Science and Technology, 1 (1996) 1- 19

The Stratigraphy and Structure of the Madamar-Salakh-Qusaybah Range and Natih-Fahud Area in the Oman Mountains

Samir S. Hanna* and John D. Smewing#

**College of Science, Sultan Qaboos University, PO Box 36, Al-Khod 123, Muscat, Sultanate of Oman, and #Earth Resources Institute, University College Swansea, SA28PP, UK.*

خلاصة : شهدت فترة العصر الكريتاوي المتأخر نمواً تركيبياً ملحوظاً بالمنطقة الضحلة أثناء ترسيب مجموعة الأروما. حيث تم الاستدلال عليه من خلال انتشار فتاتيات قمة تكوين ناطح في الصخور الطينية الموجودة في قاع هذه المجموعة . هذا ويعتقد أن المنطقة الضحلة بمنطقة جبال مضمار - صلاخ - قصيبة وحتى منطقة فهود قد مرت بنفس فترة النمو التركيبي أثناء فترة العصر الكريتاوي المتأخر . منطقة فهود بها فالق عادي انزلق الجزء السفلي منه تجاه الجنوب وتسبب في زيادة سمك مجموعة الأروما بقرابة اكم . وتوجد مجموعة فتاتية انسيابية بمجموعة الأروما أقل عمراً في منطقة صفرة الخيس جنوب جبل صلاخ يتراوح عمرها ما بين عصري الكمبانين / المسترختين وفتاتيات هذه الصخور الانسيابية أصلها من الحجر الجيري لتكوين سمسمه فقط . أما فتاتيات تكوين ناطح فهي غير موجودة نهائياً، وقد اعتبر هذا دليلا على أن منطقة سلاسل جبال مضمار - صلاخ - قصيبة كانت مغطاة برواسب مجموعة الأروما في ذلك الوقت وأنها لم تكن بالارتفاع الذي نراها عليه حالياً . أي أن هذه السلسلة تم نموها خلال العصر الكريتاوي المتأخر ولكن عمرها يمتد أساساً إلى ما بعد المسترختين . وأن ما شهدته منطقة سلاسل جبال مضمار - صلاخ - قصيبة من أحداث ما بعد المسترختين تسبب في وجود مجموعة من الطيات المزدوجة الانغطاس في صخور العصر الكريتاوي . تتضمن هذه الطيات مجموعة كثيفة من الصدوع والشروخ الشيرية الممثلة في فوالق عادية وكسور مفتوحة . كما توجد بالفوالق رواسب مطحونة يلاحظ أنها تصل الفجوات الموجودة بالصخر بعضها بالبعض الآخر . واذا وجدت هذه الظاهرة في طيات مغلقة تحت سطح الأرض كما هي عليه على سطح الأرض في سلاسل جبال مضمار - صلاخ - قصيبة فان هذه الفوالق والشقوق تمثل أنابيب تسهل عملية انسياب النفط الذي يمنع نزوحه إلى السطح صخور طينية صماء خاصة بمجموعة الأروما التي تعلوها مما قد ينتج عنه تجمع نفطي في هذه المنطقة .

ABSTRACT: Melanges and debris flows with clasts derived from the top of the Natih Formation found in shales in the base of the Aruma Group indicate that a period of structural growth on the platform took place during Aruma deposition in the Late Cretaceous. In this respect the platform in the Jebel Salakh area may have undergone a similar period of structural growth in the Late Cretaceous to the Fahud area where a syn-Aruma normal fault down throwing to the South accounts for a difference in the stratigraphic thickness of the Aruma of 1 km. A younger series of debris flows in the Aruma of the Sufrat al Khays area to the South of Jebel Salakh is dated as Campanian/Maastrichtian. The clasts in these flows were derived exclusively from the Simsima limestones, Natih-derived clasts are conspicuously absent. This is taken to indicate that the Madamar-Salakh-Qusaybah range was covered by Aruma sediments at this time and did not form the distinctive positive feature seen at present - i.e. Madamar-Salakh-Qusaybah range folding though partly Late Cretaceous is mainly Post-Maastrichtian in age. This Post Maastrichtian event in the Madamar-Salakh-Qusaybah range produced a series of doubly-plunging anticlines in the Cretaceous strata. These folds show a high degree of brittle extension in the form of normal faults and extensional fractures. The faults are delineated by fault gouge with visibly interconnected void space. In the subsurface, if such fractures were developed in a fold closure similar to those seen at the surface in the Madamar-Salakh-Qusaybah range, then they could provide preferred conduits for oil flow and the barrier to fluid flow provided by the Aruma shale seal could lead to a hydrocarbon accumulation.

The study area is located in the southern foothills of the Oman mountains foreland fold and thrust belt where a series of Cretaceous carbonates are exposed in five doubly-plunging anticlines (periclines) [Fig. 1]. These five anticlines are arranged in an arcuate form concave towards the hinterland (North) in a similar way only on a smaller scale to that bounding the northern side of Saih Hatat, Jebel Nakhl, Jebel Akhdar and Hawasina window to the North. To the South of this arcuate belt, anticlines exposing Tertiary carbonates, overlie two of the main oil-producing fields in Oman, Natih and Fahud. A major objective of the work was therefore to study the structure of these folded Tertiary sediments to see what light they shed upon the accumulation of hydrocarbons in these specific areas. The line of folded Cretaceous sediments in the Madamar-Salakh-Qusaybah range was studied to compare it with the structural style and history of Natih and Fahud. The stratigraphy of the Madamar-Salakh-Qusaybah range and overlying Aruma sediments was studied to determine the age of structural growth in the Cretaceous shelf carbonates and lastly the nature of the northward extension of the Maradi fault zone into this area was addressed.

The study involved measuring five representative

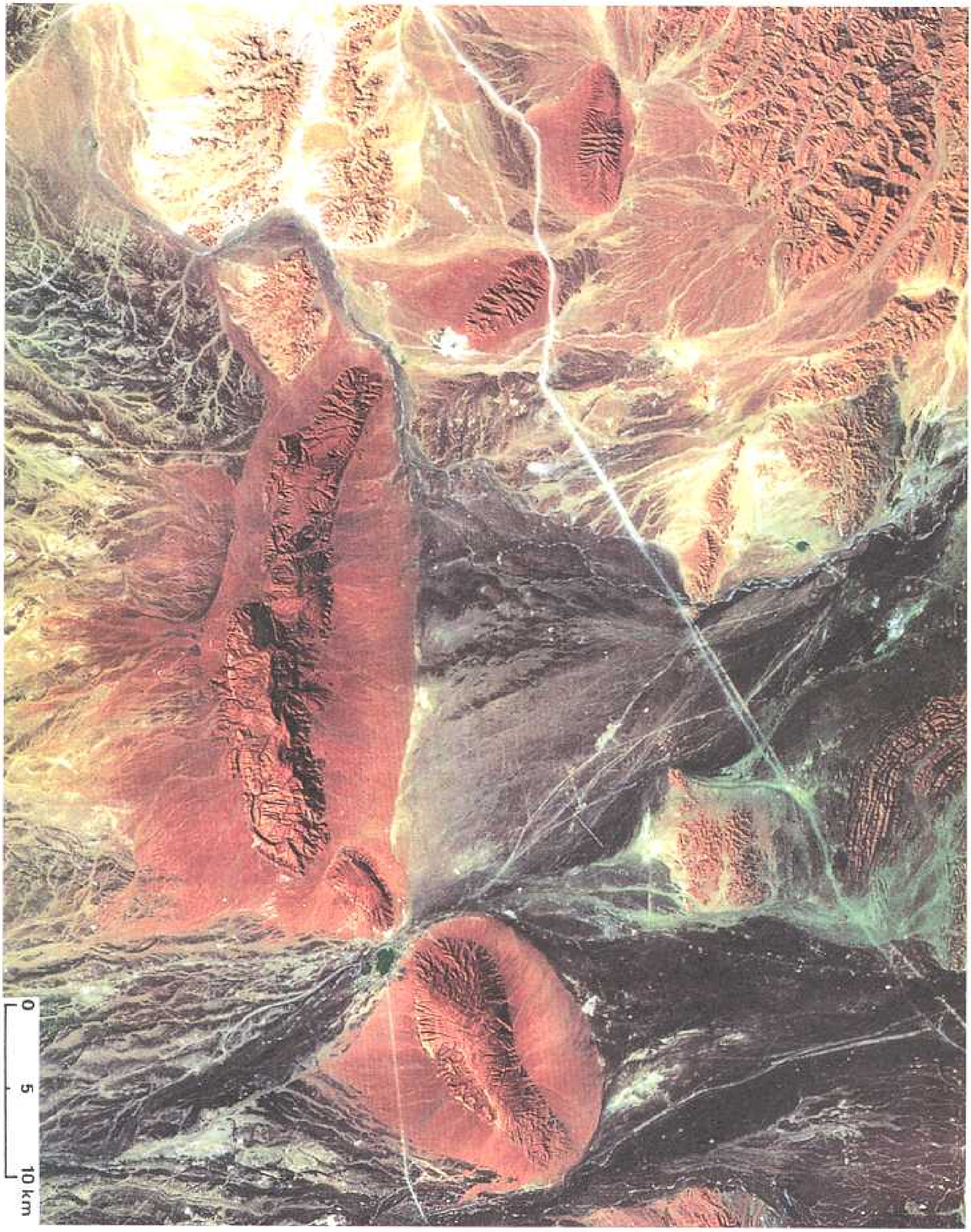

Figure 1. Landsat photograph of the five doubly plunging anticlines (periclines) of Madamar-Salakh-Qusaybah range. A: Adam, M: Madamar, S: Jebel Salakh, R: Jebel Rashid, Q: Jebel Qusaybah, Sf: Sufrats, HD: Hamrat Duru Range, MFZ: Maradi Fault Zone.

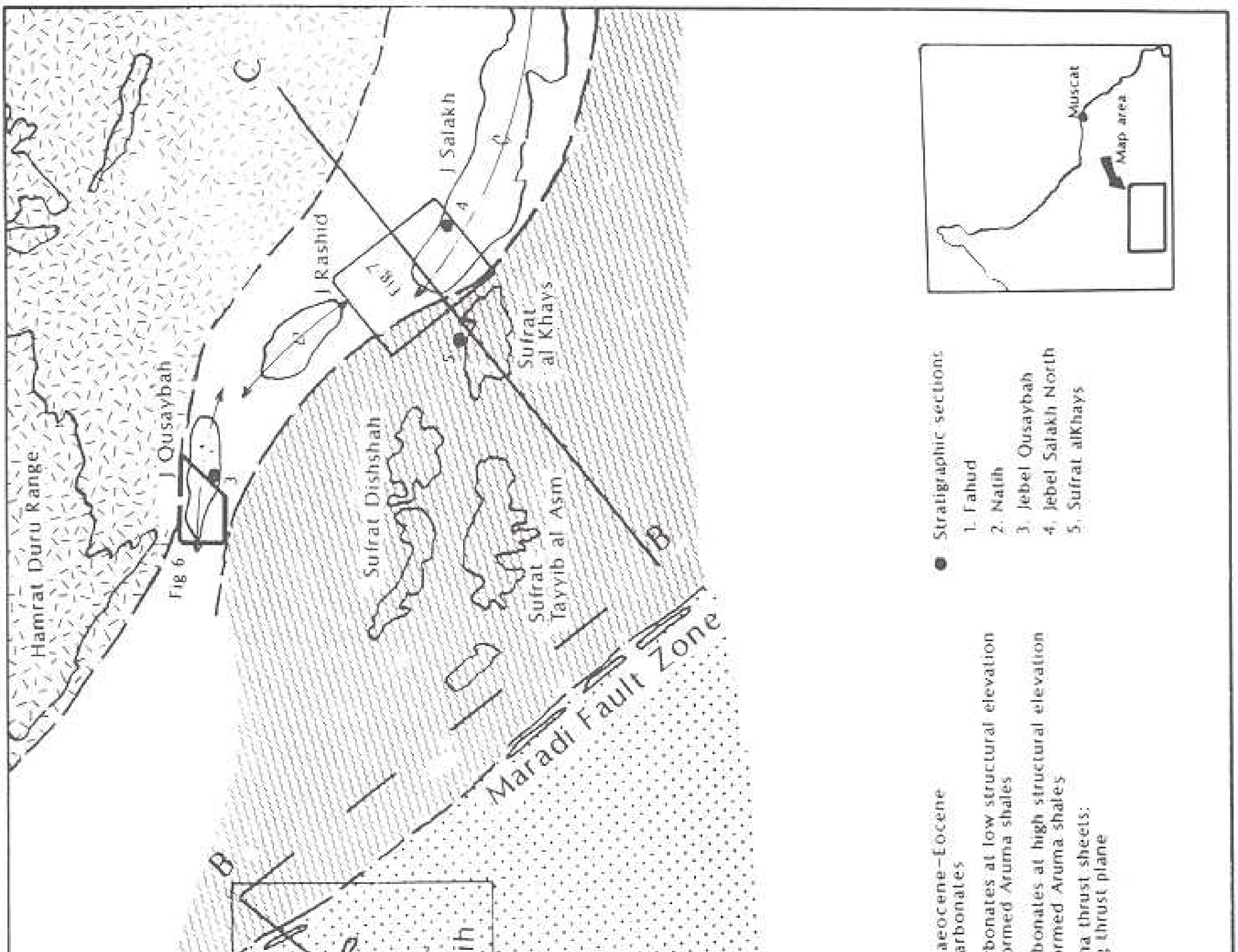

Figure 2. Geological map of the study area showing locations of measured stratigraphic sections, areas of detailed mapping and line of structural section.

stratigraphic sections and constructing geological maps of selected areas (scale 1:20,000). The field work lasted about six weeks.

Geological Setting

Rock units in northern Oman (Glennie *et al.* 1974, Robertson *et al.* 1990) are conveniently divided into three supersequences (Hanna 1995). From structurally lower to structurally higher positions these units include supersequence A with a *pre-Permian sequence* of Late Proterozoic to early Permian igneous and metamorphic rocks and the *Hajar Supergroup* representing a Late Permian to Late Cretaceous carbonate platform succession; supersequence B with the (allochthonous) *Sumeini Group* and *Hawasina assemblage* which contain Permian to Late Cretaceous marine strata and rare basalts that accumulated in slope, abyssal plain, and offshore reef environments, and the *Samail ophiolite* of Late Cretaceous (±95 Ma) age; and supersequence C composed of Tertiary and Quaternary sedimentary rocks.

Between A and B is the Aruma Group, composed of synorogenic clastic sediments that accumulated in a foreland basin upon the carbonate platform and deeper marine equivalent.

The term Aruma Group was initially used by Owen and Nasr (1958) in Southern Iraq, Kuwait and Saudi Arabia for all units between the Wasia Group at the top of the platform (Cenomanian/Turonian) and the Cretaceous - Tertiary boundary. The Wasia-Aruma contact is a regional unconformity known as the Wasia-Aruma break. The Aruma Group was subdivided into the carbonates of the Simsima Formation above and the shales of the Fiqa Formation below.

In the study area Supersequence B is missing apart from the very NE corner. Elsewhere the Hajar Supergroup of Supersequence A is overlain by the Aruma Group which is in turn unconformably overlain by Supersequence C.

Some 80% of the area of study is covered by recent fluvial wadi deposits. Figure 2 shows an extrapolation of the surface data to portray the surface and subsurface geology of the area. Four geological provinces can be recognized. In the North-East the Hamrat Duru range comprises northward-dipping Hawasina thrust sheets with imbricated Aruma sediments overlying Cretaceous platform carbonates at depth. These carbonates appear at surface in the Madamar-Salakh-Qusaybah range, to the South of the southern limit of the Hawasina/Aruma thrust sheets. The carbonates of the Madamar-Salakh-Qusaybah range are thrust over Aruma calciturbidites, shales and debris flows of the "Sufrats". These are separated by a normal fault, down throwing to the South-West, which is likely to be the representation of the Maradi Fault Zone (Hanna and Nolan 1989), from the south-westernmost province, comprising the gently folded Tertiary strata of Natih and Fahud.

Two cross-sections through the area are depicted in Figures 3 and 4. Stratigraphic and structural studies were concentrated in the last three of these provinces, viz., the Madamar-Salakh-Qusaybah range, the "Sufrats" and the Natih-Fahud area. These areas are described below.

The Madamar-Salakh-Qusaybah Range

STRATIGRAPHY: The oldest rocks of the area, the Cenomanian to early Turonian Natih Formation, are exposed in the Madamar-Salakh-Qusaybah range and are locally seen to be in depositional contact with the overlying Aruma Group. The stratigraphy has been studied at two points, one on Jebel Qusaybah and one on Jebel Salakh (Figure 2). Correlation of the two sections is facilitated by the widespread development of lithologically distinct units (Figure 5).

The Jebel Qusaybah section exposes 160 m of carbonates at the top of the Natih Formation. The lowermost 60 m consists of thickly-bedded, intensely burrowed bioclastic calcareous wackestones with radiolitid rudists, corals, bivalves, (including *Chondrodonta)*, gastropods, benthonic foraminifera including miliolids, *Praealveolina* and *Pseudocrysallidina conica*, and planktonic foraminifera. Many of the beds have a rusty, pitted appearance due to the selective weathering out of the burrows. These lower beds are overlain by 40 m of recessive interbedded black bituminous shelly lime mudstones with abundant *Exogyra africana* (Scott 1990) and pink-weathering argillaceous lime mudstones and shales. Other common fauna found in these beds include *Pholadamia* sp., *Plicatula reynesi* and *Exogyra mermeti* (Scott 1990). Planktonic foraminifera and calcispheres are abundant and occur throughout this unit. The recessive shelly beds are abruptly overlain by thickly bedded grey lime mudstones with abundant planktonic foraminifera, sponge spicules and calcispheres which continue to the top of the section broken only by a distinctive brown weathering unit 20 m from the top which contains abundant replacement chert within the limestones. The contact with the overlying Aruma Group is not exposed in the Jebel Qusaybah section. However, it is exposed in the Jebel Salakh North section where the upper beds of the Natih Formation can be readily correlated with Jebel Qusaybah (Figure 5). The Jebel Salakh North section starts at the contact between the shelly, bituminous lime mudstones and the thickly bedded grey foraminiferal lime mudstones. The brown chert marker can be readily identified.

A slope truncation surface has been identified within this marker bed at the north-western tip of Jebel Salakh at Grid Reference 190768, 5 km WNW of the section.

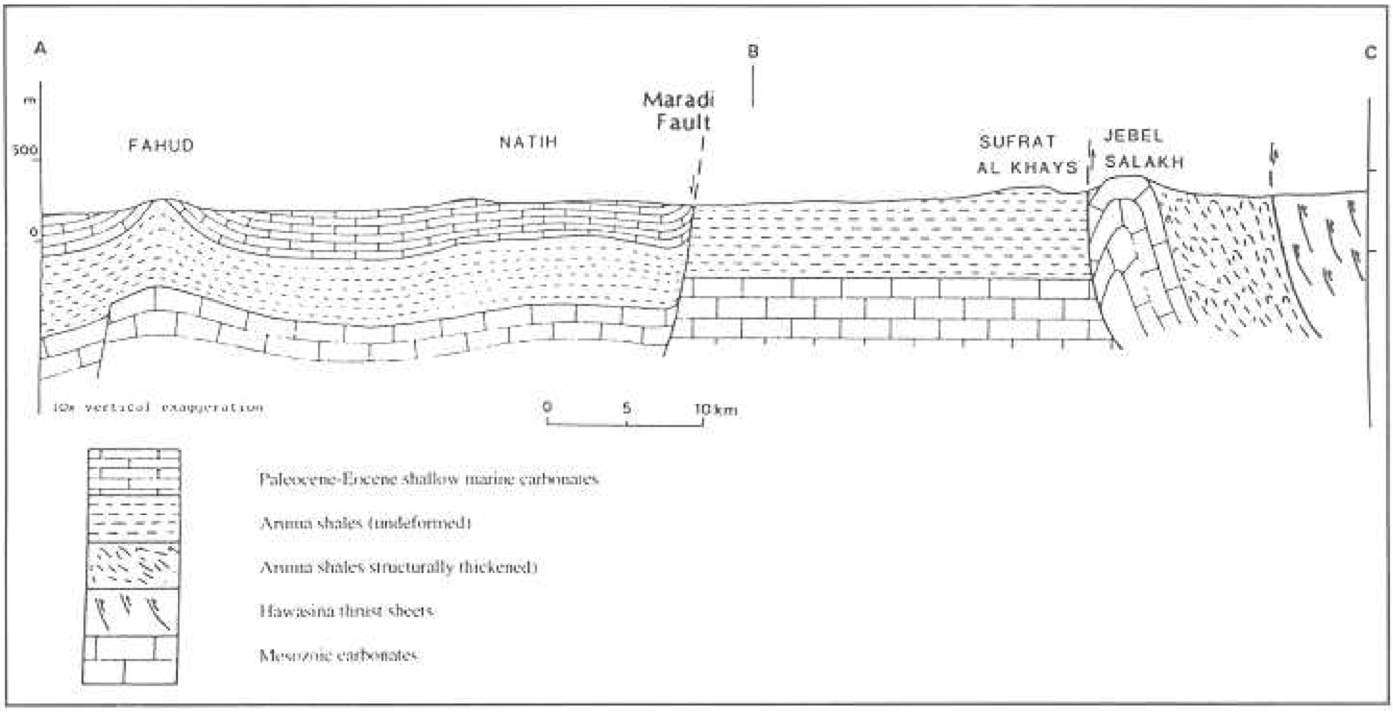

Figure 3. Structural cross-section from Fahud anticline to Hawasina foreland fold and thrust belt (Section along A-B-C in Figure 2).

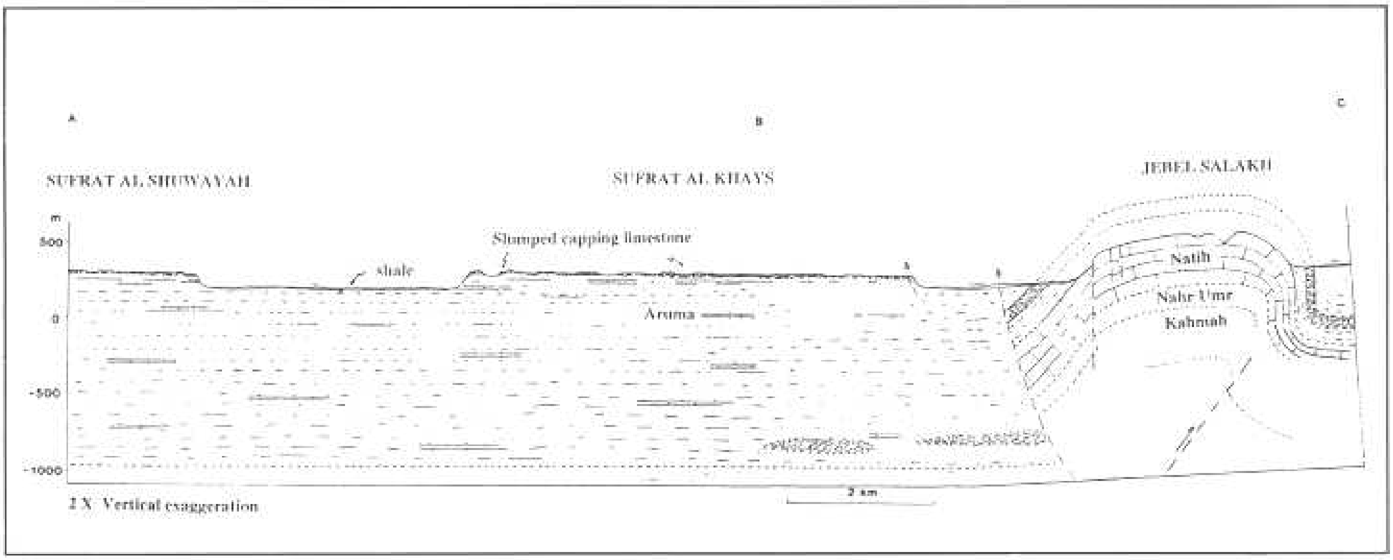

Figure 4. Structural cross-section of B-C area of Figure 2.

Evidence of shallowing upwards appears in the unit above the brown chert marker which consists of thickly-bedded bioclastic lime wackestones with miliolids, corals, echinoids, gastropods and sparse planktonic foraminifera. These beds then pass up into thickly bedded lime mudstones with abundant planktonic foraminifera, sponge spicules and oyster shells. The Natih/Aruma contact is marked by a hardground at the top of these beds where they contain conspicuous Fe/Mn oxide concretions up to 10 cm long occur. The Natih/Aruma contact is marked by an abrupt colour change from grey lime mudstones to dark red lime mudstones and shales. In thin section, the basal lime mudstones of the Aruma Group contain abundant planktonic foraminifera and evidence of extensive iron oxide impregnation. Oolitic layers are also found in the basal Aruma consisting of ferruginous carbonate coatings on shelly fragments in a calcite cement. The ferruginous limestone units at the base of the Aruma are only some 1 m thick and they pass up into red and oraange non-calcareous shales. Above some 150 m of shales a distinctive grey-brown melange/debris flow unit is exposed. It consists of

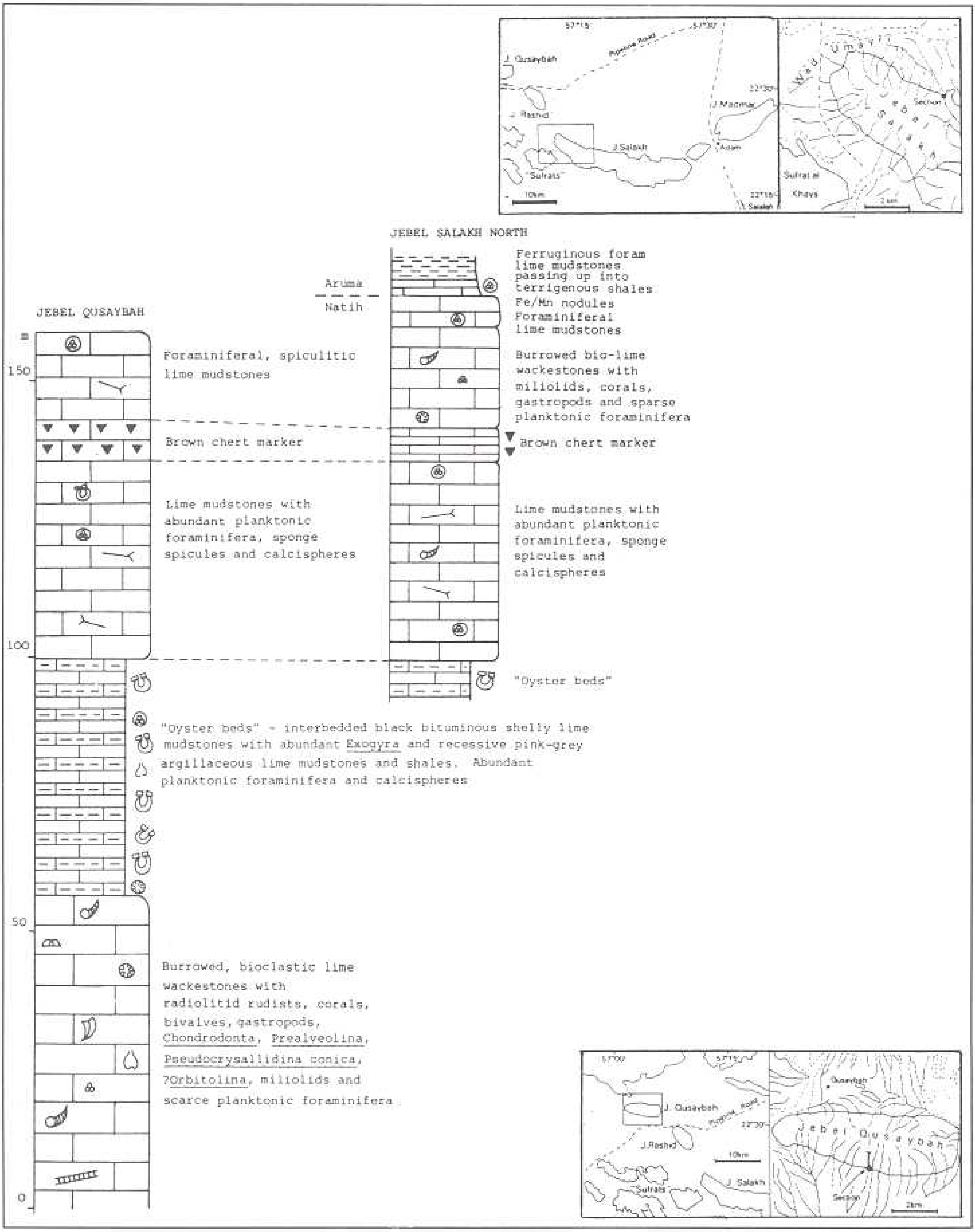

Figure 5. Simplified stratigraphic sections of upper Natih carbonates and basal Aruma shales in Jebel Qusaybah and Jebel Salakh.

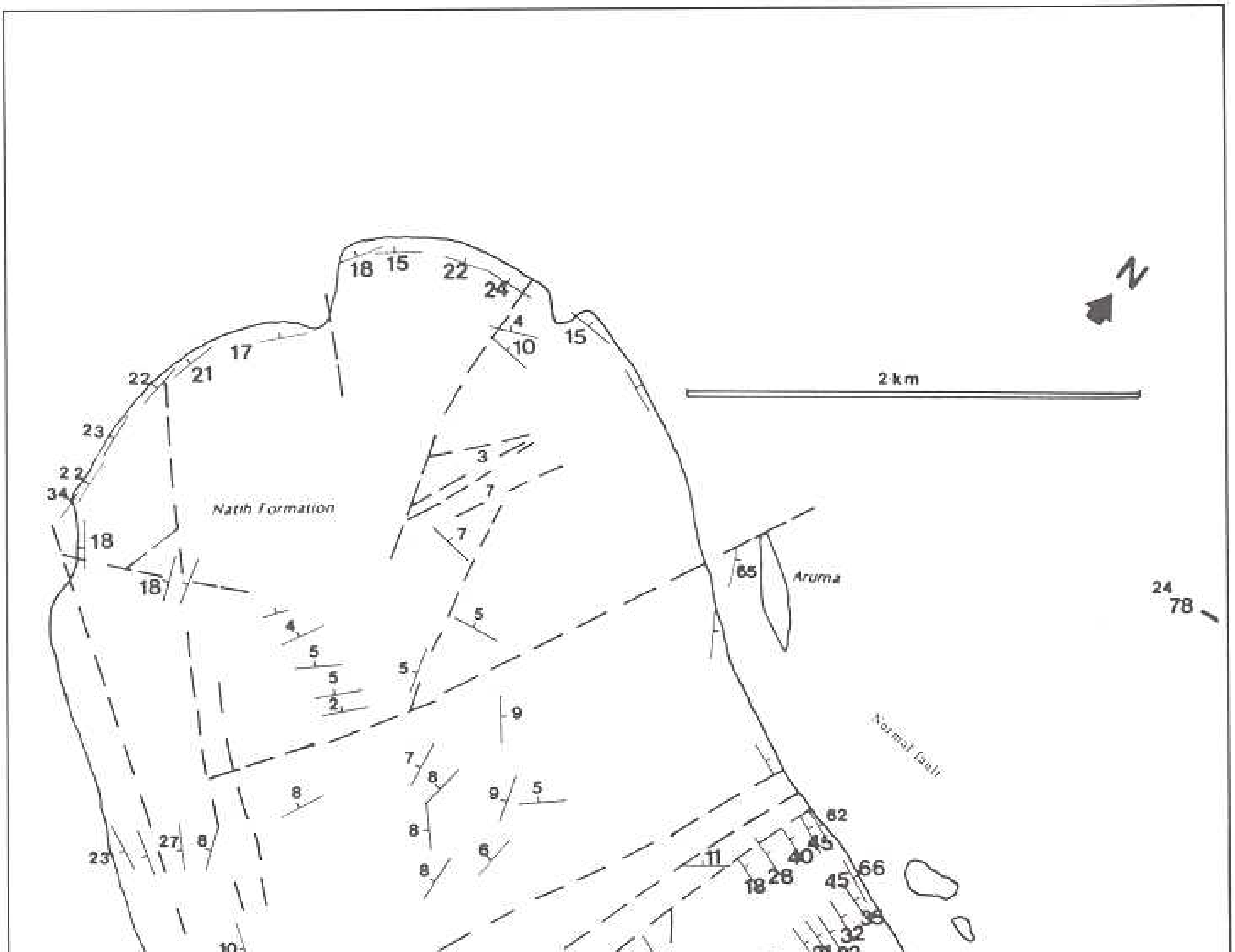

Figure 6. Geological map of the western tip of Jebel Salakh.

chaotic melanges with sub-rounded, poorly sorted blocks up to 10 m wide and lenticular debris flows in a poorly-exposed shaly matrix. In the case of both the melanges and the debris flows, the clasts are derived exclusively from the upper levels of the Natih Formation. The melange/debris flow unit is again overlain by shales which are only patchily exposed in the gravel plains away from Jebel Salakh.

Foraminifera and ammonites from the top of the Natih Formation in the Jebel Salakh area are dated as Late Cenomanian/Early Turonian (Simmons and Hart 1987). The planktonic foraminiferal assemblage of the ferruginous lime mudstones at the base of the Aruma Group consists of *Heterohelix globulosa, Whiteinella archeocretacea* (?), *Whiteinella alpina* and *Marginotruncana sp.* and is accordingly dated as Turonian (Simmons and Hart 1987).

STRUCTURE: The Madamar-Salakh-Qusaybah range consists of five doubly-plunging anticlines arranged in an arcuate form concave towards the north and with an overall length of 60 km. Geological maps at scales of 1:10,000 and 1:25,000 respectively, have been made of Jebel Quasaybah and the western end of Jebel Salakh (Figs. 6 and 7).

The Qusaybah anticline is an elongate dome-shaped structure (8.8 km x 3 km) with an E-W trend. It is almost symmetrical with a maximum dip of 20° on the northern limb and 18° on the southern limb. The dominant structural elements are:

i. *Shear zones*: These represent the only evidence of internal deformation within the Natih Formation andappear to be entirely brittle rather than ductile in nature. They occur either as single shear zones with a sinistral sense of movement, arranged in parallel sets, trending NNE-SSW, or in conjugate sets with dextral shear zones trending 160° and sinistral shear zones trending 130° (giving a maximum compressional strain of NNW-SSE).

ii. *Normal faults:* A NNW-SSE (cross or transverse) and an E-W (longitudinal) set are developed (Figure 8a) forming a series of horst and graben structures, which, with the N-S set dominating over the E-W set, have the effect of dissecting Jebel Qusaybah into a series of horsts and grabens trending perpendicular to the fold axis. The E-W faults show consistent

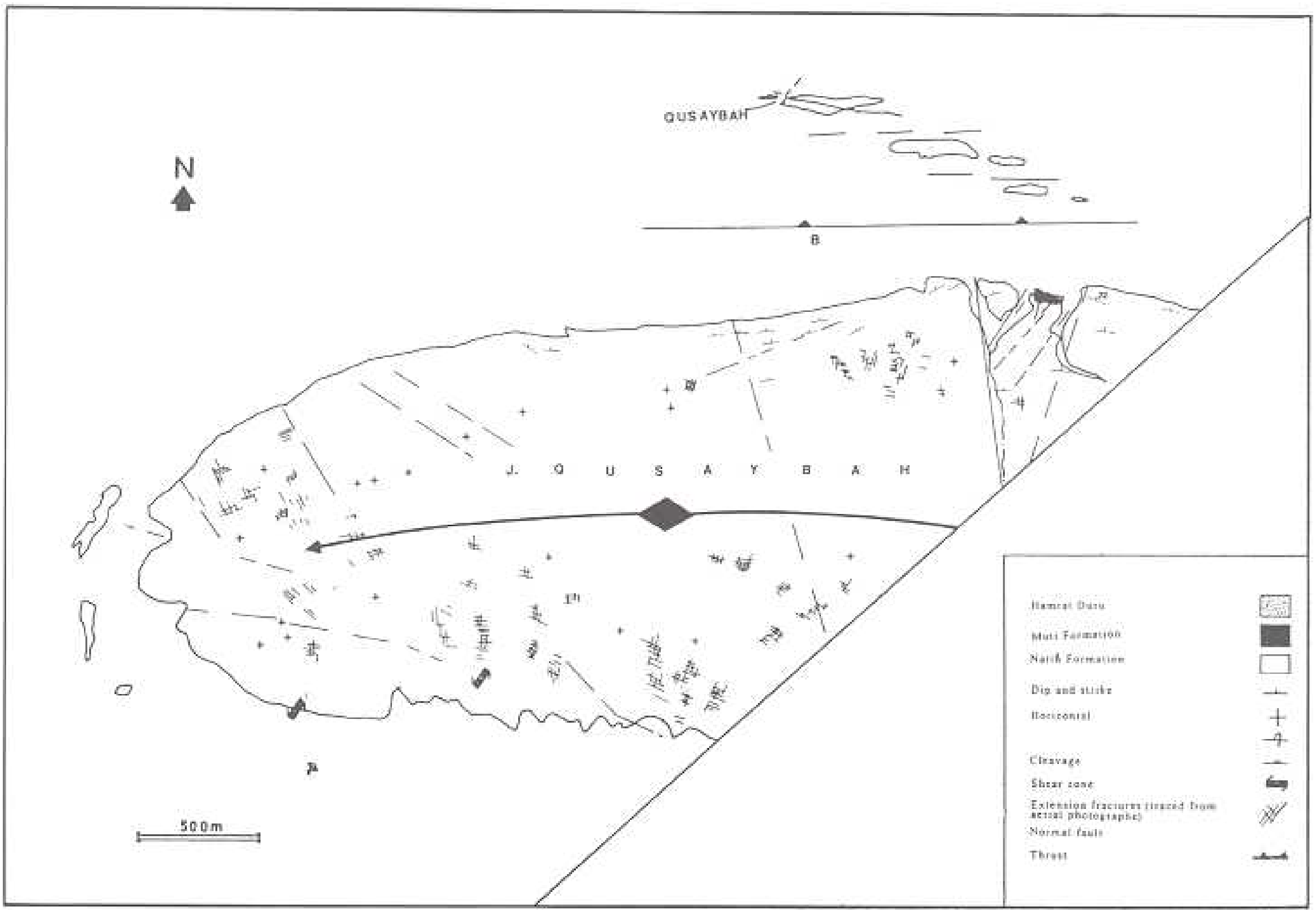

Figure 7. Geological map of the western part of Jebel Qusaybah showing the basal Hawasina thrust.

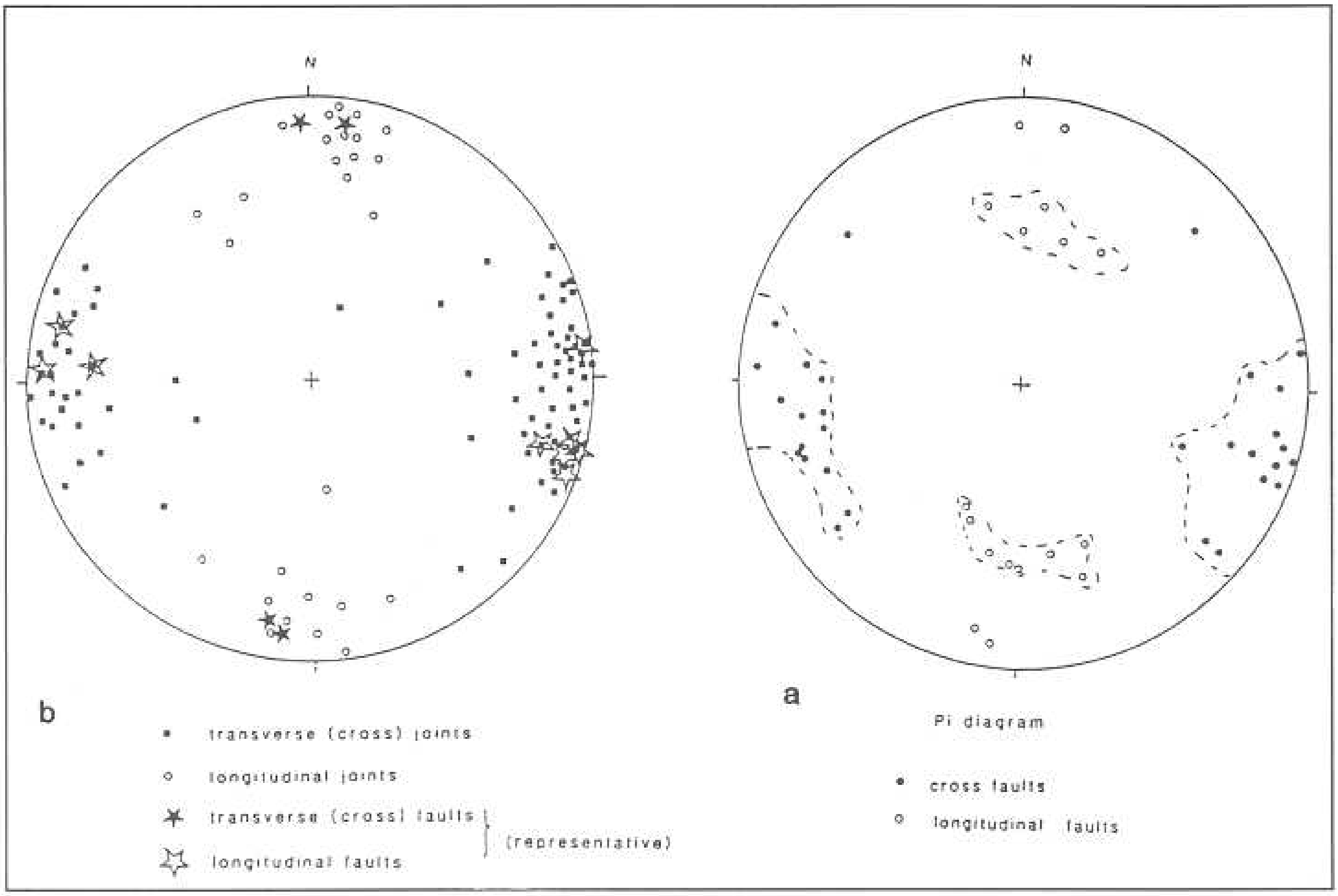

Figure 8 (a). Equal area, lower hemisphere stereo-plot of poles to normal faults, Jebel Qusaybah.
Figure 8 (b). Equal area, lower hemisphere stereo-plot of poles to joints and some representative faults, Jebel Qusaybah.

northern downthrow on the northern flanks of the jebel and southern downthrows on the south. The N-S set is consistently cut by the E-W set. Many of the faults on Jebel Qusaybah are associated with zones varying from a few centimetres to 2 m in width of iron-stained fault gouge consisting of fragments of the Natih Formation, crystalline calcite and orange-red soft marly sediments that have clearly percolated down the open fissures.The fault gouges invariably show visibly interconnected void spaces which are partly occluded by the percolated sediments.

iii. *Strike-slip faults*: Several strike-slip faults occur in Jebel Qusaybah of which the best example is in the NE corner of the mapped area where red ferruginous oolitic grainstones of the basal Aruma Group are abruptly terminated along a strike-slip fault, striking 030°, against the Natih Formation. The displacement is 2 m and the sense of rotation of the beds into the fault suggests sinistral movement.

iv. *Joints:* Joints are well developed in E-W and N-S directions - i.e. normal and parallel to the trace of the fold hinge. Another set of joints which is oriented to the fold hinge was also recognized but found to be less common. Characteristically, the joints are regularly spaced at 4-5m, steeply dipping and, as with the normal faults, the E-W set cut across the N-S set. Figure 8b illustrates a stereo plot of some 130 measured joints in Jebel Qusaybah with some associated normal faults. The fractures are partly filled by crystalline calcite which locally is slickensided indicating some movement along the joint surface.

Mapping of the NW-plunging anticline at the NW end of Jebel Salakh (Fig.7) has shown that the Natih Formation is exposed in an asymmetric box fold with a moderately steep NE flank (maximum dip 60°), a less steep SW flank (maximum dip 35°) and a gently SW-dipping crest (approximately 4°). Joints and normal faults aligned dominantly parallel to and perpendicular to the foldaxial trace are once again common. A very distinctive feature of the crest of the fold is dip-parallel extension represented by numerous calcite veins running parallel to strike with or without significant differential movement across them and with an average spacing of 10-20m. In

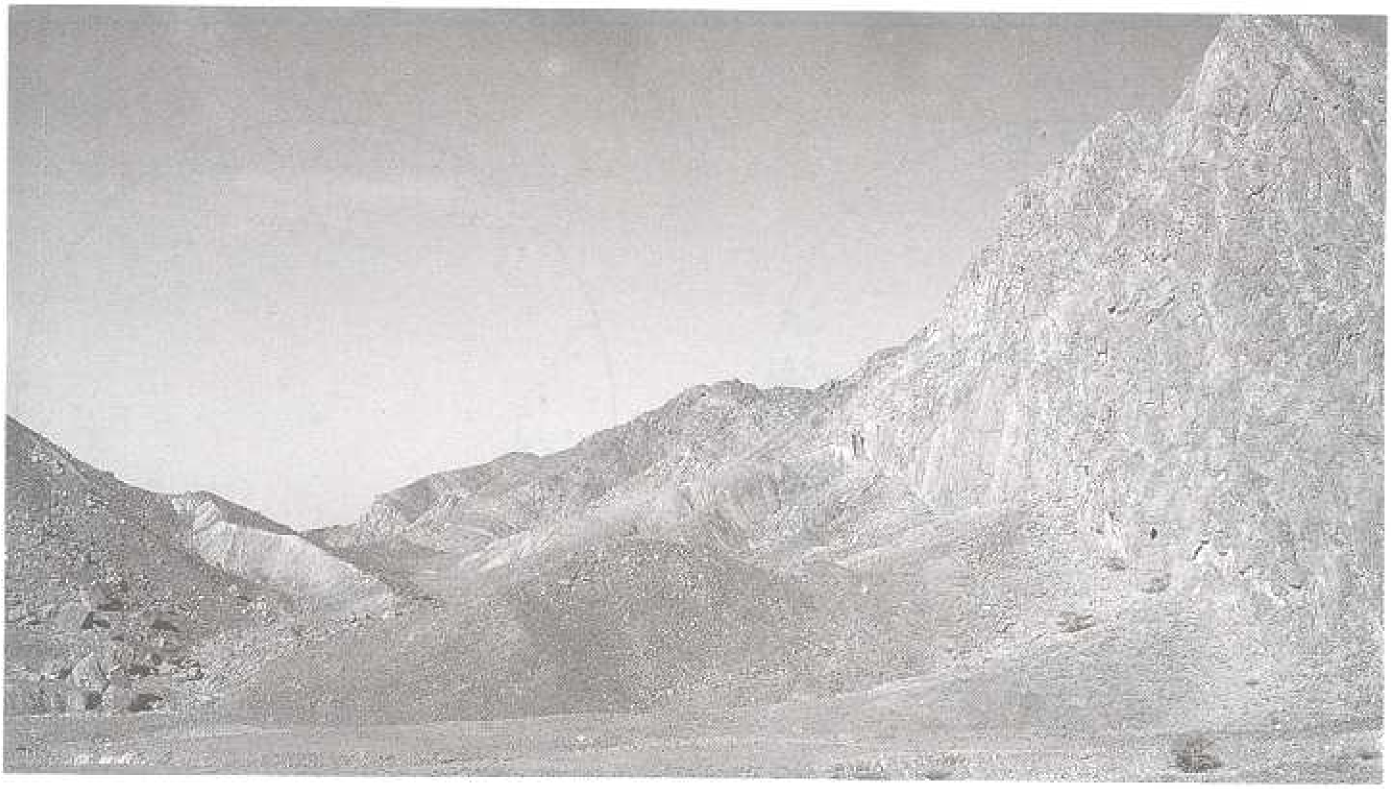

Figure 9. Photo (looking West) of the frontal thrust, southern side of Jebel Salakh. Natih Formation lies on top of the Aruma Shale.

contrast, extension parallel to the hinge of the fold appears to be restricted to a few discrete zones.

v. *Frontal Thrust*: Field evidence from the eastern end of Jebel Salakh suggests that the folded Cretaceous carbonates of the Madamar-Salakh-Qusaybah range are separated from weakly undeformed Aruma sediments to the south by a major N-dipping thrust, with a throw possibly as high as 450m, and with the Madamar-Salakh-Qusaybah range folds nucleating on the hanging wall of this thrust. The surface expression of this thrust can be seen along the south-east flank of Jebel Salakh where green and red Aruma shales are exposed in the foot-wall of the thrust beneath the Natih Formation (Fig. 9).

vi. *Back Thrust*: Evidence of a back thrust is seen in Jebel Qusaybah where a south dipping reverse fault occurs in the northern flank of the anticline. The displacement is about 35 m. Similar back thrusts were mapped along strike in the Hamrat Duru range where they are associated with N verging folds (Hanna 1991).

The Sufrat Al Khays Area

This area which is represented by a series of low, flat-topped jebels to the west of Jebel Salakh, all bearing the name "Sufrat", is bounded to the NE by the thrust separating it from the Madamar-Salakh-Madamar range trend and to the SW by the Maradi fault zone. These flat-topped jebels are made up entirely of sub-horizontal sediments of the Aruma Group, but the sediments here differ markedly from the Aruma exposed above the Natih Formation on Jebel Salakh, in that they consist of light grey-green, very recessive argillaceous lime mudstones and shales punctuated by creamy calciturbidites and carbonate debris flows with orbitoids, radiolitids and echinoid fragments. No base or top to the Aruma of the Sufrat al Khays area is exposed. The relative proportion of redeposited carbonates increases up section and the distinctive mesa-type topography of the Sufrat al Khays area is due to the ubiquitous presence of a resistant capping, channelised, bioclastic lime grainstone at the top of the visible section.

Figure 10 shows one of the more complete and thicker Aruma sections of Sufrat al Khays and in overall sequence is typical of the Aruma of this area. The section starts in light green-grey argillaceous lime mudstones and shales with planktonic foraminifera and sponge spicules. These beds are punctuated by debris flows which contain clasts of pel-foram lime grainstone with radiolitid and echinoid fragments, *Orbitoides* and *Omphalocyclus*. A single 1 m calciturbidite was also recognized within this sequence with a rudaceous base and a cross-bedded arenaceous top. Radiolitid rudists, echinoid fragments, *Orbitoides* and *Omphalocyclus* are found in both the lithoclasts and the matrix of this flow. The argillaceous

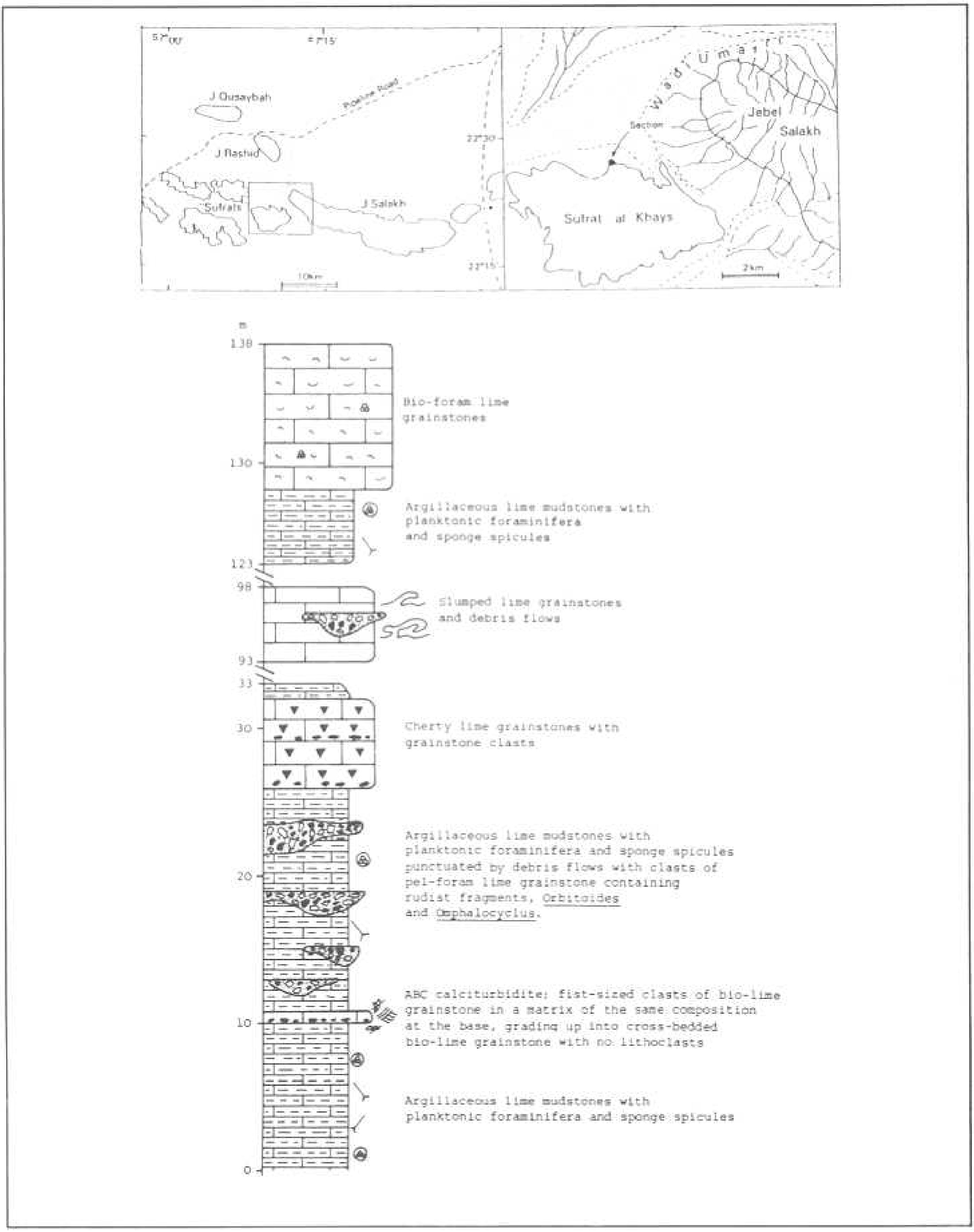

Figure 10. Simplified stratigraphic section of Aruma sediments, Sufrat al Khays.

lime mudstones and shales are overlain by 5 m of cream coloured cherty lime grainstones and shales again. Above a 60 m non-exposed section, 5 m of slumped lime grainstones and debris flows occur. These slumped beds, with associated debris flows, are well developed throughout the Sufrat al Khays area near the top of the visible Aruma section. In places it appears that the debris flows have been emplaced as single events - i.e. they form part of an intact, non-disrupted stratigraphy, and elsewhere they appear to be formed during slumping. In all probability, the one is in part at least, a precursor of the other with local slumping feeding debris flows in more stable parts of the basin. The section is completed by 5 m of argillaceous lime mudstones and shales and 10 m of the capping lime grainstone.

Channel shapes and cross-bedding in the redeposited carbonates indicate palaeocurrents to the North, North-East and East. In addition, down to basin slump scars on the eastern flank of Sufrat al Khays indicate a north-east dip to the palaeoslope. Slumping apparently took place mainly towards the east.

The Aruma sediments of the Sufrat al Khays area are dated as Campanian/Maastrichtian from the orbitoid fauna in the matrix of the redeposited carbonates.

The Natih-Fahud Trend

STRATIGRAPHY: Figure 11 is a simplified geological map of Natih area. The youngest rocks of the study area, the Palaeogene shallow marine carbonates, are exposed in the two doubly-plunging anticlines of Natih and Fahud. The more complete section is found in the better exposed Fahud structure where 350 m of Palaeogene carbonates are seen to overlie, with an angular unconformity, Aruma shales in the core of the anticline. A shorter section has been logged on the south flank of the Natih anticline which can be correlated with Fahud by means of a distinctive meganodular unit (Figure 12).

The carbonates of Natih and Fahud are entirely platformal in character, passing upwards in Fahud from open shelf foraminiferal grainstones and packstones to restricted shelf bioclastic lime wackestones and shelly, argillaceous lime mudstones. The section in Fahud commences with argillaceous lime packstones with bivalves, gastropods, nautiloids and *Lockhartia* that pass up into higher energy lime grainstones and floatstones with bivalves, corals, gastropods, *Lockhartia* and *Nummulites*. The prominent dip slopes of Fahud and Natih are made up of the next unit, a distinctive meganodular foraminiferal lime grainstone with gastropods, bivalves, miliolids, alveolinids and *Lockhartia*.This unit shows patchy dolomitisation in Fahud. Above a distinctive alveolinid packstone and a series of cross-bedded lime grainstones, the section passes up into interbedded chalky bioclastic lime wackestones with ostracods and *Lockhartia* and shelly argillaceous lime muds. The top of the section is covered by recent wadi gravels.

STRUCTURE (INCLUDING MARADI FAULT ZONE): The Natih and Fahud folds are separated from the Sufrat al Khays area by a NW-SE trending oblique strike-slip fault downthrowing to the SW. The folds appear to the southern side of and with an angle to this major structure known as the Maradi fault zone. It is a transtensional strike-slip fault (Hanna and Nolan, 1989). In the study area the sense of movement is, however, quite clearly down to the SW as shown by rotation of the bedding of the Tertiary limestones in the hanging-wall of the fault from a regional dip of 0-10° to a 70° dip towards the SW. The Tertiary limestones are exposed in a series of linear ridges on the SW side of the fault. The fault can be traced as far NW as an isolated outcrop of Tertiary sediments to the north of the Natih structure (Figure 1 & 2). Both Fahud and Natih are well-developed doubly plunging anticlines with Natih being the more open structure. Tighter folding of Fahud has led to the exposure of Aruma shales in the core of the anticline, which show an angular discordance of 7° with the unconformably overlying Palaeogene sediments. Although dips on the Fahud and Natih anticlines rarely exceed 25°, Fahud is slightly over turned towards the south and Natih towards the north.

As in Jebel Qusaybah and Jebel Salakh, several structural elements indicating either shearing or extension are well-displayed:

i. *Normal faults:* In Natih a number of small-scale normal faults were mapped on the southern limb of the anticline. Their trend appears to swing from NE-SW in the western part of the fold to NW-SE, i.e. parallel to the Maradi fault zone in the east. In Fahud, the normal faults appear to be concentrated in two sets, one parallel to and one perpendicular to the fold axial trace. Of particular interest is a 100° trending normal fault, down throwing to the south (downthrow approx. 20 m) which can be traced for 20 km along the northern flank of Jebel Fahud. The alignment and sense of movement on this fault compares rather well with the surface projection of the subsurface Fahud fault traced from Tschopp (1967). Many of the PDO producing wells are located along the trace of this fault.

ii. *Growth faults:* These syn-sedimentary faults, defined by greater stratigraphic thickness on the hanging wall than in the footwall are well developed in Natih and Fahud. The alignment of these faults appear to be dominantly perpendicular to the fold axial trace - i.e. parallel to one of the sets of normal faults.

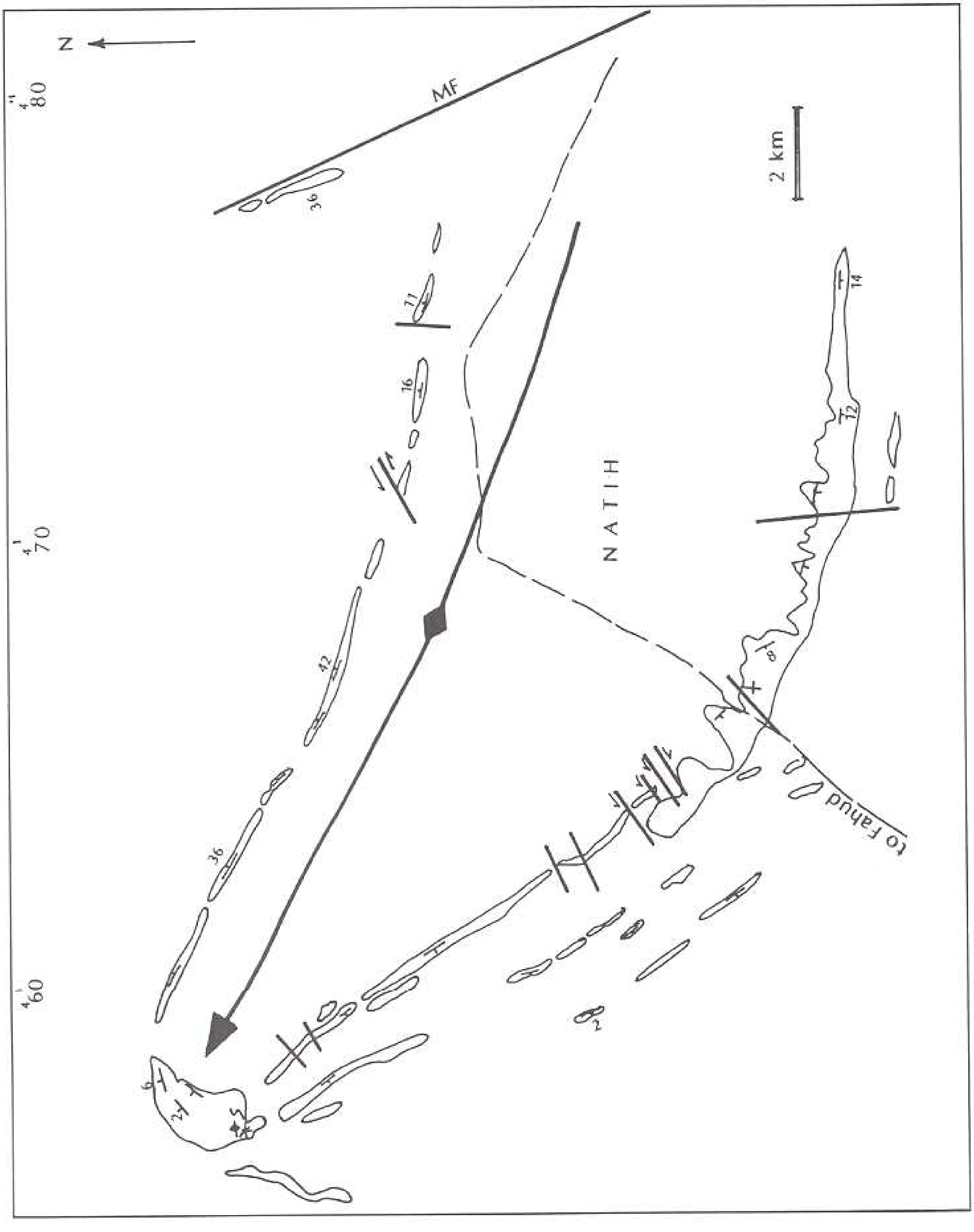

Figure 11. Geological map of Natih oil field. All exposed rocks are Palaeogene carbonates.

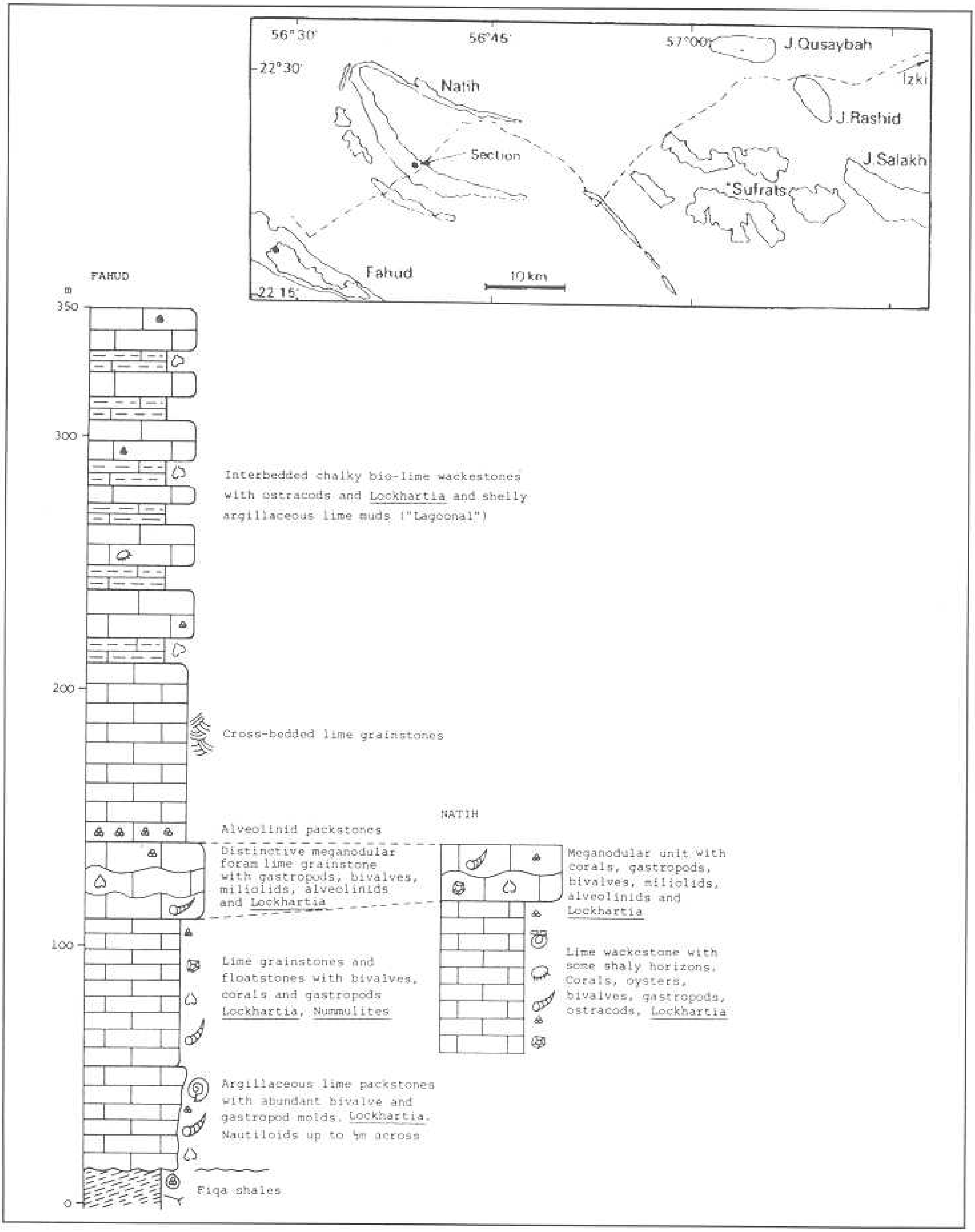

Figure 12. Simplified stratigraphic section of Palaeogene carbonates, Natih and Fahud.

iii. *Strike-slip faults:* In Natih, strike-slip faults with a NE-SW trend, a sinistral sense of movement and maximum displacements of 200m are well developed along the southern flank of the jebel. In Fahud, although Tscopp (1967) mapped some subsurface strike-slip faults with a similar trend to those seen at Natih, more have been recognized in outcrop. The sinistral sense of movement on these faults compares rather well with those mapped at Jebel Qusaybah.

iv. *Joints:* Joints are less well developed in Natih and Fahud than in Jebel Qusaybah. Here they are mostly aligned NNE-SSW, i.e. perpendicular to the fold axial traces.

Discussion

LATE CRETACEOUS STRUCTURAL GROWTH ON THE PLATFORM: Stratigraphic evidence from Jebel Qusaybah and Jebel Salakh indicate that rapid foundering of the Natih platform took place in the late Cenomanian/early Turonian with the deposition of a condensed sequence of Aruma Fe-Mn rich pelagic lime mudstones and shales on the Natih surface. Natih-derived debris flows and melanges within these Aruma shales record a period of structural growth on the platform within the Late Cretaceous In his studies of the Fahud field, Tschopp (1967) also records a period of Late Cretaceous structural growth on the platform. Here the Fahud block of Mesozoic carbonates is bounded to the South by a major normal fault downthrowing 1200 m. A one km difference in the stratigraphic thickness of the Aruma in the hanging wall and footwall of this fault confirms that it was active during the Late Cretaceous - i.e. the fault was active during the development of the Aruma basin. The Fahud fault scarp must have been an order of magnitude greater than that invoked from stratigraphic evidence for Jebel Salakh where the restriction of the clasts in the Aruma debris flows and melanges to the uppermost Natih indicate a scarp of no more than 100 m height.

To account for these phases of syn-Aruma structural growth on the platform, the tectonic environment in which the Aruma basin developed has to be established. Theoretical considerations of the behaviour of continental lithosphere during loading by thrust sheets (Beaumont 1981), Patton and O'Connor (1988) and the observation that throughout much of the Oman mountains, the syn-orogenic Late Cretaceous Aruma Group rests unconformably on the Mesozoic undergoing erosion of its crest. The Aruma Group rests unconformably on successively younger and younger sediments from the NE to SW in the Oman mountains; the amplitude of the peripheral bulge was consequently decreasing in a south-westerly direction as the effects of lithospheric loading were felt less and less on the foreland away from the thrust front.

In tectonic terms, therefore, the Aruma basin separated the extensional regime of the peripheral bulge from the compressional regime of the thrust front. As the peripheral bulge/Aruma basin/thrust front triplet migrated across the continental margin, so the foreland sediments were subjected firstly to an extensional tectonic regime, followed by a compressional one. The peripheral bulge must have migrated onto the continent at least as far as the western margin of the Suneinah trough, the depocenter of syn-orogenic sedimentation. How far onto the continent the foreland sediments were affected by the compressional regime is a debatable point. Glennie *et al.* (1974) proposed that the most proximal thrust of the Late Cretaceous allochthon was located off the platform edge on the slope of the carbonate margin and is now seen at the base of the Sumeini Group. Hanna (1990) has questioned this interpretation and shows foreland sediments as far south as Jebel Salakh affected by thrusting. So, it would be possible to explain the Late Cretaceous structural growth on the platform in both the Madamar-Salakh-Qusaybah and Natih-Fahud trends by either extensional or compressional forces. In Jebel Salakh, the Natih-derived melanges and debris flows, evidencing the structural event, are enclosed in Aruma shales which lack any Hawasina derived material, possibly indicating that these sediments accumulated well in front of the thrust front, possibly still in the extensional regime before the compressional forces had been transmitted to this part of the foreland. However, the evidence is inconclusive. At Fahud, the descriptions show a southerly downthrowing normal fault active during Aruma deposition.This could either be the southern margin of a horst block formed during the extensional phase or as a culmination collapse structure formed above a southward-verging thrust during the compressional phase. As noted above, the scale of this feature is an order of magnitude greater than at Jebel Salakh.

Mapping of Jebel Fahud has shown that structures in the outcrop can be matched fairly well with structures in the sub-surface - e.g. the Fahud fault can be shown to have been active from at least the Late Cretaceous to the Oligo-Miocene. If the Fahud fault is a culmination collapse structure above a southward-verging thrust, then it could be argued that this parent thrust was reactivated during the Oligo-Miocene to produce the present fold structure in the Paleogene strata. Indeed some support for this idea comes from the observations that the crest of the Fahud fold lies to the south of the Fahud block of Mesozoic carbonates

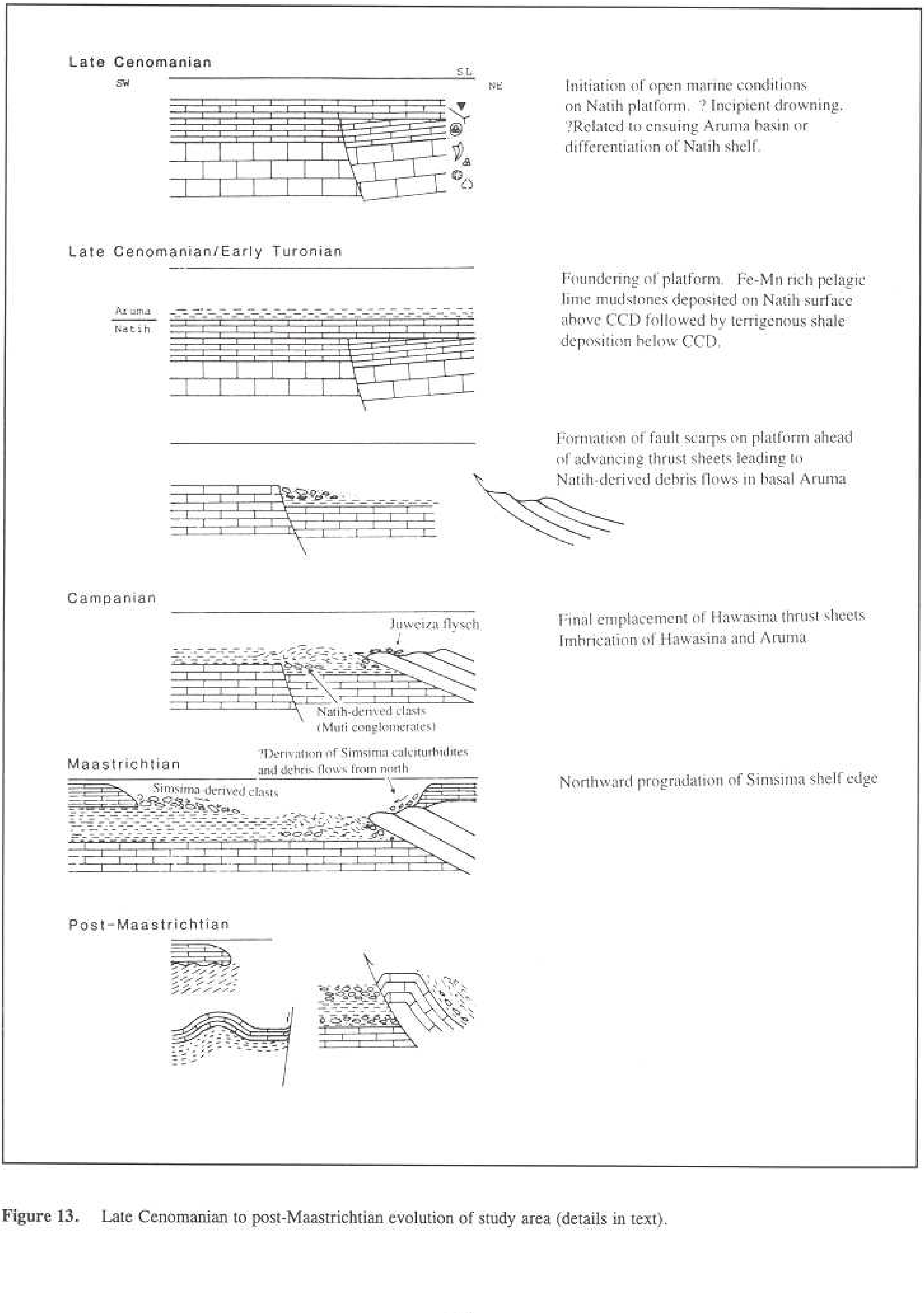

Figure 13. Late Cenomanian to post-Maastrichtian evolution of study area (details in text).

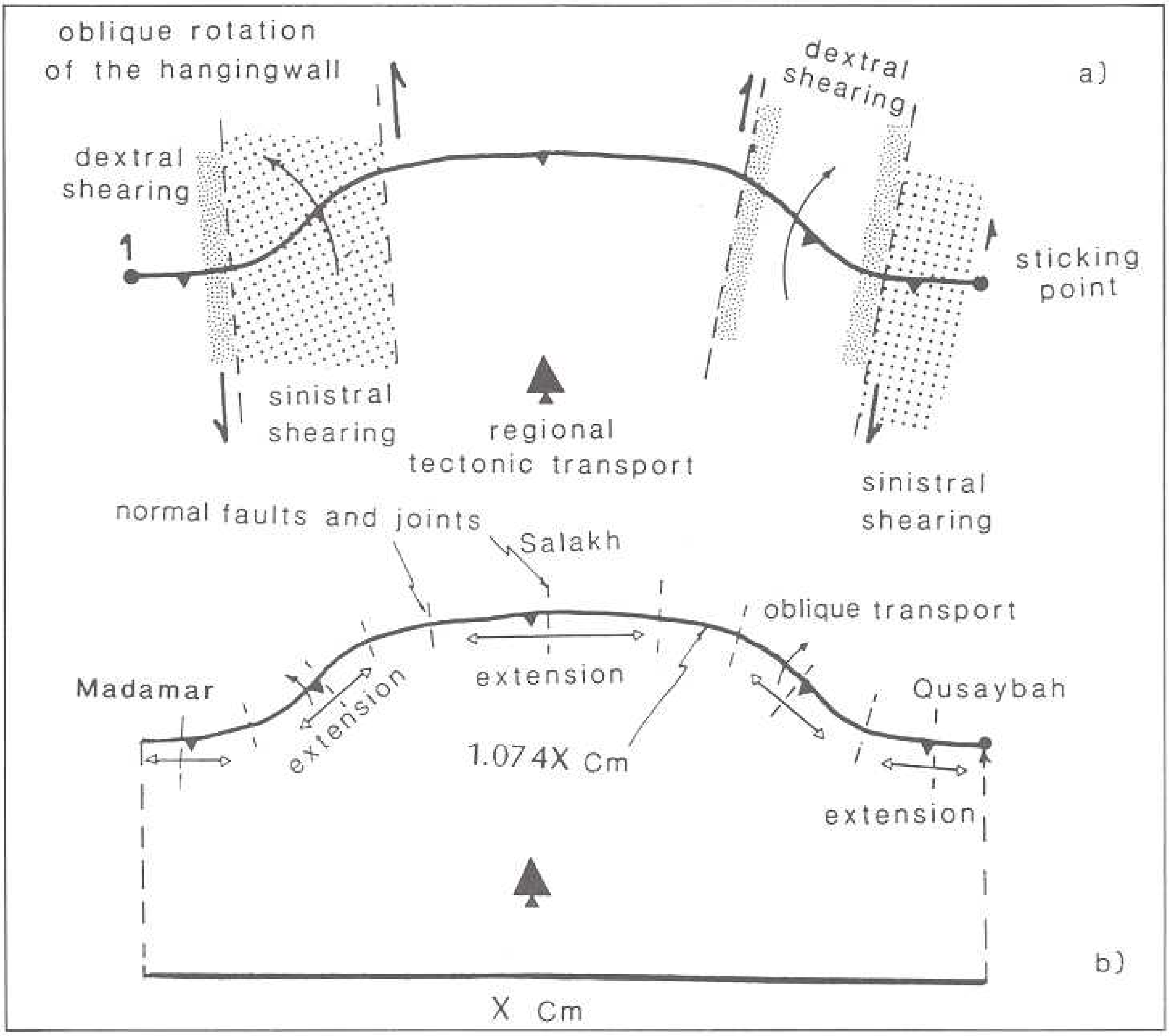

Figure 14. Diagram illustrating development of normal faults, extensional fractures and sinistral shear zones in Jebel Qusaybah by stretching of leading edge of thrust sheet along an arcuate ramp (details in text, see also Figure 1).

(most PDO producing wells are on the north flank of Jebel Fahud).

Fahud well No.1 drilled into salt beneath the Palaeozoic sequence at 3600 m. Kent (1970) doubted whether the salt was in its correct stratigraphic position and considered that it had migrated. The structural fabric of Fahud does not lend itself to an interpretation as a salt diapir - i.e. fault and joint patterns are explicable in terms of compressional forces (see below). It is possible, however, that the occurrence of salt beneath Fahud might be as an easy gliding surface on the parent thrust plane. In this way the existence of the salt might have contributed to the finite geometry of the structure but was not instrumental in its formation. Alternatively, the salt may have played a more passive role by migrating into the already developed Late Cretaceous structure.

In conclusion, structural growth on the platform took place in the Late Cretaceous in both the Natih-Fahud and Qusaybah-Madamar trends. Evidence to hand is inconclusive in assigning either an extensional or a compressional mechanism to this period of tectonic activity.

LATE CRETACEOUS AND TERTIARY TECTONIC EVENTS IN THE NATIH-FAHUD AND MADAMAR-SALAKH-QUSAYBAH RANGE: During the Campanian, final emplacement of the Hawasina thrust sheets with imbricated Aruma shales took place in the Hamrat Duru ranges, shedding the coarse flysch derived from the Juweiza into the

Aruma basin and causing structural thickening of the Aruma shales (Figure 13). A large but unknown thickness of Aruma sediments were deposited at this time when the Aruma basin was initially deepening, as what was left of the peripheral bulge migrated continentward, and later was shallowing due to isostatic compensation. The evidence for shallowing is seen in the Aruma of the Sufrat al Khays area where firstly, calciturbidites, then carbonate debris flows, and finally, channelised lime grainstones were shed into the basin from the south-west during the Maastrichtian. During orogenesis in the Oman mountains, normal platform sedimentation had continued unabated in the stable areas to the south; the debris seen in the Aruma of Sufrat al Khays records the northward progradation of the Simsima shelf edge out over the Aruma basin and marks the recovery of stable platform sedimentation as deformation ceased in the north. At this time, Simsima sediments may also have been developing on allochthonous units to the north-east of the Aruma basin, in the UAE (Nolan et al., 1990) and shedding debris into the basin from the north. However, if ever present, any record of the Simsima being deposited on the allochthonous units has subsequently been removed by erosion. Regardless of whether Simsima progradation took place from the north or the south, no Simsima platform was established in the study area; deposition remained entirely pelagic throughout the Late Cretaceous. In the Paleogene, shallow marine carbonates were deposited on slightly folded Aruma shales in the south-west of the study area and were subsequently down-faulted against the Aruma shales along the Maradi fault zone.

The Tertiary carbonates of Natih and Fahud have been folded into doubly-plunging anticlines during the Oligo-Miocene time in the Oman mountains. Because the Tertiary sediments do not come into direct contact with the folded Cretaceous shelf carbonates of the Madamar-Salakh-Qusaybah range, to determine whether the age of this folding is Late Cretaceous or Tertiary is more problematic. Some light can be shed on the problem from the stratigraphy of the Aruma Group in the Sufrat al Khays area. Here, Campanian-Maastrichtian debris flows, less than 2 km south of Jebel Salakh, contain clasts derived exclusively from the Simsima shelf edge which at that time lay at some distance to the south. Natih-derived clasts are conspicuously absent. This is taken to indicate that Jebel Salakh and, by inference, the wide range being the most adjacent potential source of Natih clasts, was covered by Aruma shales at this time and did not form the distinctive positive feature of the present day. Thus notwithstanding the evidence presented above for an early period of structural growth in the range, and the evidence that folding is thrust-related (box-fold geometry), the main folding episode is, nevertheless, post-Maastrichtian, most likely Oligo-Miocene. The very fact that the Maastrichtian marked a period of return to stable platform sedimentation again implies that Late Cretaceous deformation had ceased in the area and that the folding and thrusting of the range was a later episode separated by a period of tectonic quiescence. The extensional component along the Maradi fault zone postdates the Oligo-Miocene folding and is the youngest structural event in the area and in Oman (Hanna and Nolan 1989).

The effect of the Oligo-Miocene event in the Natih-Fahud and Madamar-Salakh-Qusaybah range was to produce a series of doubly-plunging anticlines in the Tertiary strata of the former and the Cretaceous strata of the latter. The dominant structural features of these folds are joints and normal faults, indicating extension perpendicular and parallel to the fold axial traces. It is invoked that the transverse N-S set of normal faults and joints as well as the sinistral shear zones seen in Jebel Qusaybah (Figure 14) are the result of the arcuate form in map-view of the thrust plane mapped from field data and extrapolated beneath the Madarmar-Salakh-Qusaybah range. In this model the sinistral shear zones develop at the junction of the frontal ramp of Jebel Qusaybah and the oblique ramp of Jebel Rashid. Because the hanging wall is being accommodated above a longer arcuate ramp (the original map length of the hanging wall between Jebel Madamar and Jebel Qusaybah Fig 14 a extended 7.4% in Figure 14 b). Extension of the leading edge will take place parallel to its trace (i.e. 7.4% stretching along the length of the thrust) and produces the N-S set of normal faults and joints. The E-W set of faults, which cut the N-S set, are interpreted as frontal and dorsal culmination collapse structures depending on whether they lie on the south or the north flank respectively.

If Jebel Qusaybah can be used as an analogue for a possible Natih culmination in the sub-surface, the association of fault gouge with the normal faulting may be of interest in terms of enhanced permeabilities within the reservoir. Most freshly developed fault breccias or gouge are likely to have higher permeabilities than the wall-rocks due to poor sorting and grain fracturing. These faults and associated extension fractures may then have been preferred conduits for oil flow. The high permeability of the intensely fractured Natih Formation would be abruptly cut off at the depositional contact with the less indurated Aruma shales which even if they were faulted and fractured in the same regime as the Natih Formation would develop fault gouge of low permeability. Such a barrier to fluid flow may lead to a hydrocarbon accumulation.

Acknowledgments

Samir Hanna wishes to thank Sultan Qaboos University for the support it provided and to Majid Al-Khanjari from CET, SQU, for his assistance with draughting some of the illustrations. Samir is also indebted to the Earth Resources Institute (ERI), Swansea, for the logistic and full support during both the field and writing up stages. The authors wish to thank Amoco Production Company for funding the field work and the Ministry of Petroleum and Minerals for their assistance.

References

ALLEMANN, F. and T. PETERS, 1972. The ophiolite-radiolarite belt of the north Oman mountains. *Eclogae Helvetiae*, **65**, 657-697.

BEAUMONT, C. 1981. Foreland basins. *Geophys. J.R.Astr. Soc.* **65**, 291-329.

BECHENNEC, F., J. ROGER, J. LE METOUR, and R. WYNS, 1992. Geological map of Seeb, with explanatory notes., *Ministry of Petrol. Min, Sultanate of Oman*, NF 40-03.

BOOTE, D.R.D., D. MOU, and R.I. WAITE, 1990. Structural evolution of the Suneinah Foreland, Central Oman Mountains: *in* Robertson, A.H.F., M.P. Searle, and A.C. Ries, (Eds), *The Geology and Tectonics of the Oman Region. Geological Society* of London, Special Publication **49**, 397-418.

COLEMAN, R.G. 1981. Tectonic setting for ophiolite obduction in Oman. *J. Geophys. Res.* **86**, 2497-2508.

GLENNIE, K.W., M.G.A. BOEUF, M.W. HUGHES-CLARKE, M. MOODY-STUART, W.F.H. PILAAR, and B.M. REINHARDT, 1974. Geology of the Oman Mountains. *Trans. of the Royal Dutch Geolog. Mining Soc.* **31**.3 parts.

HANNA, S.S. 1990. The Alpine deformation of the Central Oman Mountains. In Robertson, A. H. F., M.P. Searle, and A.C. Ries (Eds). *The Geology and Tectonics of the Oman Region.* Geological Society of London, Special Publication **49**, 341-359.

HANNA, S.S. 1991. En-echelon fold pattern in oblique ramp regions of foreland fold and thrust belts: example from Oman. *Annales Tectonicae*. **1** pp. 49-63.

HANNA, S.S. and S.C. NOLAN, 1989. The Maradi Fault Zoan: evidence of Late Neogene tectonics in the Oman Mountains *Journal of Geol. Soc. London*. **146**, 867 - 871.

HANNA, S.S., 1995. Field Guide to the Geology of Oman, *The Historical Association of Oman*, **180**. pp.

HARRIS, P.M. and S.H FROST, 1984. Middle Cretaceous carbonate reservoirs, Fahud Field and Northwestern Oman. *American Association of Petroleum Geologists Bulletin*, **28**, 649-658.

KENT., P.E. 1970. The salt plugs of the Persian Gulf region. *Trans. Leicester Literary and Philosophical Society* **LXIV** 56-88.

LEES, G.M., 1928. The geology and tectonics of Oman and of parts of southeastern Arabia. *Quart. J. Geol. Soc. London*. **84**, 585-670.

LIPPARD, S.J., A.W. SHELTON, and I.G. GASS, 1986. The ophiolite of northern Oman. *Mem. Geol. Soc. London*. **11**, 178.

NOLAN, S.C., P.W. SKELTON, B.P. CLISSOLD, and J.D. SMEWING,1990. Maastrichtian to Early Tertiary stratigraphy and palaeogeography of the Central and Northern Oman Mountains: *in*: Robertson A.H.F, M.P. Searle and A.C. Ries (Eds), *The Geology and Tectonics of the Oman Region.* Geological Society of London, Special Publication **49**, 495-520.

OWEN, R.M.S., and S.M. NASR, 1958. Stratigraphy of the Kuwait-Basra area: *in Habitat of Oil*. American Association of Petroleum Geologists, Special Publication, 1252-1278.

PATTON, T.L., and S.J. O'CONNOR, 1988. Cretaceous flexural history of the northern Oman Mountains Foredeep, United Arab Emirates. *American Association of Petroleum Geologists Bulletin* **72**, 797-809.

ROBERTSON, A.H.F., M.P. SEARLE, and A.C. RIES, 1990. The geology and tectonics of the Oman region. *Spec. Publs. Geol. Soc. London*. **49**, 845.

SCOTT, R.W. 1990. Chronostratigraphy of the Cretaceous carbonate shelf, southeastern Arabia. In Robertson A.H.F., M.P. Searle, A.C. Ries, (Eds), *The Geology and Tectonic of the Oman Region*. Geol. Soc. Special Publication no **49**. 89-108.

SHACKLETON, R.M., A.C. RIES, P.R. BIRD, J.B. FILBRANDT, C.W. LEE, and G.L. CUNNINGHAM, 1990. The Batain Melange of NE Oman *in* Robertson, A.H.F., M.P. Searle,and A.C. Ries (Eds), *The Geology and Tectonics of the Oman Region*. Geological Society of London, Special Publication **49**, 673-696.

SIMMONS, M.D. and M.B. HART, 1987. The biostratigraphy and microfacies of the Early to Mid Cretaceous carbonates of Wadi Mi'aidin, Central Oman Mountains: In Hart, M.B. (Ed). *Micropalaeontology of Carbonate Environments*, 176-207, Ellis Horwood, Chichester.

TSCHOPP, R.H. 1967. Development of the Fahud field. *Proc. 7th World Petrol. Congr. Mexico Vol* **2**. 243-250.

VILLEY, M., J. LE METOUR, and X. De GRAMONT, 1986. Geological map of Fanjah, with explanatory notes. *Minist. Petrol. and Min., Sultanate of Oman* NF 40-03F.

WARBURTON, J., T.J. BURNHILL, R.H. GRAHAM, and K.P. ISAAC, 1990. The evolution of the Oman Mountains Foreland Basin: *in* Robertson, A.H.F., M.P. Searle, and A.C. Ries, (Eds), *The Geology and Tectonics of the Oman Region*. Geological Society of London, Special Publication **49**, 419-429.

Received 10 January 1996
Accepted 7 July 1996