 km; layered zone 50 m; gabbro complex 2.5–3 km; dolerite dikeswarms and pillow lavas 4 km.

Peridotite and Serpentinite complex

The ultramafic rocks vary in mineralogical composition. The most common types are dunite with more than 90% olivine and harzburgite with less than 90% olivine. Orthopyroxene usually consititute the rest of the rock. Minor rock types include feldspar peridotite with a varying amount of basic plagioclase; chromitite with about 90% of chromite and pyroxenite, with more than 90% orthopyroxenes plus clinopyroxenes. These percentages are rather arbitrary since all transitions can be observed.

The olivine, which generally is present as anhedral, medium sized grains, has throughout the whole peridotite complex a composition of $Fo_{90 \pm 0.5}$. It is present as inclusion in chromite and orthopyroxene. Orthopyroxene occurs in rather course anhedral grains that are sometimes bent and have a composition of Mg_{89-90} $Fe_{8.5-9}$ $Ca_{1.5-2}$ with an Al_2O_3-content of 2–2.5 weight%. They often contain fine clinopyroxene exsolution lamellae.

The rather scarce, fine-grained clinopyroxenes in the harzburgites have the same composition as those in the lherzolitic rocks and pyroxenites: Ca_{44-48} Mg_{38-53} $Fe_{3.5-6}$ and Al_2O_3 2,5–4,0 weight%. Chrome spinel is present in anhedral grains, with colours varying from gold-yellow to brown, indicating different chromium content.

Harzburgites account for the main mass of the peridotite-serpentinite complex and are often interbanded with dunites.

Dunite is found in bands of greatly varying thickness, pinching out and passing into harzburgite; no dunite band can be followed over a great distance. In general, chromite bodies are enclosed in dunite. Cross cutting dunite dikes show no chilled contacts.

Chromitite is generally found as stringers of tabular and pod-like bodies, more or less parallel to the contact of the gabbros. Corroded textures of chromite grains in an olivine or clinopyroxene matrix are common and rarely in an anorthite matrix.

Lherzolite peridotites are rather rare in general and no systematic pattern of their occurrence could be determined.

In the uppermost zone of the peridotite-serpentinite complex – near the layered zone – *feldspar peridotites* occur in streaks and diffuse bands. Apart from the very basic plagioclase (An_{88-93}) which is often strongly altered the mineralogy is identical with the harzburgites and lherzolites.

Among the *pyroxenites*, the orthopyroxenites are the most common. Clinopyroxenites are mostly found in the upper part of the peridotite-serpentinite complex.

The sharp boundaries of the pyroxenite dikes against the host rock indicate an advanced consolidation of the latter.

In the deeper portions of the peridotite-serpentinite mass, banding, sometimes on a microscopic scale, can be observed: thin layers of fine-grained (mylonitized!) olivine aggregates are still preserved alternating with completely serpentinized layers; layers of antigorite alternate with chrysotile layers. In one case, newly-formed olivine was observed together with antigorite. Chlorite and actinolite are also common in these rocks. The banding is caused by the overthrusting at the base of the large Semail nappe.

Serpentinization

On the whole the degree of serpentinization is very low with Chrysotile (Clino- and Ortho) and lizardite as main minerals. Talc is found separating enstatite from lizardite, indicating a gradient in the chemical potential of H_2O.

Layered Zone

The layered zone marks the boundary between the peridotite-serpentinite complex and the gabbro complex. The alternation of dark ultrabasic and light-coloured basic rocks is very striking (Fig. 10). The thickness of the layered zone is variable with 30–40 meters as an average value.

The thickness of a single layer varies from a few millimeters to several tens of meters. Sometimes individual layers can be followed for several hundred meters but more often they pinch out after a few tens of meters. The layers may be sharply defined but gradual transitions from feldspar peridotite to olivine gabbro may also be observed. In Fig. 10, the amount of olivine in the gabbro increases downward, resulting in a band of feldspar peridotite. Apart from these rather regular layered sequences, feldspar peridotite bands are quite often dissolved into "Schollen" floating in a gabbro matrix. These "Schollen" are mostly aligned parallel to the general layering of the layered zone.

The composition of the rocks in the layered zone is not sharply defined, as the ratio olivine-clinopyroxene-plagioclase may vary almost continuously from one of

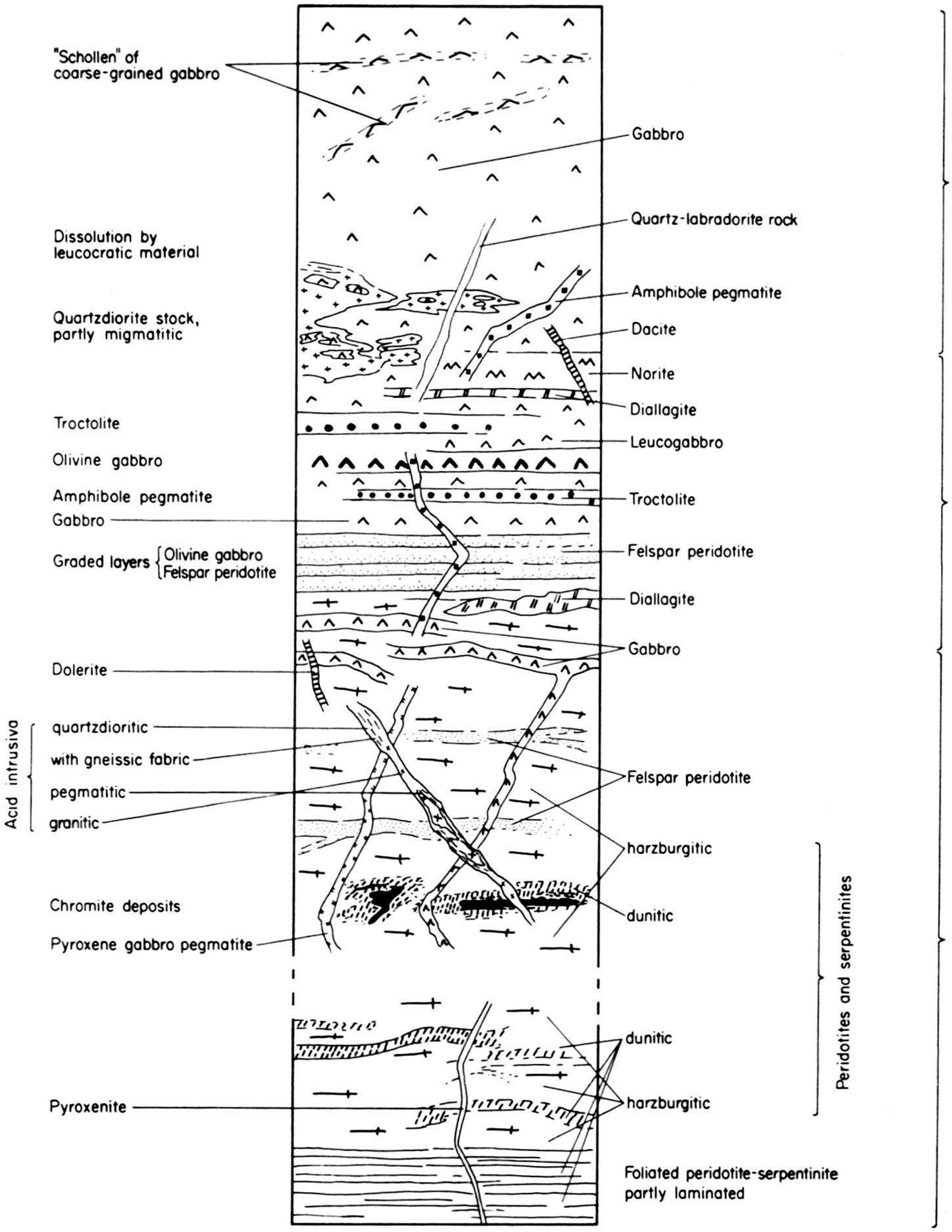

Fig. 9. A schematic section through Peridotite-Serpentinite complex, layered zone and Gabbro complex, North Oman.

Fig. 10. Layered zone. Within the layers from top to bottom continuous transition of olivine gabbro to feldspar peridotite by increase of olivine content. Wadi Farfar (Al Fujairah).

the pure minerals to mixtures of all three. In addition, orthopyroxene, chromite and magnetite may be primary constituents. Of the various rock types as e.g. feldspar peridotites, olivine gabbros, troctolites, leucogabbros, anorthosites and diallagites, only the first three are described below. As far as determined, the chemical variations of the principal minerals are very small. The variation of rock types is mainly the result of a variable cumulation of olivine in a matrix of other mineral components.

The observed accumulation of mafic minerals cannot be the result of flow differentiation. This principle can only be applied to a single channel of an upward streaming flow. In a horizontal flow no such concentration occurs besides gravitational settling. Multiple concentrations lying side by side are hardly possible. For every single band of concentrated mafic minerals a separate pipe with consolidated walls would have to be claimed.

In the *feldspar peridotites*, olivine Fo_{85} is or has been the main constituent, and is more iron-rich than the olivines in the peridotite-complex. Olivine of a composition Fo_{90-92} is quite often transformed into a mixture of prehnite, clinozoisite, pyrophyllite, hydrogarnet and idocrase, often arranged in concentric zones as described in detail by REINHARDT (1969). These reactions were interpreted by this author as autometamorphic. The influence of a possible regional metamorphism on the Semail ophiolites should, however, not be ignored. Diopsidic augite Ca_{43-45} Mg_{50-51} Fe_{5-6} generally present, is rather fresh.

Troctolites

are composed of partly serpentinized olivine (Fo_{86-89}) and a groundmass of plagioclase (An_{80-85}) partly altered into pyrophyllite. The anorthite content of coarse plagioclase crystals (An_{82-90}) may vary considerably, and it is the only mineral which forms subhedral grains. Often the olivine (Fo_{85-87}), present in rounded corroded grains and sometimes showing cumulus textures, is slightly serpentinized by forming talc and chlorite when in contact with plagioclase grains.

Part of the augite is replaced by greenish actinolitic hornblende.

Gabbro complex

The gabbro complex conformably overlies the peridotite-serpentinite complex. It is mainly exposed in the southern and eastern part of Al Fujairah. In the gabbro complex, layering and banding can frequently be observed. This layering is, however, much less persistent than in the layered zone: The layers can only be followed over a few meters, and their orientation varies considerably. Often a kind of migmatic structure can be observed with differing orientation of the layered gabbro-blocks in a matrix of a chemically similar but younger gabbro.

These gabbros are quite often dissolved by leucocratic material consisting of quartz diorite or leucoquartz diorite. Quartz diorite also occurs in small stocks within the gabbro complex.

In addition to plagioclase and augite the gabbros generally contain varying amounts of olivine, orthopyroxene and ilmenite. Green hornblende may partly or completely replace the clinopyroxene resulting in hornblende gabbros. Some of these hornblende gabbros are fine-grained and cross-cut the normal gabbros. On the whole, the mean grain size decreases from bottom to top of the gabbro complex. Some important gabbro types are described below although transitions occur between these types.

In the olivine gabbros, anhedral to subhedral twinned bytownite An_{82-87} constitutes 50% of the rock. Diopsidic augite $Ca_{45-47}\,Mg_{47-49}\,Fe_{5-6}$ shows Schiller-effects. About 25% olivine Fo_{81-87} composition is present and is only slightly serpentinized. Accessory magnetite and pentlandite can be observed.

Main constituents of the *norites* are plagioclase An_{85} and orthopyroxene $Mg_{80}\,Fe_{16}\,Ca_5$ showing a faint reddish-brown pleochroism and containing exsolution-lamellae of clinopyroxene. Some augite and accessory ore minerals are present.

The *gabbros* are in general medium-grained with subhedral Plagioclase An_{85}–An_{90} and anhedral Augite $Ca_{42-43}\,Mg_{-48-50}\,Fe_{7-10}$. Patch-like replacement by brown hornblende occurs. Some actinolitic amphibole in needle-like crystals is frequently found as an alteration product of augite.

Dike rocks and minor acid intrusions

Dike rocks are very common in the peridotite-serpentinite complex as well as in the gabbro complex. Their composition ranges from pyroxenitic to granitic, including all transitions. In the following, a short description of the mode of occurrence and mineralogy shall be presented. For more details, expecially of the basic dikes, the reader is referred to the papers of GREENWOOD and LONEY (1968) and REINHARDT (1969).

From the layered zone, *gabbro dikes* cut down into the peridotite-serpentinite complex with a direction more or less perpendicular, but never parallel to the layering of the layered zone. Near this zone, the dikes may be several meters thick showing irregular shape. Farther away from the layered zone, they appear as sharp-cutting 30 cm wide dikes. The composition of the gabbro dikes is equivalent to the gabbro in the layered complex.

In the peridotites and serpentinites *diallage-gabbro pegmatite dikes* show knife-sharp contacts against the host rock, whereas in the gabbros, their boundaries are more irregular. Porphyritic crystals of subhedral coarse-grained augite (Ca_{45} Mg_{45} Fe_{10-12}) and bytownite (An_{85}–An_{90}) occur in a matrix of fine- to medium-grained bytownite and augite. Some transformation into actinolite, chlorite, pyrophyllite and calcite has taken place.

In the upper portions of the peridotite-serpentinite complex, in the layered zone and in the lower part of the gabbro complex, *hornblende-gabbro pegmatite dikes* are common. They are composed of subhedral green hornblende and anhedral labradorite.

Occasionally in the peridotite complex, but mainly in the upper part of the gabbro complex, *dolerite dikes* are found. Chilled margins are the rule. They are fine to medium-grained, with an ophitic texture of andesine-labradorite laths. Between these feldspar laths mainly anhedral augite (Ca_{45} Mg_{45} Fe_{10}) and brown Ti-hornblende occur. Some biotite and ilmenite are also present as primary minerals.

Biotite quartz diorite dikes, granite dikes and granite pegmatites

The upper part of the peridotite-serpentinite complex, immediately below the layered zone, is in many areas characterized by the presence of abundant irregular dikes and bands of granitic and quartz-dioritic material. They can be several meters wide and may in some cases be traced over a few kilometers, but mostly they are truncated after a few tens of meters. The biotite-rich dikes, of almost quartz dioritic composition, contain sheets pegmatitic intrusions, which often fragment the biotite-rich quartz diorite into blocks.

The biotite-rich quartz diorites are mainly composed of subhedral plagioclase with an oligoclase-andesine core and a more albite-rich rim. Green-brown biotite is the main mafic constituent.

Granite pegmatites consist of coarse-grained antiperthitic alkali feldspar, containing graphic intergrowths of quartz, as main constituent and extremely varying contents of muscovite, tourmaline, garnet, lepidolite, zircon, hematite and occasionally lazulite. Fine-grained secondary green biotite, muscovite, albite and quartz occur between the strongly bent feldspar crystals.

K-Ar age determinations of a muscovite and a lepidolite from two pegmatites have given ages of 87 $\pm$ 6 m.y. and 85 $\pm$ 8 m.y.; resp. and a Rb-Sr age of 84 $\pm$ 3 was obtained for the lepidolite.

Stocks and dikes of hornblende quartz diorite

Within the lower part of the gabbro complex numerous small stocks of hornblende-quartz diorites were encountered. In Wadi Liban a larger "stock" with a diameter of about a kilometer and a thickness of about 100 meters occurs. Here the roof as well as the bottom of this "stock" are exposed, and it can be seen how fragments of gabbro, constituting the roof and floor, have been loosened and now float within the quartz diorite.

Some veins of quartz diorite penetrate also into the layered zone and some dikes of hornblende quartz diorite composition are even found in the uppermost part of the peridotite-serpentinite complex.

In thin sections these rocks contain about 50% of subhedral and euhedral plagioclase with oligoclase-andesine composition, with a centre being more basic than the rim. Anhedral quartz constitutes about 30–35% of the rock. The main mafic constituent is a bluish-green actinolitic hornblende, which may enclose a core of colourless diopsidic augite. Accessory green biotite, apatite, pyrite and magnesite are common. Epidote/clinozoisite, penninic chlorite and green biotite are present as secondary minerals. Occasionally all transitions to quartz-free diorite are encountered.

Petrogenesis of the ophiolite suite

The gradual transition from the peridotite complex over the layered zone into the gabbro complex indicates a close genetic relationship. This is supported by the temperature-pressure conditions derived from the clinopyroxene compositions and the mineral assemblages. Using BOYD and SCHAIRER'S (1964) solvus for the miscibility between orthopyroxene and clinopyroxene in the system $MgO-SiO_2-CaO$, the composition of the clinopyroxenes in the ultramafics of the peridotite complex give an equilibrium temperature of about 1000 °C. In Figure 11, the composition of these pyroxenes, coexisting with orthopyroxene and an Al_2O_3-rich phase, is plotted in the diagram by O'HARA (1967–1970) where the pressure-dependant solid solution of Al_2O_3 in clino-pyroxenes is taken into account. According to this diagram, the Oman peridotites equilibrated at very low pressures and temperatures of about 1250 °C near the

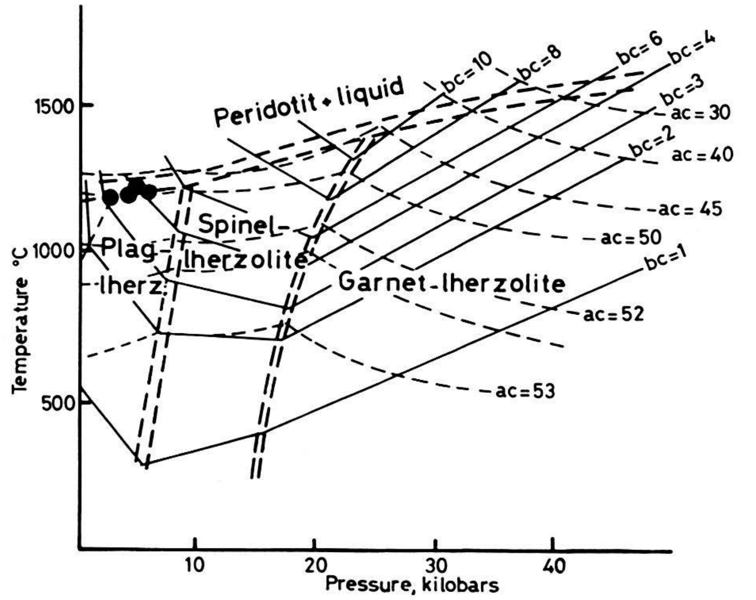

Fig. 11. Schematic diagram of stability fields for peridotite compositions. (Grid after O'Hara 1967.) Black dots: Composition of clinopyroxenes coexisting with orthopyroxenes in peridotites of North-Oman mountains.

solidus. The overlying gabbros must have crystallized under similar physical conditions. The gabbros, dolerite dike swarms, diabase sills and pillow lavas, mainly exposed in South-Oman (REINHARDT 1969) are also closely related and probably crystallized at different levels from the same basaltic magma.

A plot of chemical analyses in an AFM-diagram (Fig. 12) shows a similar trend as the Papuan and mediterranean ophiolite series (DAVIS 1971). Basalt fractionation trends of Skaergaard and Hawaiian lavas are much more pronounced than in the ophiolite series. This is probably due to the fact, that the ophiolite series did not develop from a single magma reservoir, but from a basaltic magma generated more or less continuously from the mantle. The granitic rocks from the Oman ophiolites, plotting almost in the alkali apex of Figure 12 represent a more Na and K enriched fraction than the granodiorites found so far in ophiolite series.

According to the experimental results of GREEN and RINGWOOD (1967) and O'HARA (1970) such a basaltic magma can be generated by partial melting of a peridotite with pyrolitic, spinel-lherzolitic or garnet-lherzolitic composition. After the basaltic magma has been formed and "pressed-off", harzburgite and dunite remains. The ratio of ultrabasic and basic rocks (assuming that only a part of the residue of ultramafics was sheared off in the ophiolite nappe) and the low Al, Ca and K contents of the harzburgites and dunites can be brought into accord with such a model.

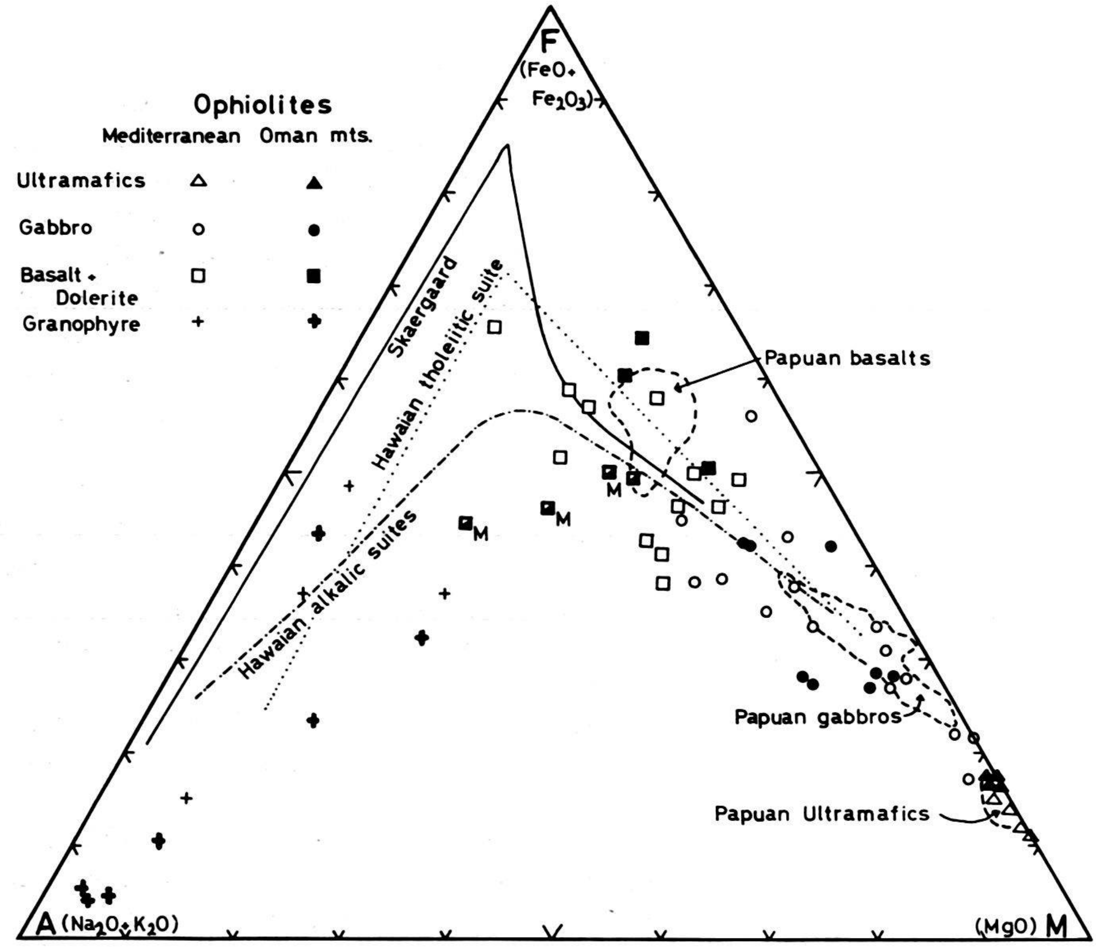

Fig. 12. Comparison of alpine ophiolite compositions with some non-organic magmatic differentiation series. M = Metamorphic basalts and pillow-lavas within the monometamorphic series.

WILSONS's (1969) interpretation of the whole Semail ophiolite as autochthonous, regarding as extrusives both the basic igneous as well as the ultramafics, must be disregarded in view of experimental petrological and field evidence. Ultrabasic lavas need temperatures of at least 1100–1200 °C which, together with their huge thickness, gives an enormous heat capacity, which would be capable of producing a very large contact aureole. No such contact aureole is observed around the Oman peridotites. On the contrary: the sediments at the base of the ophiolite nappe are completely unmetamorphosed and the lowest part of the peridotite complex shows strong tectonic laminations.

Neoautochthonous Sediments

Nomenclature: Neoautochthonous sediments are post-orogenic, laid down unconformably onto nappes or imbricated structures after their final emplacement on an autochthonous substratum (see also RIGO DE RIGHI and CORTESINI 1964).

Maastrichtian: In the Oman mountains, Upper Maastrichtian marine shallow-water limestones (in cases with a very coarse transgressive boulder bed a the base) overlie with occasionally a strong angular unconformity, either Hawasina sediments or else the Semail ophiolite nappe (Plate I). There is unambiguous accordance among all investigators about this fact (LEES 1928; GLYNN JONES in HUDSON et al. 1954; MORTON 1959; TSCHOPP 1967; WILSON 1969). Excellent outcrops reveal this transgression onto the serpentinite front e.g. in the J. Faiyah- J. Mulayhah area. A good account of the fauna has already been given by Glynn Jones in HUDSON et al. 1954. *Siderolites calcitrapoides*, *Orbitoides media*, *O. apiculata*, *Lepidorbitoides socialis*, *Omphalocyclus macroporus* and *Loftusia* farther south, represent a faunal association which is restricted – worldwide – to the Upper Maastrichtian. This Upper Maastrichtian transgression onto the completed nappe pile of the Oman mountains is observed on both sides of the mountain chain. It proves beyond doubt that there is but one single diastrophic event which formed the Oman mountain structural skeleton, in pre-Upper Maastrichtian time. Compared with this event, all Upper Maastrichtian-Tertiary tectonism hardly affected the structural style of the mountains (mainly slight folding and partly severe faulting in the desert foreland and final uplift of the axial mountain region).

The youngest beds incorporated in the nappe building below the undisturbed Upper Maastrichtian cover are Campanian (–? Lower Maastrichtian) pelagic sediments. This dates the paroxysmal orogenic movement rather precisely as Upper Campanian–Lower Maastrichtian. After emplacement of the highest Semail nappe unit, a short erosional phase of the axial region took place (rounded serpentinite boulders in transgressive Upper Maastrichtian beds).

In contrast to the importance of the Maastrichtian events, the Tertiary–Quaternary is of no special interest with respect to the discussion of the mountain area proper. The following data may suffice:

On both sides of the mountains, Paleocene is found disconformably on Maastrichtian.

Eocene, locally Oligocene and few Miocene outcrops complete the Tertiary section west of the mountains. In the Oman Gulf area, Tertiary becomes more clastic basinwards. No Tertiary rocks are found within the mountain area (Plate I, Upper Maastrichtian–Tertiary).

Plio(?)-Pleistocene terrace material is widespread in the central valleys of the mountains. Several terrace systems exist. Along the Oman Gulf coast, Pleistocene marine terrace remnants have been lifted sub-recently several tens of meters above sea level.

Along the western mountain front, the Semail peridotites and part of the Musandam Limestone front are covered by birbirite (brown chert) (p. 660) at the base, and capped by white dolomite and fluviatile conglomerates. The white dolomite of 1–2 m seems to be of pure chemical origin. The fluviatile boulder beds, surpassing 20 m thickness, contain a dolomitic matrix near the base. These dolomites and conglomerates are also found as erosional remnants in some of the deeply incised Ruus al Jibal valleys.

STRUCTURE

The Oman mountain area may structurally be subdivided into 6 main units:

1. Sedimentary Cover of Arabian Platform in Jebel Akhdar and Sayh Hatat

The autochthonous-(?)parautochthonous Precambrian-Upper Cretaceous sediments form a thick gently folded and faulted sheet. This unit is exposed in the core of the domal uplifts mentioned above. It is not certain whether this sedimentary sheet is in situ or slightly displaced to the west, since the Precambrian crystalline basement is not exposed.

2. Ruus al Jibal Unit

It forms a huge parautochthonous thrust sheet of over 40 km width. The thickness of its Permian-Lower Cretaceous carbonate section is nearly 4000 m. This overthrust slice is a marginal strip cut out of the Arabian sedimentary platform which correlates well with the J. Akhdar and Sayh Hatat section (Fig. 1, 2, 7).

The dominant internal structural features of the Ruus al Jibal thrust unit are N-S folds, high-angle tear faults of several directions and low-angle thrust faults in the western half of the unit (Figs. 2, 8).

A number of thrust sheets are developed along the western mountain front. The direction of movement is clearly from E to W. The westernmost frontal sheet reveals a slightly W-dipping thrust plane. The sheet itself resembles the upper limb of a recumbent fold, with the inverse limb truncated by an axial thrust plane. The frontal portion, including the youngest Cretaceous sediments, is vertical or overturned and causes a sharp cliff-like western mountain border (Fig. 7).

The frontal upper limb of the semi-recumbent thrust fold of the Ruus al Jibal unit overrides Hawasina radiolarites almost horizontally. This overthrust is clearly exhibited in the famous Hagil window east of Ras al Khaimah. The net slip along the thrust plane is more than 4 km. For details, see the important paper by Hudson et al. (1954). The frontal fold of the Ruus al Jibal unit can be followed from the Hagab area down to the southern tip of the unit (Fig. 2, 7, 8).

Permo-Triassic beds line the eastern shore of the Oman Gulf. Their structural position illustrate primarily a considerable displacement of the Ruus al Jibal unit along thrust planes and, secondarily, a respectable piercing through and subsequent thrusting over the thin westernmost part of the earlier displaced Hawasina slide-mass (Plate I, Lower Maastrichtian).

There is, however, no evidence of the unit being a rootless nappe structure. It is considered to be an upthrusted slice from the edge of the Arabian platform (Plate I).

3. Hawasina Complex

This structural unit of the first order overlies with a thrust contact the $\pm$ autochthonous sedimentary cover of the Arabian platform in the J. Akhdar and Sayh Hatat area as well as the upthrusted para-autochthonous Ruus al Jibal unit (Plate I). It is in turn overthrust by a metamorphic series or by the Semail ophiolite unit. The Hawasina Complex is a tremendous pile of small and large lenses and sheets of different sedimentary and volcanic series. The single sheet varies in size and internal structural feature. Multiple repetitions of thin monoclinal sheets built up by basinal sediments alternate with thin to mountain-size olistholites of shallow marine sediments.

Successions with undisturbed bedding may alternate with sheets which show extremely violent small-scale folding. Both types vary from metre-thick lenses to several hundred metre-thick units.

The tectonic sheets are superimposed in the manner of roof-tiles or of strongly imbricated lenticular masses. It is not difficult to distinguish sheets of basinal sediments from the shallow-water olistholites. It is, however, nearly impossible to determine whether the superposition is the effect of gravity sliding and/or caused by imbrication of late compressional forces (trench forming). It is easy to recognize late tectonic influence if – as frequently seen – monoclinally imbricated series of internally-undisturbed sequences grade laterally into contorted or chaotic masses within less than a km-distance.

The base and top of the Hawasina Complex may be imbricated with tectonic chips of the underlying or overlying units (Fig. 7).

In Al Fujairah, the monoclinal Hawasina sheets generally dip ESE. The average strike of the whole complex shows a regular SW-NE trend. The overthrust contact to the Ruus al Jibal unit is well exposed along Wadi Ausaq–Wadi Khabb. The contact to the higher tectonic units, either the Metamorphic Series or else the Semail Ophiolite nappe, is always a thrust plane throughout the area investigated (Fig. 7).

4. Metamorphic Series

Two different metamorphic rock series can be distinguished in Al Fujairah: monometamorphites and polymetamorphites (Fig. 7, 2).

Both occur as large thrust bodies capping the Hawasina Complex. The Metamorphic Series with their predominantly steep dip, are in turn overthrust almost horizontally by the huge Semail Ophiolite nappe.

The monometamorphites show at least two phases of isoclinal foliations and folds. They have a consistently easterly dip conformable to the underlying Hawasina sheets. The polymetamorphites reveal a primary metamorphic banding, subsequent intrusion of acid rocks and finally the main deformation into steep isoclinal folds, caused by the second metamorphism.

The metamorphites in the north near Diba are in parts delimited by steep NE-SW trending strike-slip and upthrust faults. They reflect considerable vertical and lateral displacement and cut deeply into the Hawasina Complex. This fault direction roughly parallels the thrust plane between the Hawasina and the Ruus al Jibal units.

A narrow zone of metamorphites can be followed southward to Masafi–Fujairah. Here, the almost vertically dipping metamorphites cut the flat lying Semail Ophiolites into two halfs along steep thrust faults.

5. Semail Ophiolite Nappe

The Semail Ophiolites form a huge nappe structure covering a vast area (Fig. 1, 2). This ophiolite nappe is the highest tectonic allochthonous unit of the Oman mountains. It overlies the Metamorphites and the Hawasina Complex with a conspicious tectonic unconformity. In places, it cuts horizontally through steeply dipping Metamorphites or Hawasina radiolarites.

The areal extent of the Semail Ophiolites is limited by NE-trending thrust faults of the Diba zone (Fig. 2). The minor serpentinites which are imbricated within the Hawasina sheet-pile NW of this line are genetically not related with the main Semail unit. To the south, Semail covers the larger portions of the Oman mountains (Fig. 1, 2)..

The total thickness of the nappe is about 10 km. The minimum net slip of this overthrust nappe exceeds 200 km. It overrides a tectonic unit (Hawasina Complex) which itself has already travelled to the west for more than 100 km.

The Semail nappe presents a very uniform succession from peridotites at the base–layered zone–gabbros (in Al Fujairah, where the higher units are eroded)–dolerites and pillow lavas (only in Muscat, see REINHARDT 1969) at the top. These sharply defined zones produce a domal structure which is well exposed throughout the mountain chain. This sequence, with subaquatic effusives at the top, has been transported in its entirety onto the pile of Hawasina nappe-sheets and Metamorphites. Its original zonation (Fig. 9) has been well preserved despite the considerable dislocation. The thickness of the extensive peridotite peel-nappe to the west, is not the original one. but has been produced by a thinning-out within the peridotite masses by gravity sliding. The stacked units of Hawasina, Metamorphites and Semail Ophiolites (top) override the Arabian platform edge for more than 100 km.

6. Neoautochthonous Sediments

These sediments form post-orogenic, mildly folded and faulted wedge-shaped sheets which thin out considerably from both sides toward the mountain chain (Plate I).

SEQUENCE OF TECTONIC EVENTS

This chapter is offered as an explanation of the orogenic evolution schematically drawn on Plate I. Thicknesses are approximately to scale, but in many instances somewhat exaggerated for drafting purposes. The lateral distances are taken from outcropping series (Ruus al Jibal unit; ± total of measurable sections of olistholites) and roughly estimated from the sedimentary basin content of the younger Hawasina

Complex. For the monometamorphic series, which represent a radiolarite-shale belt metamorphosed in Upper Cretaceous time, the few dozen km taken into account are a minimum.

The reconstructed and estimated total distance of about 200 km from the Arabian platform edge to the axial portion of the basin in Paleozoic-early Mesozoic time must be regarded as a minimum.

Precambrian-Triassic

The continental crust of the Arabian shield thins out rapidly to the east. The continuation may be a thin layer of the same rocks, a mixture of these rocks with old oceanic crust material or an old, thin oceanic crust only. These statements are purely theoretical, since no crystalline basement rocks are involved anywhere in the Oman mountains with the possible exception of the polymetamorphic series and the vague old age of the imbricated serpentinite chips in the Hawasina Complex (p. 674).

Precambrian sediments are observed only in Jebel Akhdar and Sayh Hatat. Pre-Permian Paleozoic sediments are not recorded in the Hawasina belt with the exception of the Ordovician grits at the base of the Jebel Qamar olistholite and thin, nonfossiliferous clastic and carbonate sediments (Muqhtaraqeh, Fig. 2).

Permo-Triassic sediments reveal decreasing thicknesses to the east (olistholite sections). Although we assume it to be so, it is unknown whether a thin Paleozoic sedimentary cover extends to the Paleozoic basin centre.

It is noteworthy to mention that no Precambrian basement rock nor serpentinite has ever been found in the many pre-Santonian breccias and conglomerates, contrary to the enormous amount of Permian-Mesozoic carbonate rock fragments in the Hawasina clastics. Erosion obviously never reached basement levels in the Oman basin.

Liassic-Malm

A quiet shallow marine carbonate regime characterizes the slightly subsiding Arabian platform (J. Akhdar, Ruus al Jibal).

Liassic foraminifera, and in other cases Middle Jurassic types, are encountered in turbidites of the Hawasina Complex. It might be an indication for turbidite transport of contemporaneous shallow-water sediments into deeper basins, but reworking from older rocks cannot be excluded. So far, no authigenic microfauna is found older than Upper Tithonian. Planktonic microfossils of this age are observed in micrite intercalations of radiolarite sequences. Turbidites which occur in the same radiolarites may carry older Upper Jurassic shallow-water fossil remnants in lithoclasts.

It is assumed, in connection with Upper Triassic movements, that the central part of the older Mesozoic Oman basin shows sinking tendency below the carbonate compensation depth. Radiolarites and shales are now deposited onto the extremely thin carbonate substratum (partly removed by pre-Liassic erosion?). This assumption is justified by the fact that these radiolarite series, metamorphosed by subduction into the Upper Cretaceous trench, carry few carbonate layers. Since these monometamorphites tectonically overlie the nonmetamorphic Hawasina rocks in all cases, they are to be regarded as the easterly portion of the Hawasina basin.

Berriasian-Albian

Continuation of quiet carbonate sedimentation on the platform (J. Akhdar, Ruus al Jibal) with a short interruption in Valanginian time (Ruus al Jibal). Within the Hawasina belt, highs are accentuated. Berriasian micrites are found intercalated in radiolarites. On the other hand, turbidites within the same litho-units carry reworked Upper Tithonian calpionellids in carbonate rock components. This proves that within the short interval from Upper Tithonian to Berriasian, lithified sediments of rather deep-water origin are lifted to levels near, or in parts above, sea level. It reflects, moreover, migration of the highs.

Valanginian-Hauterivian authigenic fauna is not found and – with the exception of Lower Valanginian – not to be expected. Barremian-Aptian-Lower Albian micro-faunas are widespread. Orbitolina-bearing shallow-water limestones characterize the platform sediments throughout.

Within the Hawasina Complex, turbidites with numerous isolated Orbitolinas mainly of Aptian age indicate a transport of penecontemporaneous unconsolidated sediment. Yet, Orbitolina-bearing lithite-components in other turbidites show that shallow-water sediments of this age must have been lithified and persisted on highs until their later removal by erosion. Such components appear in many turbidites or as conglomerate boulders in Santonian transgressive sediments of Jebel Agah and another small olistholite farther east.

At about this time, in the oceanic crust and Upper Mantle, a probable old fracture zone was reactivated. It is assumed that the first layer, generally composed of sediments, was very thin and that the second and third layer represent an old oceanic crust. Although Hess (1962) suggested the third layer to be serpentinized peridotite, most other authors (Vogt, Schneider, Johnson 1969) favour a basaltic composition. Below the Moho, the Upper Mantle is in most places composed of peridotite, which shows a mineralogical zoning with spinel lherzolites in the higher levels and garnet lherzolites below 80 km (O'Hara 1970).

With the reactivation of the fracture zone occurs an upward buckling of the isotherms, This upward buckling can be produced by pressure release and upwelling of an ultrabasic slush (Cann, 1968 or by a process of partial melting initiated in the low velocity zone at a depth of 250 km as proposed by Wyllie (1971) who explains the melting in the presence of traces of H_2O. Contemporaneous with the opening of the fracture zone and uprise of the zone of partial melting, convection movements start from the expansion zone towards the continent. A small cell with a width of about 200 km is assumed. The metamorphic rocks, which were probably metamorphosed during subduction of radiolarian cherts etc. into the trench give a Turonian-Coniacian cooling age. The formation of this trench, contemporaneous with the spreading from the fracture zone requires a time of perhaps 20 m.y., assuming a spreading rate of 1 cm/yr. This gives us an Upper Albian or lower Cenomanian age for the beginning of the upwelling (Plate I).

Cenomanian

Carbonate sedimentation continues in the Jebel Akhdar-Sayh Hatat area. No sediments younger than Upper Aptian–Lower Albian are exposed in the Ruus al

Jibal unit. In fact, this part of the platform might well have been uplifted to the erosional niveau.

On the Jebel Agah olistholite, which occupies a rather westerly position in the Hawasina basin, Upper Albian-Lower Cenomanian pelagic marls (locally) are transgressively overlapping Lower Cretaceous slope carbonates of the olistholite core.

Farther east in the Hawasina basin, coarse turbidites with isolated penecontemporaneous shallow-water and planktonic foraminifera alternate with thin radiolarite sequences which include micrites with authigenic planktonics. These series (see Fig. 6), together with thick volcanic deposits in other places, reveal rapid intensification of the orogenic movements affecting the Hawasina belt. Consideration of the cooling age of the monometamorphites show that the radiolarite sediments laid down until Albian-Cenomanian time in the central basin, are now moving into the migrating trench. After subduction, they are metamorphosed at around this time.

In the centre of the basin, barren of the now receding sediments, the upward buckling of isotherms continues till the basalt solidus reaches the oceanic crust. Basalt, generated by partial melting of the lherzolitic Upper Mantle extrudes under subaquatic conditions forming pillow lavas. In tension fissures, rapidly chilled basalt liquid builds swarms of dolerite dikes. Removal of the basalt fraction leaves a residue of Harzburgite and dunite. On top of this peridotitic residue and below the insulating newly-formed oceanic crust, a magma reservoir could form, especially toward the end of the movement when the spreading rate diminished. At the bottom of the magma chamber crystal settling occurred with the formation of layered accumulates. In higher levels coarse- and fine-grained gabbros crystallized from the differentiating basaltic magma. Succeeding batches of magma from the mantle resulted in the different generations of gabbro intrusives.

During the strong increase in spreading rate, highs and depressions were accentuated in the Hawasina belt, resulting in numerous turbidites. The strong subaeric and subaquatic volcanic activity in the Hawasina series must be closely related with the maximum in the upward buckling of isotherms, generating basaltic magmas by partial melting of peridotites below the Hawasina belt. The rare andesitic volcanics flows could indicate partial melting of subducted sediments of the old oceanic crust below the root of the trench.

Turonian-Campanian

The Turonian-Lower Santonian interval is represented by an erosional gap in the J. Akhdar-Sayh Hatat area. In Upper Santonian-Campanian time, the Muti formation transgressively overlay the Cenomanian top of the Mesozoic carbonate section.

The Ruus al Jibal unit does not contain sediments of this age in situ. The Campanian pelagic marls with coarse conglomerates (Ausaq beds, Fukhairi beds) – as equivalents of the Muti formation – are thought to represent deposits of a migrating depression in front of the advancing Hawasina sheet-pile and subsequently also in front of the Ruus al Jibal unit.

In Campanian time, the main mass of the advancing nappe-building has obviously reached but not buried the Ruus al Jibal area.

At Jebel Agah, Coniacian-Santonian pelagic marls with a coarse transgressive conglomerate (including boulders of Orbitolina-limestones among others) overlap Lower Cretaceous carbonates or else – locally – Upper Albian-Lower Cenomanian pelagic carbonates.

The absence of Campanian deposits indicates a possible overthrust of the area by advancing Hawasina units at this time.

Within the Hawasina belt east of Jebel Agah, no sediments younger than Lower Turonian are found.

The uppermost part of the Semail ophiolite complex is composed of pillow lavas, indicating subaquatic conditions during the formation of the suite for its whole length. As no sediments overlie the pillow complex the extrusives must have formed a high on the ocean floor.

At this period the isotherms started to withdraw. The quantitatively rather small, but petrogenetically very important, series of acid differentiates ranging from quartz diorites to Li-pegmatites consolidated after the basalt solidus isotherm withdrew to deeper levels.

The end of metamorphism in Coniacian–Lowermost Santonian is within the error limits of the cooling ages.

Lower-Middle Maastrichtian

No sediments of this age are dated with certainty within the mountain area. The Ausaq beds, with abundant planktonics, may be of this age, but Campanian cannot be excluded on the basis of the present samples.

At about this time, the main mass of the Hawasina sheets over-rode the Arabian platform edge. Northwest of the Diba fracture zone (Fig. 2) the parautochthonous Ruus al Jibal unit overthrust the frontal Hawasina units. It is overridden in turn subsequently by the large mass of the Hawasina sheet-pile moving into the westward migrating depression. Within this depression the accumulating sheets were gliding successively farther onto the subsiding platform.

Strong uplift of the ophiolite suite and the metamorphic zone caused by compressional forces in the trench zone enabled a thin but around 100 km wide sheet from the top of the ophiolite suite to move into the depression farther west (gravity sliding?). Thereby, it tectonically cuts through Hawasina and upthrust metamorphic beds. In a subsequent phase, metamorphic series cut obliquely through the almost horizontal overlying Semail Ophiolites. A short erosional period which lasted to the Upper Maastrichtian time is reflected by the

Upper Maastrichtian

From both sides of the Maastrichtian high, Upper Maastrichtian transgressive shallow-water carbonates advanced toward the already completed nappe complex. Large peridotite boulders at base of this sequence prove this, beyond any doubt. No Tertiary tectonism affects the Maastrichtian structural style.

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