STRUCTURE AND DEFORMATIONAL HISTORY OF THE HAWASINA COMPLEX IN THE SUFRAT AD DAWH RANGE, WESTERN FOOTHILLS OF THE OMAN MOUNTAINS, EASTERN ARABIAN PENINSULA

PAUL DOMINIQUE BARRETTE

STRUCTURE AND DEFORMATIONAL HISTORY OF THE HAWASINA COMPLEX IN THE SUFRAT AD DAWH RANGE, WESTERN FOOTHILLS OF THE OMAN MOUNTAINS, EASTERN ARABIAN PENINSULA

by

A thesis submitted to the School of Graduate
Studies in partial fulfillment of the
requirements for the degree of
Master of Science

Department of Earth Sciences
Memorial University of Newfoundland

April 1985

St. John's Newfoundland

FRONTISPIECE

The Sufrat ad Dawh Range.

ABSTRACT

The Semail ophiolite dominates the geological framework of the Oman Mountains and represents the southern extension of a discontinuous belt of ophiolites emplaced on the eastern edge of the Arabian continental margin in the Late Cretaceous. Its obduction led to the telescoping and emplacement of shelf, slope and basinal sedimentary sequences of Mesozoic age, corresponding to the Hajar Supergroup, the Sumeini Group and the Hawasina Complex, respectively.

The Sufrat ad Dawh Range is underlain by units of the Hawasina Complex, namely the Hamrat Duru Group and the Wahrah, Al Ayn and Haliw formations. The deformational style in this area is dominated by a regular hinterland-facing imbricate thrust stack. Two sets of imbricate thrust faults are recognized. The faults of the predominant set dip northwards, and are generally parallel to bedding. In the Wahrah nappe, they define an impressive array of connecting, rejoining and diverging splays with minor folding. This set of faults is folded on a macroscopic scale along E-W trending axes, and these folds are, in turn, truncated by steeply northerly-dipping reverse faults belonging to the second set. This second set defines a large-scale re-imbrication system, systematically repeating the Hawasina tectonostratigraphy. Open folding along N-S trending axes occurs in the southern part of the Sufrat ad Dawh Range.

The tectonic evolution of the Hawasina Complex in the Sufrat ad Dawh Range is divided into three stages. The first stage is an early imbrication event related to the telescoping of the Hawasina sequences into separate nappes, and to the tectonic superposition of these nappes in the stacking order generally displayed in the Oman Mountains. The second stage corresponds to the folding of the nappes at distinct intervals across the strike of the allochthons, and with additional shortening in the N-S direction, to the disruption of the limbs of these folds and re-imbrication of the Hawasina nappes. The last stage results either from inhomogeneous compression in the E-W direction, or bending of the nappes over a N-S oriented ramp at depth. The timing of deformation cannot be ascertained and several alternatives are presented. The re-imbrication is thought to extend at depth beneath the shelf carbonate sequences of the Hajar Supergroup.

ACKNOWLEDGMENTS

This M.Sc. project was financed by a grant from Amoco Oil Int. to Memorial University, through the intermediary of the Earth Sciences and Resources Institute (ESRI), University of South Carolina. I wish to express my appreciation primarily to T. Calon for his careful supervision in the field and during the preparation of this thesis. Thanks go to D. Cooper for many interesting discussions in the field, and for enlightening me on several aspects of the stratigraphy and the sedimentology of the Hamrat Duru Group. This study has also benefited from helpful discussions with D. Bernoulli, S. Hanna, P. Cawood and K. Green. Efficient logistical support for the field work was provided by B. Clissold. I would further like to thank B. Clissold, J. Smewing, S. Hanna and all other ESRI colleagues for providing me with an enriching experience in the Sultanate of Oman. The animated conversations on the roof of the villa, in the midst of tranquil evenings, and the occasional gourmet dinners at the local "chicken shacks", will not soon be forgotten.

Early versions of the geological maps were drafted by the ESRI personnel of the University College of Swansea, U.K. Technical assistance was provided by W. Marsh and G. McManus for photographic reductions and reproductions. L. Dodds kindly shared the task of colouring the maps.

Table of Contents

List of Figures

List of Tables

LIST OF ABBREVIATIONS

AA	Al Ayn Formation
Ch	Chert Member of the Wahrah Formation
Glst	Limestone Member of the Guwayza Formation
Gsst	Sandstone Member of the Guwayza Formation
Ha	Haliw Formation
HD	Hamrat Duru Group
J.	Jebel ("mountain" in arabic)
LL	Lower Limestone Member of the Wahrah Formation
Md	Mudstone Member of the Wahrah Formation
Mt	Metamorphic rocks of the Haybi Complex
N	Nayid Formation
NHD	Northern Hamrat Duru belt
S	Sid'r Formation
SaD	Sufrat ad Dawh Range
SHD	Southern Hamrat Duru belt
UpHD	Upper Hamrat Duru Group
UL	Upper Limestone Member of the Wahrah Formation
Wa	Wahrah Formation

Chapter 1

INTRODUCTION

1.1 General perspective and rationale of the present study

The Oman Mountains are located along the north-eastern coast of the Arabian peninsula, in the Sultanate of Oman (figure 1-1). They form an arcuate chain, 700 kilometers in length, that extends from the Strait of Hormuz in a south-easterly direction towards the Indian ocean. They separate the Gulf of Oman to the north-east from the arid deserts of Saudi Arabia to the south-west. This region is well known, geologically, for hosting the Semail ophiolite, which represents one of the largest and best exposed fragments of ancient oceanic lithosphere in the world (e.g. Coleman, 1981). At the end of the Cretaceous, the Semail ophiolite was emplaced from the north-east onto the Arabian continental margin, in conjunction with a telescoped Mesozoic succession of slope to basinal sedimentary rock sequences deposited along this margin. These units, designated the Hawasina Complex (Glennie et al., 1973, 1974), are now superbly exposed in the foothills of the western, external part of the mountain belt, and in windows centered on antiformal culminations in the internal part of the belt.

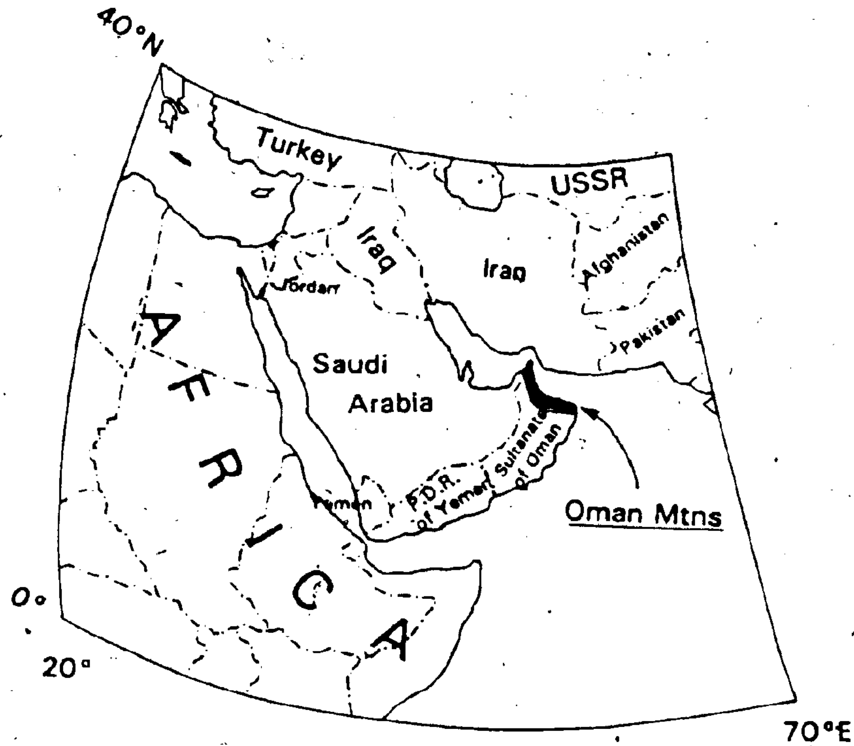


Figure 1-1: Location of the Oman Mountains in the Middle-East.

Regional geological investigations conducted by Glennie et al. (1973, 1974) in the Oman Mountains, showed that the deformational style of the Hawasina nappes is typically dominated by extensive hinterland-facing imbricate thrust stacks, and southwesterly verging folds. Moreover, the Hawasina Complex is composed of a series of tectonostratigraphic units, or nappes, each formed of a folded and thrusted succession of sedimentary rocks of a distinct facies. A number of these nappes are recognised in the Oman Mountains. The way in which they are structurally "stacked" follows a very consistent order, which is interpreted by Glennie et al. (1973, 1974) in terms of a simple palinspastic reconstruction, such that the higher nappes within the Hawasina Complex originated farther from the Arabian continental margin, than did the lower nappes. The Hawasina Complex now lies tectonically above the shelf carbonate sequences of the Arabian platform, and is overlain by the Semail ophiolite in the internal part of the mountain belt.

The Sufrat ad Dawh Range provides a well exposed segment of the Hawasina Complex in the western foothills of the Oman Mountains. This range is of particular interest, because it displays large-scale structures that are not characteristic of the deformational style of the Hawasina Complex in the Oman Mountains. Glennie et al. (1974) revealed the occurrence of a major reversal in the usual tectonic superposition of the Hawasina nappes, referred to as one of several local exceptions to an otherwise consistent tectonic pattern. Further, these workers indicated the possible existence of an E-W trending antiformal culmination in this area, affecting the contact of two distinct Hawasina nappes and leading to the formation of a tectonic window. Such a structure has not been reported elsewhere in the western foothills.

1.2 Purpose and methods of the present study

The purpose of the present study is to examine in detail, in the light of recent advances in modern thrust tectonics, the internal structural geometry of the Hawasina Complex in the Sufrat ad Dawh Range, and to determine the kinematic evolution of the Hawasina nappes exposed in this area.

To achieve these goals, a N-S trending structural transect of the Sufrat ad Dawh Range was mapped at scales of 1:20 000 and 1:50 000. Several structural cross-sections were drawn to aid in the understanding of the geometrical configurations and relationships of the Hawasina nappes in this area. The mapping was carried out mainly with the use of 1:60 000 black and white air photographs with overlays. Coloured, oblique aerial photographs, taken during a low altitude plane overflight, and stereograms are provided to corroborate the information conveyed by the geological maps.

1.3 Physiography and climate

The general physiographical outline of the Oman Mountains is shown in figure 1-2. The backbone of the mountains is dominated by the Jebel Akhdar - Jebel Nakhl - Saih Hatat topographical lineament, which is formed of rugged peaks and ridges rising 3000 meters above sea level. These mountains are deeply incised by tortuous wadis (dry creeks) generally less than a few hundred meters in width. In the foothills, the topography consists of vast surface areas of hilly bedrock terrain ranging in elevation up to several hundreds meters, with variable proportion of stony gravel plains.

Oman is essentially a desert. Apart from the luxuriant date tree oases occasionally encountered along the wadis, the vegetation is restricted to sparsely distributed thorny acacia shrubs. The degree of rock exposure rather depends on the amount of gravel plain. The average exposure in the mountains reaches 100%, while in the foothills it exceeds 80%.

The temperature in the western foothills varies from 10^{o}-30^{o}C in January to 30^{o}-45^{o}C in July. The humidity is much higher along the coast than at the western side of the mountains. Because of the high temperature experienced in the summer, the winter months are more propitious for field work.

Although the winter is referred to as the rainy season, the annual precipitation averages less than 500 millimeters, most of it occurring during short, sudden rainstorms. In

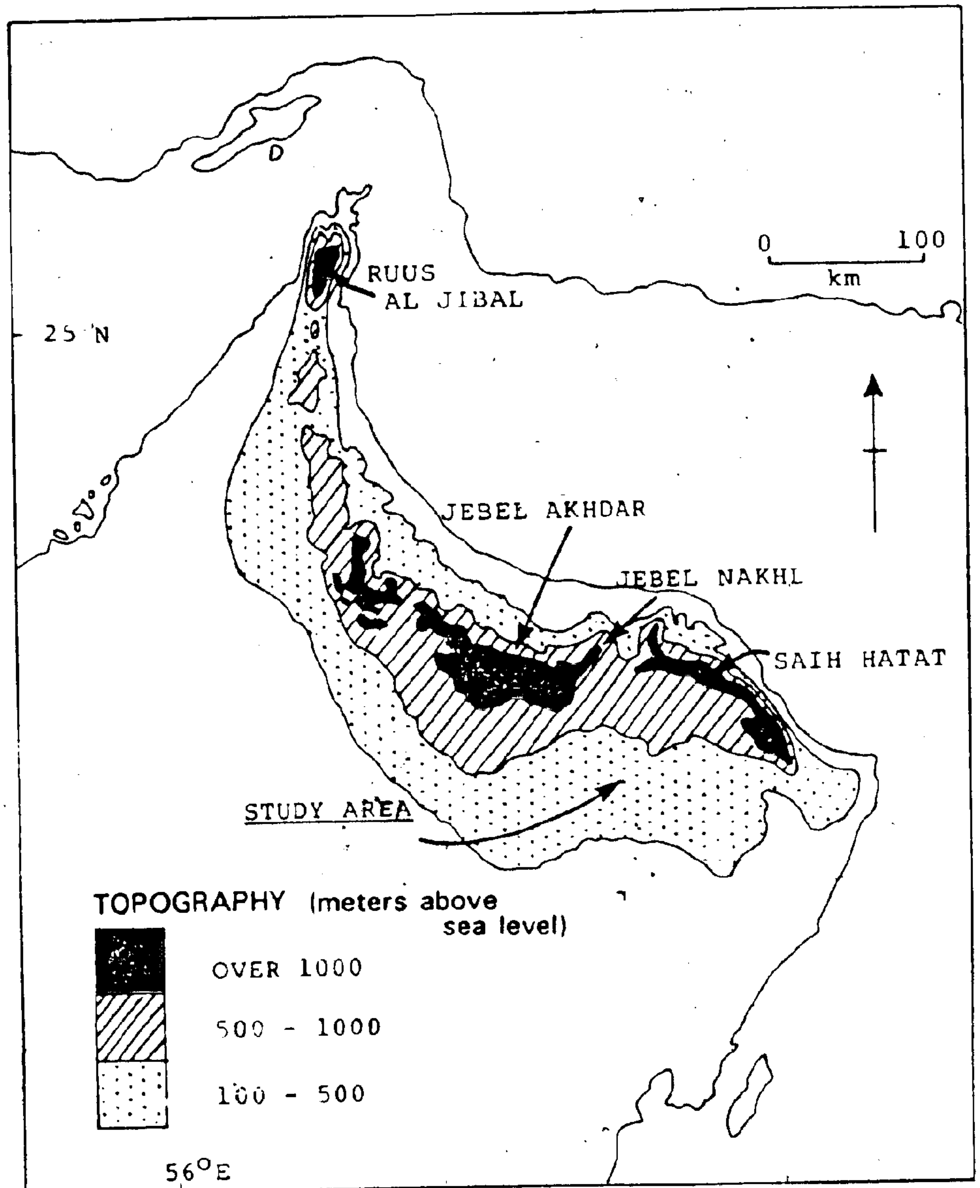


Figure 1-2: Physiography of the Oman Mountains.

the mountains, these storms result in very hazardous "flash floods" dashing down the wadis and sweeping everything in their paths. The remainder of the time, however, Oman enjoys a wide open sky.

1.4 Location, accessibility and logistics

The Sufrat ad Dawh Range is located 30 kilometers south-east of Nizwa (figure 1-3). It occupies a surface area of approximetely 500 square kilometers and lies between longitude 57°40' and 58°00'E, and latitude 22°30' and 22°50'N. It is linked to the Nizwa - Muscat highway by a major graded road and can be accessed by four-wheel drive vehicles along numerous tracks and wadis.

The field work for this study was carried out during the winters of 1983 and 1984, from January to March. From a permanent base situated near Muscat, the author either drove or was dropped off to a campsite with camping gear, food and water provisions for periods of time ranging from 3 to 10 days, which alternated with 2 to 3 days back to Muscat for re-supply.

The desert was found to be very hospitable. The weather is highly conducive to field work and the evenings are starry and extremely peaceful. The study area being fairly remote from any main centre of population, it is only inhabited by a number of bedouins and their herds of goats and camels. These people manifested much friendlyness, interest, and perhaps, sympathy for this lonesome foreigner with quite ... peculiar preoccupations.

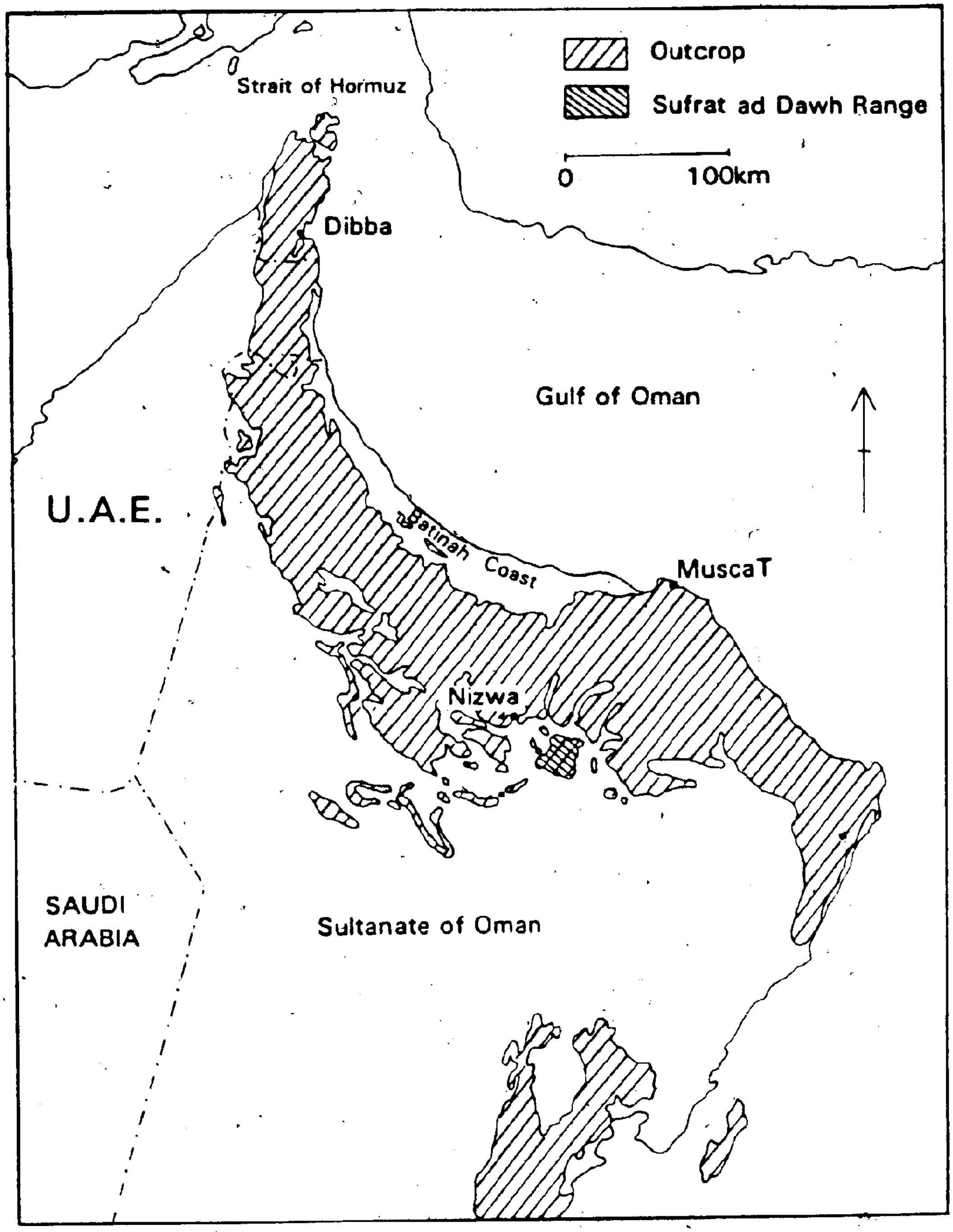


Figure 1-3: Outcrop map of the Oman Mountains and location of the Sufrat ad Dawh Range.

Chapter 2

GEOLOGICAL BACKGROUND

2.1 Regional tectonic setting of the Arabian Peninsula

The Arabian Peninsula forms a distinct element in the tectonic framework of the Middle-East (figure 2-1). It is cored by a crystalline basement of Proterozoic age referred to as the Arabian shield. This basement is exposed along a stucturally uplifted area in Yemen and western Saudi Arabia (Powers et al., 1966), as well as in the central and the south-eastern part of the Sultanate of Oman (Glennie et al., 1974; Gorin et al., 1982). In the remaining part of the peninsula, the basement is overlain by a thick and relatively undeformed succession of sedimentary rocks, whose age spans the Early Cambrian to the Pliocene (Powers et al., 1966; Murris, 1980). This succession is composed predominantly of an alternation of non-marine clastic rock sequences, such as sandstones, shales and shaly marls, and carbonate rock sequences of platformal affinities (Powers et al., 1966). The Arabian peninsula behaved essentially as a stable platform throughout the Paleozoic and the Mesozoic eras, as well as most of the Cenozoic.

To the west and the south, the Arabian shield is separated

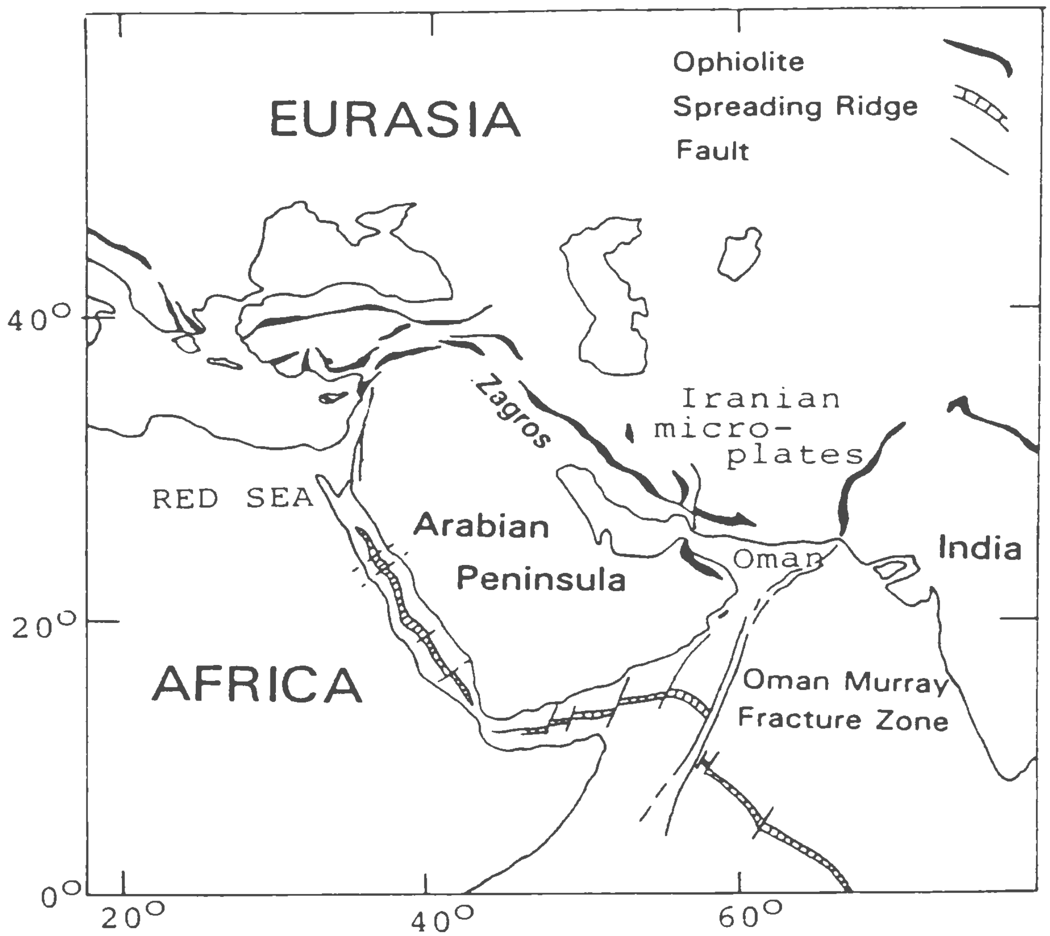


Figure 2-1: Regional tectonic setting of the Arabian peninsula (modified after Coleman, 1981).

from the African continent by the Red Sea Rift which was initiated in the Late Cretaceous (Girdler, 1980). To the south-east, it is bounded by the Oman-Murray Fracture Zone (Coleman, 1981). Towards the north and the east, the Arabian platformal sequences become progressively more deformed as they reach the Zagros suture zone (Powers et al., 1966; Falcon, 1967). This belt is part of the Alpine-Himalayan mountain chain, and stretches easterly from the Mediteranean Sea into Turkey and south-easterly into

Iran towards the Strait of Hormuz, then extends southwards in the Sultanate of Oman (see figure 2-1). It coincides with a discontinuous alignment of ophiolites and radiolarites; the southernmost extension of this belt is represented by the Semail ophiolite and the Hawasina Complex (Ricou, 1971).

North-east of the Zagros belt, across the Gulf of Oman, lie the Iranian microplates and Eurasia (Stocklin, 1974; Adamia et al., 1980). In the late Precambrian and Paleozoic time, the Arabian peninsula and Iran were in cratonic continuity and formed part of Gondwanaland (Stöcklin, 1974). Rifting and fragmentation of this landmass began in the Triassic, and led to the formation of the Afro-Arabian plate and the Iranian microplates, which were separated by the "Neo-Tethys" seaway from the Triassic to the Late Cretaceous (Stocklin, 1974; Hsu and Bernoulli, 1978; Adamia et al., 1980). This rifting episode proceeded concurrently with the closure of a Paleo-Tethys ocean to the north, separating the Eurasian continent and the Iranian microplates (Adamia et al., 1980). The closure of the Neo-Tethys occurred when the Afro-Arabian continent was drifting north towards a north-dipping subduction zone beneath Iran. In Late Cretaceous time, the Afro-Arabian continent and the Iran microplates collided and this resulted in the obduction of the ophiolites and the emplacement of radiolarites and other pelagic Mesozoic sedimentary sequences onto the eastern margin of the Arabian continental margin (Ricou, 1971, 1976; Adamia et al., 1980).

A large part of the deformation in the Zagros Fold Belt occurred in the Pliocene and consisted of an early phase of SW-NE oriented, horizontal shortening which resulted in south-west directed thrusting and NW-SE oriented upright folding (Ricou, 1976). Post-Oligocene deformation is also recognized in Oman (Morton, 1959), but the importance of this deformation is difficult to assess, due to the scarcity of post-Late Cretaceous, pre-Miocene rock cover. Rock units of that age are extensively exposed along the Zagros Fold Belt.

Seismic evidence indicates that the alpine tectonics are still active today. In Iran, this is also shown by the tilting of terraces and beaches and recent volcanic activity (Adamia et al., 1980). The present Zagros belt is the locus of regional strike-slip movement (Ricou, 1976; Adamia et al., 1980).

2.2 Previous geological investigations in the Oman Mountains

The first significant contribution to the geology of the Oman Mountains was made by Lees (1928) who established a broad stratigraphical framework. He identified the Pre-Permian basement, its cover of shallow-marine Mesozoic shelf carbonate sequences, the complexly deformed "Hawasina Series", the "Semail Igneous Series" and the post-Senonian shallow-marine carbonate sequences. On the basis of limited paleontological and field evidence, Lees deduced the allochthonous nature of the Semail and the Hawasina Series, and placed constraints on the time of their emplacement, relating it with the pre-Gossau movements of the Alps (pre-Cenomanian).

Morton (1959), in a synopsis of geological investigations carried out by oil companies, presented a more elaborate account of the stratigraphy, and refuted the allochthonous thesis of Lees (1928). He proposed an in-situ origin for the Semail Igneous Series, by then referred to as an ophiolitic suite, and the Hawasina Series. This was supported by Wilson (1969), who provided additional arguments in favour of the concordant nature of the Hawasina succession, attributing the deformation of this succession to "gravity slumping".

Reinhardt (1969) conducted a field and petrological study of the Semail ophiolite, and suggested that this ophiolite originated in a deep-seated crustal environment not reconcilable with its present position on the Arabian continental margin. He proposed that these rocks formed at an ancient oceanic spreading center and were later emplaced onto the Arabian continental margin by gravity sliding. Allemann and Peters (1972) provided new field and paleontological evidence conflicting with Wilson's (1969) data, and reaffirming Lees (1928) conclusions on the allochthoneity of the Hawasina and the Semail units.

The first systematic analysis of the stratigraphical, petrological and structural aspects of the whole of the Oman orogenic belt was presented by Glennie et al. (1973, 1974).

These authors provided a comprehensive petrological and geological account of the Semail ophiolite. Furthermore, they convincingly demonstrated that the Hawasina Series of Lees (1928) can be subdivided into a succession of tectonostratigraphic units that are chronostratigraphically equivalent to the shelf carbonate sequences that they overlie. They proposed that the Hawasina units along with the Sumeini Group, a new unit which they introduced, represent slope to basinal sedimentary sequences that were deposited on the eastern margin of the Arabian continent between the Permian and the Middle Cretaceous, and were emplaced on this margin during the obduction of the Semail ophiolite. Moreover, Glennie et al. (1974) presented a series of schematic structural sections running across the trend of the Oman Mountains. These demonstrate a consistency of the tectonic stacking order of the various allochthonous elements. The Sufrat ad Dawh Range, however, displays a major exception to this scheme. This is shown in figure 2-2. In the northern part of this range, the Wahrah nappe overlies tectonically the Hamrat Duru nappe. This is in accordance with the usual tectonic relationship of these nappes as displayed elsewhere in the Oman Mountains (as discussed in the next section). To the south of this range, however, the opposite relationship is shown to occur. Glennie et al. (1974) interpreted this geometry either as a result of "secondary imbrications or thrusts, created after the two units had already been tectonically superimposed in

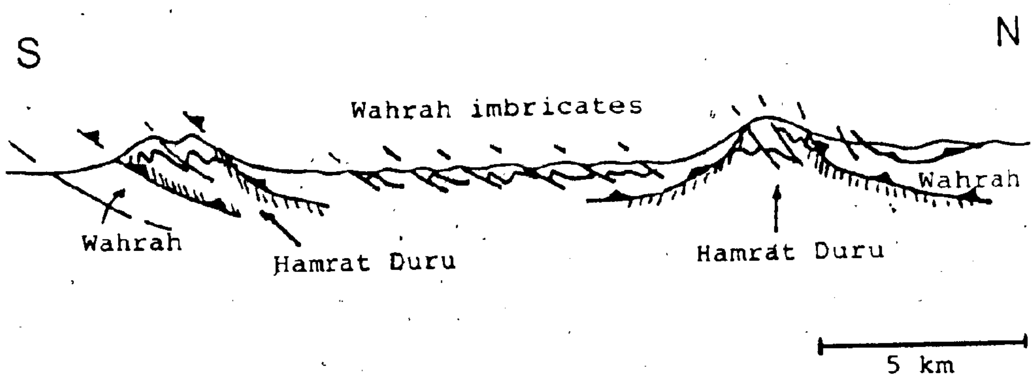


Figure 2-2: Schematic cross-section of the Sufrat ad Dawh Range (Glennie et al., 1974, Enclosure 5, section 9).

a normal way", or due to a "local envelopment of the overlying Wahrah Formation in front of the Hamrat Duru thrust sheet" (p.342). Further, while the internal structure of the Hawasina Complex in the western foothills is characterised by a regular hinterland-facing imbrication, Glennie et al. (1974) indicate the occurrence of a major antiformal culmination in the northern part of the Sufrat ad Dawh Range.

The allochthonous nature of the Hawasina and the Semail units has gained the acceptance of later workers, and various models for the emplacement of the allochthons were proposed (Elliott, 1976; Dewey 1976; Welland and Mitchell, 1977; Gealy, 1977; Graham, 1980a,b; Coleman 1981).

Searle (1980) and Searle and Malpas (1980, 1982) documented the nature and the origin of the metamorphic and volcanic rocks beneath the Semail ophiolite which they designated the Haybi Complex. The results of an extensive petrological, geochemical and structural account of the Semail ophiolite was presented by Coleman (1981) in a special issue of the Journal of Geophysical Research.

The only detailed structural investigation of the Hawasina nappes was carried out by Graham (1980a,b) in the Hawasina Window. The aim of this study was to determine the stratigraphic and structural evolution of the Mesozoic Arabian continental margin and the processes of emplacement of the Semail ophiolite.

2.3 Stratigraphy of the Oman Mountains

The rock units in the Oman Mountains have been divided into seven distinct stratigraphic assemblages, based on their lithology, their age, and their stratigraphic and tectonic relationships (Glennie et al., 1973, 1974; Searle, 1980; Searle and Malpas, 1982). These are:

- The basement units
- The autochthonous Hajar Supergroup
- The Aruma Group
- The par-autochthonous Sumeini Group
- The Hawasina Complex
- The Haybi Complex
- The Semail ophiolite
- The neo-autochthonous carbonate units

Figure 2-3 presents a geological map of the Oman Mountains showing the distribution of these assemblages. The tectonostratigraphic relationship of the assemblages is shown in figure 2-4. Note that these assemblages and the internal tectonic slices of the Hawasina Complex are generally not all present in any one area.

2.3.1 The basement units

These are exposed in the central part of the mountains in the core of the J.Akhdar-J.Nakhl-Saih Hatat windows, and along the south-eastern coast (figure 2-3 and 2-6(d)). The oldest units consist of amphibolites, gneisses and schists, intruded by granitic rocks of Late Precambrian age. These underlie a deformed and partly metamorphosed sequence of siliciclastic and carbonate units of Late Precambrian to Early Paleozoic age (Morton, 1959; Glennie et al., 1974; Gorin et al., 1982). They correlate with the Arabian basement exposed in the western part of the peninsula (Gorin et al, 1982). The deformation and metamorphism of these units is thought to be related to an Hercynian orogeny (Glennie et al. 1974; Michard et al., 1984).

2.3.2 The autochthonous Hajar Supergroup

The Hajar Supergroup consists of up to 3 kilometers of mainly shelf carbonate sequences of Middle Permian to Middle Cretaceous age, resting unconformably on the basement units (Glennie et al., 1973, 1974). They occur in the northern

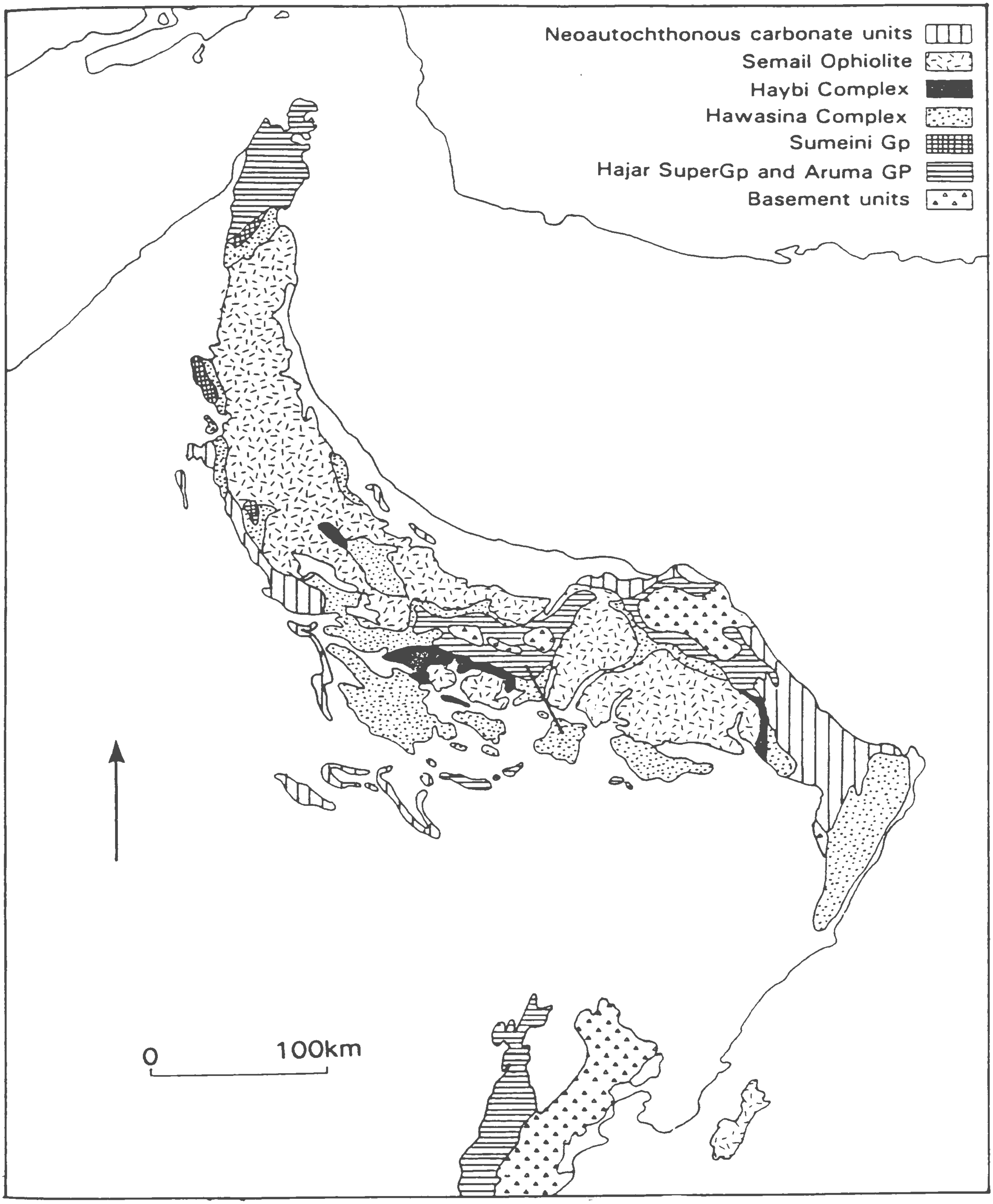


Figure 2-3: Geological map of the Oman Mountains (modified after Glennie et al., 1973, 1974). The line of section of figure 5-2 is shown.

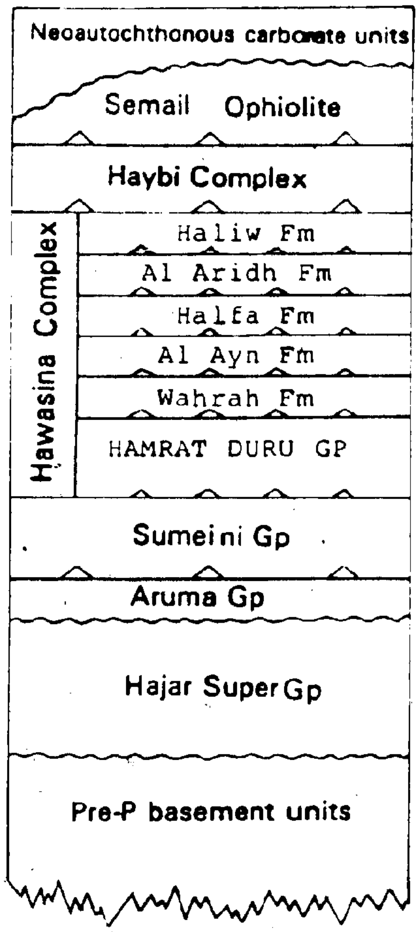


Figure 2-4: Stratigraphy of the Oman Mountains (modified after Glennie et al., 1973, 1974).

and the central part of the mountains, as well as in the western foothills. The base of the Hajar Super Group is formed of open-marine limestones, becoming progressively of a more restricted marine character towards the Middle to Late-Jurassic interval. These sequences are conformably overlain by pelagic porcellanites and cherts of Late

Jurassic to Early Cretaceous age which in turn grade into shallow-marine carbonates of Middle Cretaceous age.

2.3.3 The Aruma Group

The Aruma Group is of Late Cretaceous age and overlies unconformably and disconformably the shelf succession (Glennie et al., 1974). It contrasts with the shelf carbonates, as it is dominated by shales, turbiditic units and conglomerates. It marks a drastic change in the depositional regime in the Late Cretaceous, being related to the formation of a foredeep along the eastern part of the Arabian peninsula. The Aruma Group is locally par-autochthonous, and imbricated with the lower Hawasina nappes.

2.3.4 The par-autochthonous Sumeini Group

The Sumeini Group is only exposed in the northern part of the Oman Mountains. It ranges in age from Permian(?) to Middle Cretaceous, and comprises shallow-water dolomites, sandstones and marls, grainstones and conglomerates interbedded with shales and chert, and reefoid boundstones. Glennie et al. (1974) interpreted these lithologies "to have been deposited in the environment of a submarine reefal scree slope close to a carbonate shelf edge, or that of an outer continental shelf and slope". This slope was facing to the east. These units are referred to as par-autochthonous, because the distance over which they were transported onto the shelf sequences is believed to be relatively small.

2.3.5 The Hawasina Complex

The Hawasina Complex consists of an association of distinct litho-stratigraphic successions that are in tectonic contact and, most significantly, whose ages overlap considerably, ranging from the Triassic to the Middle Cretaceous (Lees, 1928; Allemann and Peters, 1972; Glennie et al. 1973, 1974). The number of these thrust-bounded successions varies in any one area. In the central part of the Oman Mountains, the principal ones are the following: The Hamrat Duru Group, and the Wahrah, Al Ayn, Halfa, Al Aridh and Haliw Formations (Glennie et al., 1974). These sequences are believed to have been deposited in an oceanic basin, termed the Hawasina basin, lying to the north-east of the Arabian continental shelf (see also Searle and Graham, 1982). The tectonic position of each of these sequences within the Hawasina assemblage is remarkably consistent throughout the Oman Mountains. It follows the order given above, with the Hamrat Duru Group being contained in the lowest nappe and the Haliw Formation in the highest nappe (see figure 2-4).

The Hamrat Duru Group comprises four formations. These are, from bottom to top: the Early to Late Triassic Zulla Formation, the Late Triassic to Late Jurassic Guwayza Formation, the Lower Cretaceous Sid'r Formation, and the

Middle Cretaceous Nayid Formation. The Wahrah Formation is of Early Jurassic to Middle-Cretaceous age, and the Al Ayn Formation is Late Triassic to Early Jurassic age.

These formations mainly comprise lithoclastic lime grainstones and quartz sandstones derived from the Arabian carbonate shelf edge to the west or southwest, and sequences of bedded radiolarian chert (Glennie et al., 1973, 1974). On the basis of lithology, faunal assemblage and paleocurrent data, Glennie et al. (1973,1974) interpreted the Hamrat Duru Group as the most proximal of the Hawasina sequences with respect to the Arabian continental margins, and the Wahrah Formation as a distal equivalent of the Hamrat Duru Group. Furthermore, these authors suggested that the Al Ayn Formation is a distal equivalent of the lower Guwayza Formation of the Hamrat Duru Group.

The Haliw and Halfa Formations are chiefly represented by thin-bedded radiolarite sequences and shales of Triassic to Mid-Cretaceous age (Glennie et al., 1973, 1974). They are considered by these workers as distal equivalents of the Hamrat Duru and the Wahrah sequences. The Al Aridh Formation consists to a large extent of turbiditic grainstones, and reefal conglomerates with volcanic clasts, and also includes radiolarian cherts. This formation ranges in age from Triassic to Middle Jurassic and is thought to have been deposited east of the Haliw and the Halfa Formations, along the slopes of reef-capped guyots or seamounts with a volcanic substrate (Searle and Graham, 1982). The guyots were located adjacent to the site of initial rifting of the Oman continental margin (Glennie *et al.*, 1973, 1974), or above the transitional zone within the Hawasina basin (Searle and Graham, 1982). In either case, the Al Aridh Formation is thought to have been derived from an easterly source.

2.3.6 The Haybi Complex

The Haybi Complex is a sequence of Upper Cretaceous sedimentary mélange, Upper Permian to Mid-Cretaceous volcanic rocks, isolated Upper Permian and Upper Triassic limestone exotics (Oman Exotics of Glennie *et al.* (1974)) and metamorphic rocks and serpentinites (Searle, 1980; Searle and Malpas, 1980, 1982). It lies tectonically between the Hawasina complex and the Semail nappe.

The Oman Exotics are interpreted as "reef-associated carbonate build-ups deposited in part on oceanic islands or seamounts, close to the site of initial rifting of the Oman continental margins" (Searle and Graham, 1982, p. 43). The metamorphic rocks consist of amphibolites and greenschists. They are interpreted to be a dynamothermal metamorphic aureole produced during obduction of the Semail ophiolite nappe, mainly by transfer of residual heat from the overlying ultramafic rocks (Allemann and Peters, 1972; Ghent and Stout 1981; Searle, 1980). The age of metamorphism is Senonian (Allemann and Peters, 1972).

2.3.7 The Semail ophiolite

The Semail ophiolite nappe occupies a surface area of 6000 square kilometers as a series of distinct plates and dominates the geological framework of the Oman Mountains. It displays the classical "ophiolite stratigraphy" comprising from bottom to top: 1) harzburgite tectonites, representing residual upper mantle, 2) a transition zone between the harzburgites and overlying layered ultramafic cumulate rocks, 3) cumulate gabbroic rocks, 4) hypabyssal gabbroic rocks and plagiogranites, 5) sub-volcanic feeder dykes and 6) mafic volcanic rocks (Reinhardt, 1969; Glennie et al., 1974; Hopson et al., 1981). Petrological, geochemical and seismic investigations have suggested that these rocks are part of a cogenetic suite formed at some ancient oceanic spreading ridge in Cenomian to Turonian time (Reinhardt, 1969; Glennie et al., 1973, 1974; Coleman, 1981). The Semail nappe is the highest tectonic unit in the Oman stratigraphy (figure 2-4).

2.3.8 The neo-autochthonous carbonate units

Maastrichtian and Tertiary shallow-marine carbonate sequences are exposed along the Batinah coast in the south-eastern part of the Oman Mountains and in the western foothills. They overlie unconformably all older units (Morton 1959; Tschopp, 1967; Glennie et al., 1973, 1974), and herald the transgression of an early Tertiary shelf sea over the late Cretaceous, allochthonous terrains and the Arabian Mesozoic platform.

2.4 Structure

The basic structural framework of the Oman Mountains is characterised by nappe tectonics. The Hajar Supergroup and the Aruma Group, considered as autochthonous, are overlain successively by the Sumeini nappe, the Hawasina Complex, the Haybi Complex and lastly, the Semail ophiolite. These nappes are internally deformed to various extent according to the type of lithologies involved. While the Hawasina, the Sumeini and the Haybi units are generally strongly folded and imbricated (Graham, 1980; Searle, 1980; K. Watts, 1984, pers. comm.), the structure of the Semail ophiolite nappe is more cohesive; imbrication occurs, but is much less important. The Maastrichtian and Tertiary carbonate units are also deformed, but to a lesser extent. This deformation consists of simple folding, and imbrication is not a major feature.

The internal structural grain of the Mesozoic allochthons parallels the Oman coastline, trending in a NW-SE direction in the north and the central Oman Mountains, deflecting to a NE-SW orientation south of Muscat (figure 2-5). Two major sets of fold axes are recognized. Folds belonging to the predominant set parallel the structural grain of the Oman Mountains, and affect all units of the Oman stratigraphy. The second set is not as widespread as the former, and is generally perpendicular to the regional grain. It is not recorded in the neo-autochthonous carbonate units.

The physiographical apex of the Oman Mountains (see

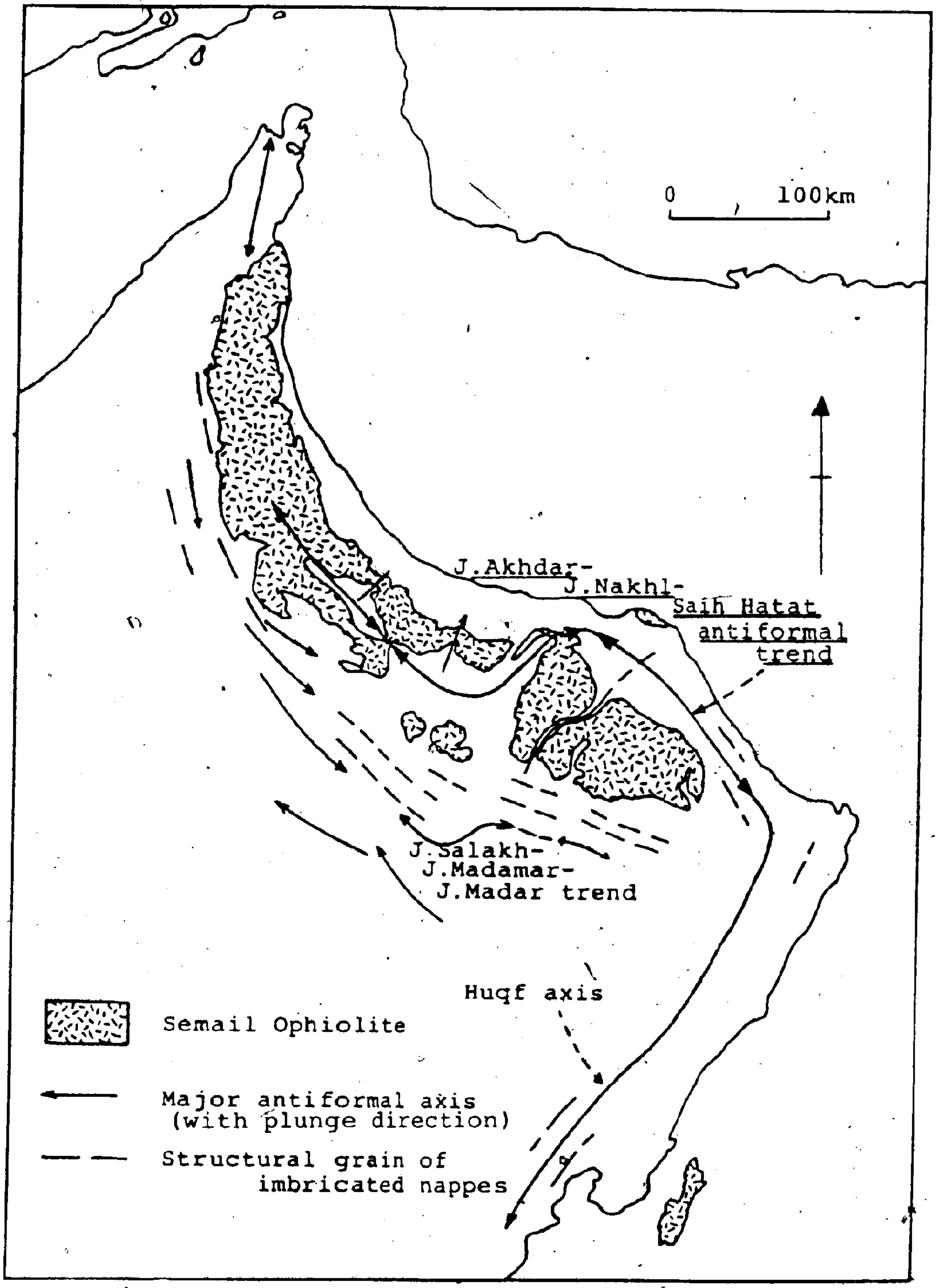


Figure 2-5: Generalized structural map of the Oman Mountains.

figures 1-2 and 2-5) is the expression of a prominent antiformal axis, termed the J.Akhdar-J.Nakhl-Saih Hatat antiformal culmination. The entire tectonostratigraphy of the Oman mountains is exposed in the core of this structure. The culmination is variably plunging and bears an overall NW-SE orientation and may thus be assigned to the main set of fold axes. This culmination, however, also comprises two NE-SW oriented segments represented by J.Nakhl and the Huqf axis, which parallel the second set of fold axes.

Another belt of variably plunging antiforms of a smaller amplitude occurs in the western foothills. It is recorded in the Mesozoic shelf carbonate sequences and roughly parallels the J.Akhdar-J.Nakhl-Saih Hatat structure. This structure is referred to as the J.Salakh-J.Madamar-J.Madar antiformal trend.

2.5 Tectonic evolution of the Oman Mountains

The pre-Permian

During the late Precambrian and most of the Paleozoic, when Arabia and Iran were in cratonic continuity, the depositional history of Oman was dominated by shallow-marine sedimentation in a wide epicontinental sea (Glennie et al., 1974; Gorin et al., 1982; Lovelock et al., 1981). These sequences were deformed and metamorphosed during the Hercynian orogeny (Glennie et al., 1974; Michard et al., 1984).

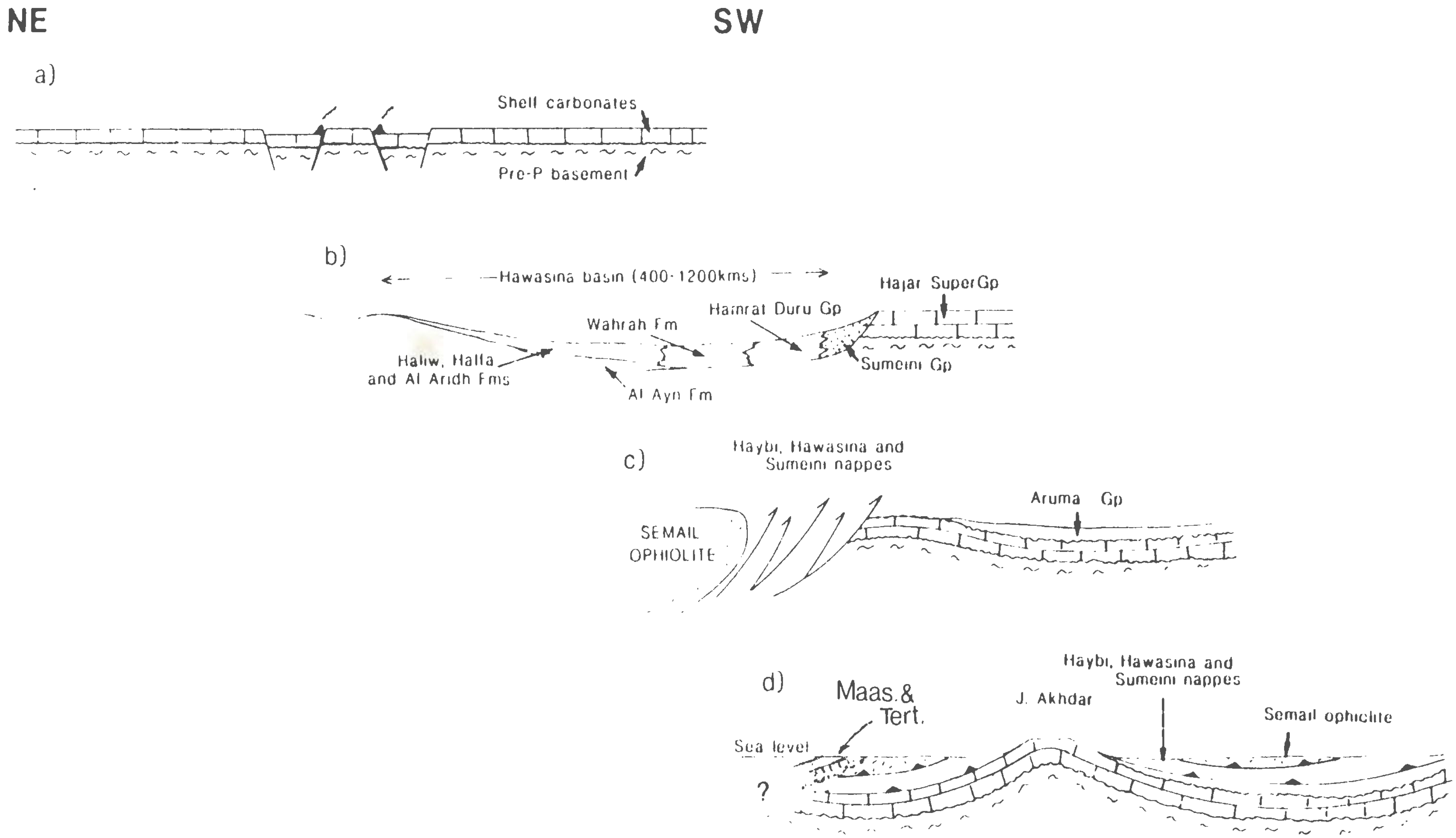


Figure 2-6: Tectonic evolution of the Oman Mountains (see text for discussion).

From the Permian to the Late Cretaceous: Rifting and development of a carbonate margin

The onset of continental fragmentation took place in the Permian (Glennie et al., 1974; Graham, 1980a; Searle and Graham, 1982) (figure 2-6a). In the Late Triassic, the Hawasina ocean had already opened and basinal sedimentation took place, which proceeded until the Middle-Cretaceous. The Hajar Supergroup, the Sumeini Group and the Hawasina sequences represent the shelf-slope-basin transition, respectively, of the Oman continental margin. The paleogeographic reconstruction of the Hawasina sequences proposed by Glennie et al. (1973, 1974) is shown in figure 2-6b. They estimated the width of the Hawasina depositional basin as ranging between 400 and 1200 kilometers. Later work by Graham (1980a) supported the former figure.

The Late Cretaceous: Obduction of the Semail ophiolite and emplacement of the Hawasina nappes

The obduction of the Semail ophiolite began in the Cenomanian as indicated by the age of the oldest flysch deposits of the Aruma foredeep. The emplacement of the allochthons on the Arabian continental margin proceeded in a south-westerly direction, and was completed in Campanian, prior to the deposition of the youngest units of the neo-autochthonous carbonate sequences (Glennie et al., 1973, 1974). In the process of obduction, "the Mesozoic sediments were removed from their substrate in the Hawasina ocean" and were transported "as a series of nappes across the south-eastern margin of the Arabian continent for distances that could exceed 100 kilometers" (Glennie et al., 1974, p. 397). The Hajar-Aruma depositional break is a consequence of continental uplift, followed by the formation of an ensialic foredeep basin (figure 2-6c). Figure 2-6d depicts the present tectonic setting of the Oman Mountains (modified after Glennie et al., 1973, 1974).

Glennie et al. (1973, 1974) have suggested that the emplacement of the allochthons operated in a very systematic fashion, such that the highest nappes in the Oman tectonostratigraphy are the furthest travelled with respect to the Arabian continental margin. This is a simple kinematic model for stacking of the nappes, and is in agreement with the models of footwall accretion outlined by previous workers for other fold and thrust belts (Williams, 1975; Gee, 1978; Boyer and Elliott, 1982). Glennie et al. (1974) presented an alternative to the reconstruction of the Hawasina basin shown in figure 2-6(b), but this alternative was rejected by them because it would have required a more complex kinematic model for the emplacement of the nappes.

It is now generally accepted that the emplacement of these nappes is related to the closure of the Tethys ocean and is correlatable with similar events that occurred in other areas along the Alpine-Himalayan orogenic belt (Ricou, 1971; Stocklin, 1974). In Oman, however, continental collision was not achieved.

The Maastrichtian and the Tertiary

The emplacement of the Late Cretaceous allochthons was followed by marine transgressions in the Maastrichtian and the Paleogene, which led to the widespread deposition of shallow-marine carbonate sequences (Lees, 1928; Morton, 1959; Tschopp, 1967).

Regional horizontal compressive movements in the Paleogene affected these sequences and resulted in additional structural complications of the geology of the Oman Mountains (Morton, 1959). The origin of the J.Akhdar-J.Nakhl-Saih Hatat culmination trend has repeatedly been attributed to these movements (Lees, 1928; Morton, 1959; Wilson, 1969; Glennie et al., 1974). This, however, is currently being challenged by Bernoulli (1982, unpubl. ESRI rep.) and Hanna (1983, unpubl. ESRI rep.), who propose that these structures were formed during the emplacement of the nappes as a result of structural ramping at depth within the pre-Permian basement. This is of considerable significance, as it implies that the basement and the overlying Mesozoic shelf successions are not autochthonous.

Chapter 3

LITHOSTRATIGRAPHY OF THE SUFRAT AD DAWH RANGE

3.1 Introduction

The purpose of this chapter is to provide a description of the lithological units of the Hawasina Complex that occur in the Sufrat ad Dawh Range. This area exposes mainly units belonging to the Hamrat Duru Group and the Wahrah Formation. Rocks of the Al Ayn and the Haliw Formations occur to a lesser extent in the northern part of the study area. The distribution of these units is shown in the geological map marked as inset C, included with this thesis. The general appearance in outcrop, and the stratigraphic and sedimentological characteristics of these units will be described in the following sections.

Irregularly distributed outcrops of metamorphic rocks occur in the northern part of the study area. These rocks and the lithologies of the Semail ophiolite, which dominate the northern margin of the study area, were not studied in detail, and will only be briefly described.

3.2 The Hawasina Complex

3.2.1 The Hamrat Duru Group

Units of the Hamrat Duru Group occur in two east-west trending belts, 4 to 5 kilometers wide and up to 16 kilometers in length, in the northern and southern parts of the Sufrat ad Dawh Range. The relief in these belts generally exceeds 100 meters, and occasionally reaches 450 meters in the southern belt. The Hamrat Duru Group is represented by the Guwayza, the Sid'r and the Nayid Formations. The Zulla Formation is not exposed.

Two representative stratigraphic sections were measured in the northern and the southern belts, respectively. These sections are shown in figure 3-1. Figure 3-2 is a photograph of the Hamrat Duru Group in the northern Hamrat Duru belt.

The Guwayza Formation ranges in thickness from 130 to 330 meters. The lower contact of this formation is always tectonic. The formation is sub-divided in two conformable members (Glennie et al., 1974): a lower Sandstone Member and an upper Limestone Member. The Sandstone Member consists of centimeter- to meter-bedded calciturbiditic, oolitic grainstones (figure 3-3) with variable amounts of detrital quartz grains, minor lime mudstones, conglomerates and red shales. This member is characterised by a distinctly dark grey to brown weathering colour (figure 3-2).

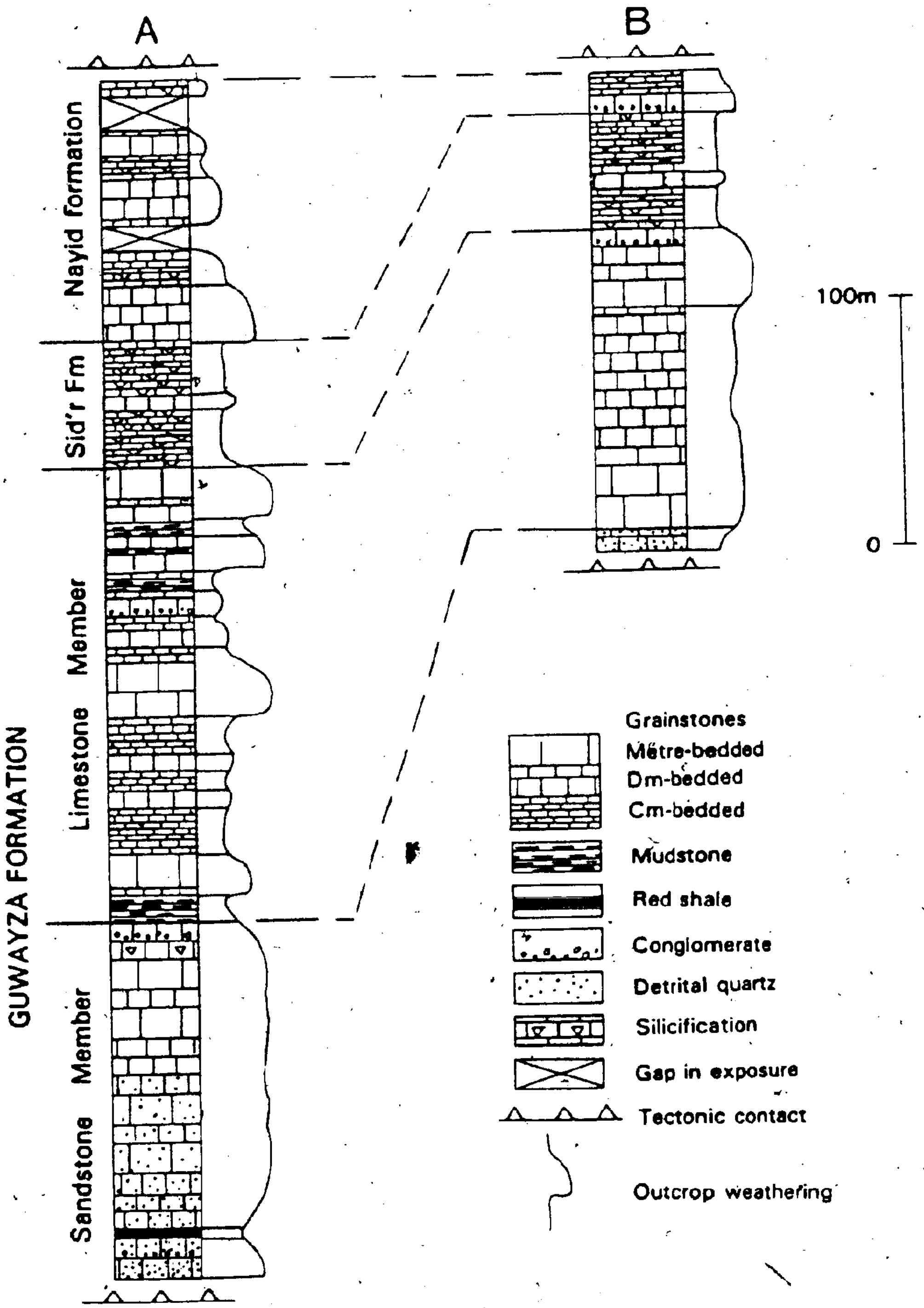
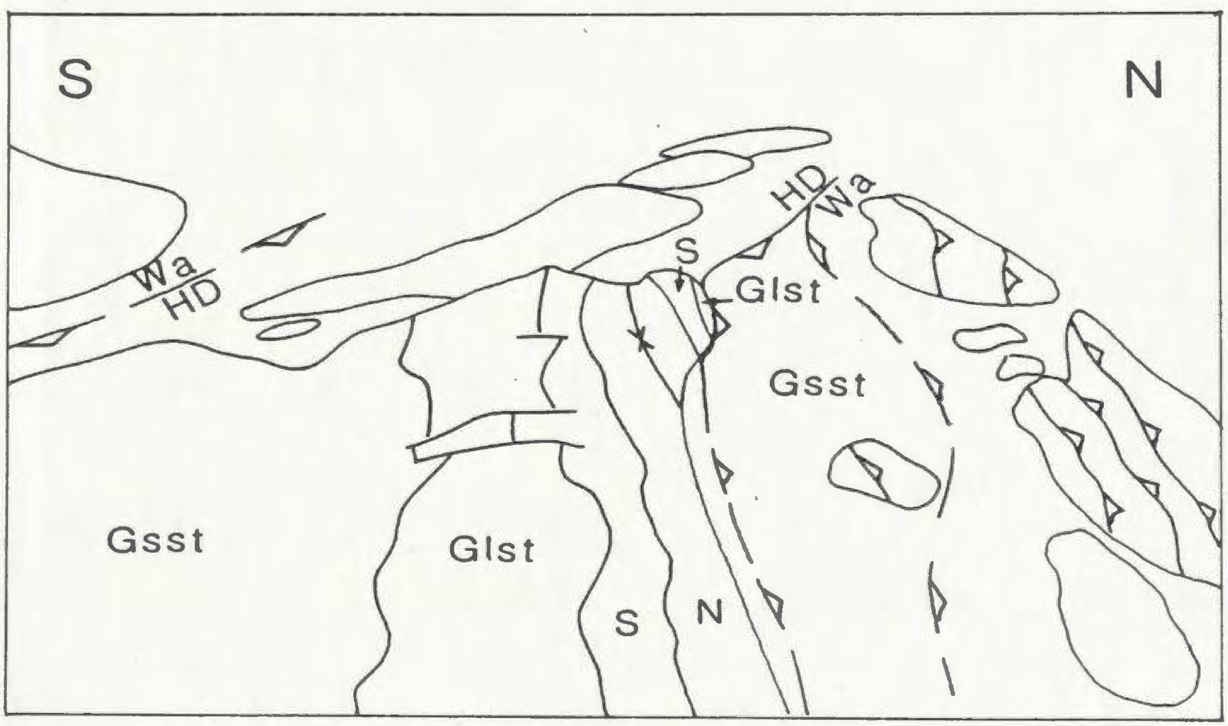


Figure 3-1: Measured stratigraphic sections of the Hamrat Duru Group. A: Northern Hamrat Duru belt, B: Southern Hamrat Duru belt. (modified after D. Cooper, written comm.).

Figure 3-2: The Hamrat Duru Group in the northern Hamrat Duru belt (see list of abbreviations).



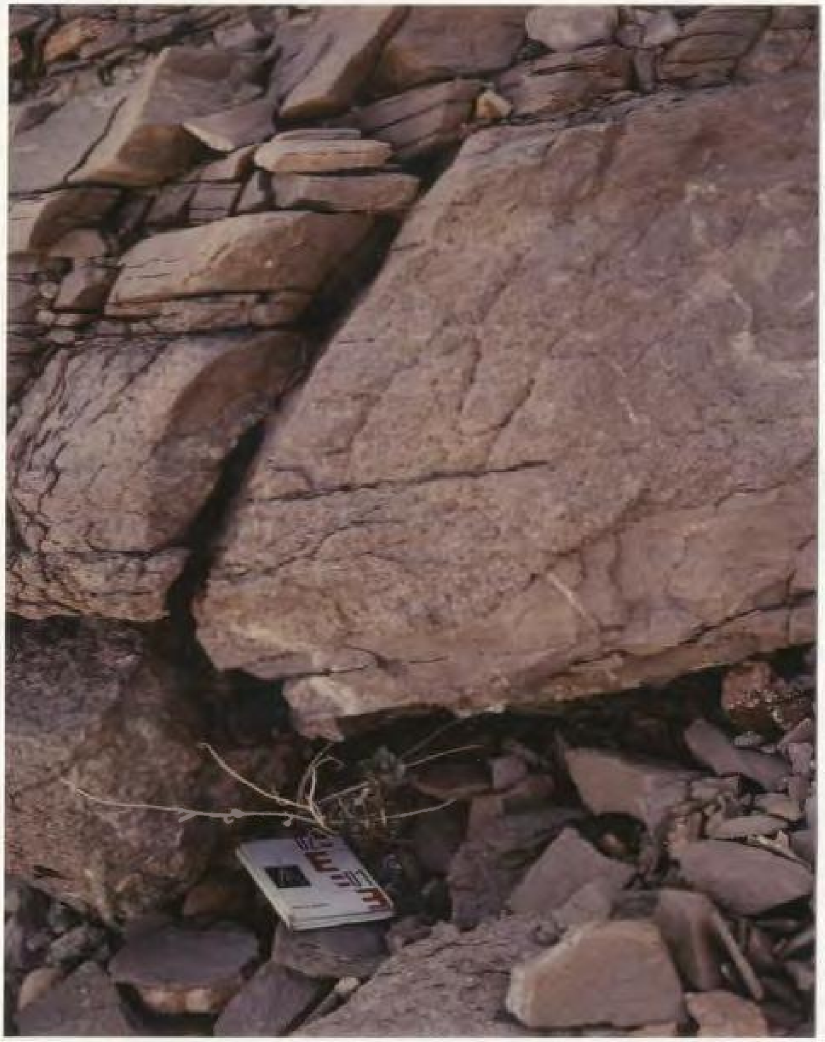


Figure 3-3: Turbiditic bed in the Sandstone Member of the Guwayza Formation showing a well-developed Bouma Ta-d transition.

The Limestone Member contrasts with the Sandstone Member by its light grey colour (figure 3-2). The beds, often reaching several meters in thickness, are composed of well-sorted, oolitic grainstones that do not contain any detrital quartz. Sole structures are well developed (figure 3-4). These units commonly display a conspicuous stylolitic cleavage (figure 3-5). Minor intervals of light-yellow marlstones are irregularly distributed throughout the section.

Figure 3-4: Flute casts at the base of a steeply overturned bed in the Limestone Member of the Guwayza Formation.

Figure 3-5: Stylolitic cleavage in the oolitic grainstones of the Guwayza Formation. The rock surface represents the plane of bedding.

The Sid'r Formation abruptly, but conformably, overlies the Guwayza Formation. It is 50 meters thick, and consists of a sequence of largely silicified, centimeter- to decimeter-bedded calci-turbiditic grainstones and calcareous mudstones (figure 3-6). Its typical rusty brown colour and relative resistance to erosion makes this formation a useful marker horizon in complexely deformed areas.

The Sid'r Formation is conformably overlain by the Nayid Formation which consists of more than 100 meters of partly silicified, centimeter- to decimeter-bedded lithoclastic grainstones and mudstones also of turbiditic affinities. These lithologies are generally light-coloured and the silicification, which takes place preferentially along the finer-grained horizons, causes these units to bear a platy appearance (figure 3-7). The Nayid Formation is usually intensely folded and imbricated, due to its relatively low competency and to the fact that it lies often directly below a major thrust surface.

The lithostratigraphy of the Hamrat Duru Group in the Sufrat ad Dawh Range is largely consistent with the type-section of this group presented by Glennie <u>et al</u>. (1974). However, an important facies variation is found in the northern Hamrat Duru belt. On the southern side of this belt, the Limestone Member of the Guwayza Formation consists predominantly of silicified, laminated radiolarian mudstones intercalated with oolitic grainstones. A thick olistotromal horizon occurs towards the top of the sequence. The

Figure 3-6: Silicified distal calci-turbiditic beds of the Sid'r Formation.

Figure 3-7: Partly silicified distal calci-turbiditic beds of the Nayid Formation.

olistostrome has a matrix of yellow marlstones and contains large blocks of mafic volcanic rocks, Permian and Triassic reefoid shallow-water limestones and Lower Triassic red cephalopod-bearing pelagic limestones. Olistostromes have not been documented from the Hamrat Duru Group in other parts of the Oman Mountains. They have important implications for the paleogeographic reconstruction of the Hawasina basin, and their analysis will be the subject of a separate publication (Calon and Barrette, in prep.).

The stratigraphical thickness of the Guwayza Formation is considerably greater in the northern than in the southern Hamrat Duru belt (see figure 3-1). Thinning of the Guwayza Formation was also locally reported by Glennie et al. (1974), elsewhere in the mountain belt. These workers interpreted this trend "as representing deposition in increasingly distal areas from the shelf source of the carbonate sediments" (Ibid, p. 111). Hence, the trend observed in the Sufrat ad Dawh Range would indicate that the Guwayza Formation is of a more proximal character in the north than in the south of this range.

3.2.2 The Wahrah Formation

The northern and the southern Hamrat Duru belts are separated by a large area entirely occupied by units of the Wahrah Formation. Units of the Wahrah Formation also fringe the northernmost and the southernmost outcrop areas of the Sufrat ad Dawh Range. These areas are characterized by low topographic relief compared with areas underlain by the Hamrat Duru Group. They consist of a succession of east-west oriented elongated hills with a maximum relief of 100 meters.

Four distinct lithological sequences are recognized in the Wahrah Formation of the Sufrat ad Dawh Range. These are:

1. Centimeter- to decimeter-bedded, red radiolarian cherts (figure 3-8).

2. Centimeter-bedded, light - yellow - coloured mudstones and shales (figure 3-9).

3. Light brown, decimeter- to meter-bedded, lithoclastic, turbiditic grainstones with well-developed sole structures and cross-stratification, interbedded with calcareous shales and marls (figure 3-10).

4. Centimeter- to decimeter-bedded, lithoclastic grainstones and packstones interbedded with chalky white, shaly mudstone units (figure 3-11). They are poorly graded and display ill-developed cross-statification, and thus rarely yield indications on the stratigraphical tops of the lithologies. These units are usually poorly exposed and are distinguished from the grainstone sequences mentioned above by a dark brown colour.

The mudstones of sequence 2 and the chert lithologies of sequence 1 are in general very similar in outcrop appearance. The mudstones often alter to a darker colour, while the chert lithologies tend to leach to a yellowish colour. Moreover, these two sequences are intensely imbricated and their stratigraphic thicknesses are difficult to estimate because stratigraphic and tectonic contacts cannot be distinguished easily. For this reason, they have not been mapped separately.

Figure 3-8: Chert lithologies of the Wahrah Formation.

Figure 3-9: Light-coloured mudstones of the Wahrah Formation.

Figure 3-10: Light-brown grainstones of the Wahrah Formation, bearing well-developped cross-stratification.

Figure 3-11: Dark-coloured grainstones of the Wahrah Formation with poorly developped cross-stratification, and intervals of chalky-white mudstones.

These four units are not uniformly distributed in the Sufrat ad Dawh Range. Instead, they define three distinct assemblages. Each of these assemblages forms an east-west trending belt ranging from 2 to 10 kilometers in width (figure 3-12). The northernmost assemblage (assemblage A) only comprises the light-coloured grainstones (sequence 3) (figure 3-13), and rims the northern and southern margins of the northern Hamrat Duru belt. The central assemblage (B) mainly comprises the chert and the mudstone units (sequences 1 and 2, respectively) and minor amounts of the light-coloured grainstones (sequence 3) (figure 3-14). The southernmost assemblage (C) occurs to the north and the south of the southern Hamrat Duru belt and comprises the chert and the mudstone sequences (sequences 1 and 2, respectively), as well as the dark grainstones (sequence 4) (figure 3-15).

A reconnaissance survey of the Wahrah nappes in the western foothills showed that the same lithostratigraphic distribution exists in Al Hammah, situated east of the Sufrat ad Dawh Range (see figure 3-12). West of the Sufrat ad Dawh Range, in Jebel Hammah, assemblage C does not occur and assemblage B is present to the north and to the south of assemblage A.

Glennie et al. (1973, 1974) have divided the Wahrah Formation into four conformable members. These are, from bottom to top, a Lower Limestone Member, a Mudstone Member, a Chert Member and an Upper Limestone Member. Figure 3-16

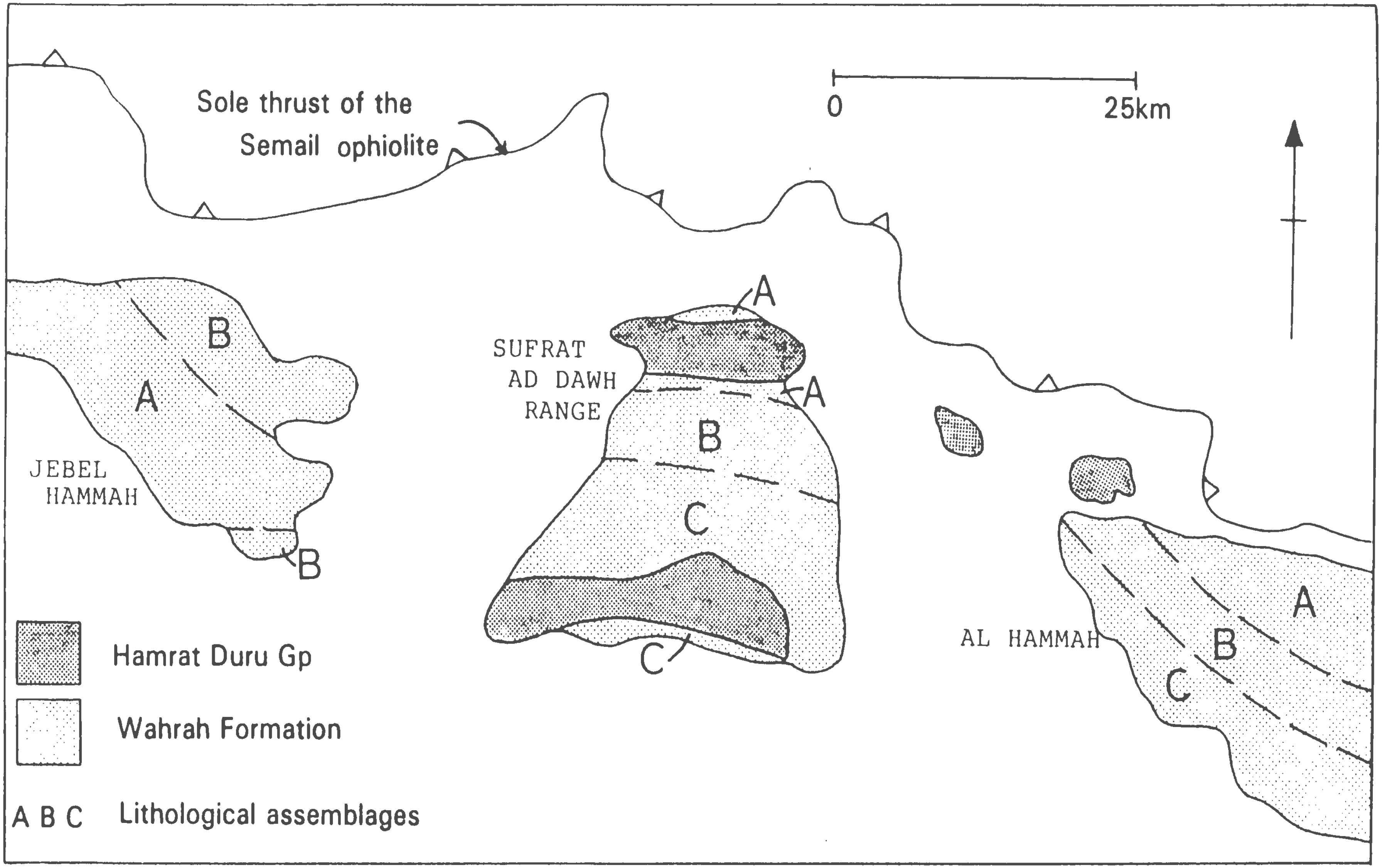


Figure 3-12: Generalized geological map displaying the distribution of the lithological assemblages of the Wahrah Formation in Jebel Hammah, the Sufrat ad Dawh Range and Al Hammah.

Figure 3-13: Assemblage A of the Wahrah Formation, consisting of the structural repetition of the light-coloured grainstone lithologies (sequence 3 in text).

Figure 3-14: Assemblage B of the Wahrah Formation, consisting of the structural repetition of the chert (sequence 1, in red), the mudstones (sequence 2, in yellow) and the light grainstone lithologies (sequence 3, light-brown).

Figure 3-15: Assemblage C of the Wahrah Formation, consisting of the structural repetition of the chert (sequence 1, in red), the mudstones (sequences 2, in yellow) and the dark, poorly exposed grainstone lithologies (sequence 4, in dark).

is a stratigraphic section of the Wahrah Formation. In Jebel Hammah and in the Sufrat ad Dawh Range, Glennie et al. (1974, p.216) have assigned the light coloured grainstones (sequence 3) to the Lower Limestone Member. Thus, sequences 1, 2 and 4 are thought to represent the Chert, the Mudstone and the Upper Limestone Member of the Wahrah Formation, respectively. No paleontological age dating is available.

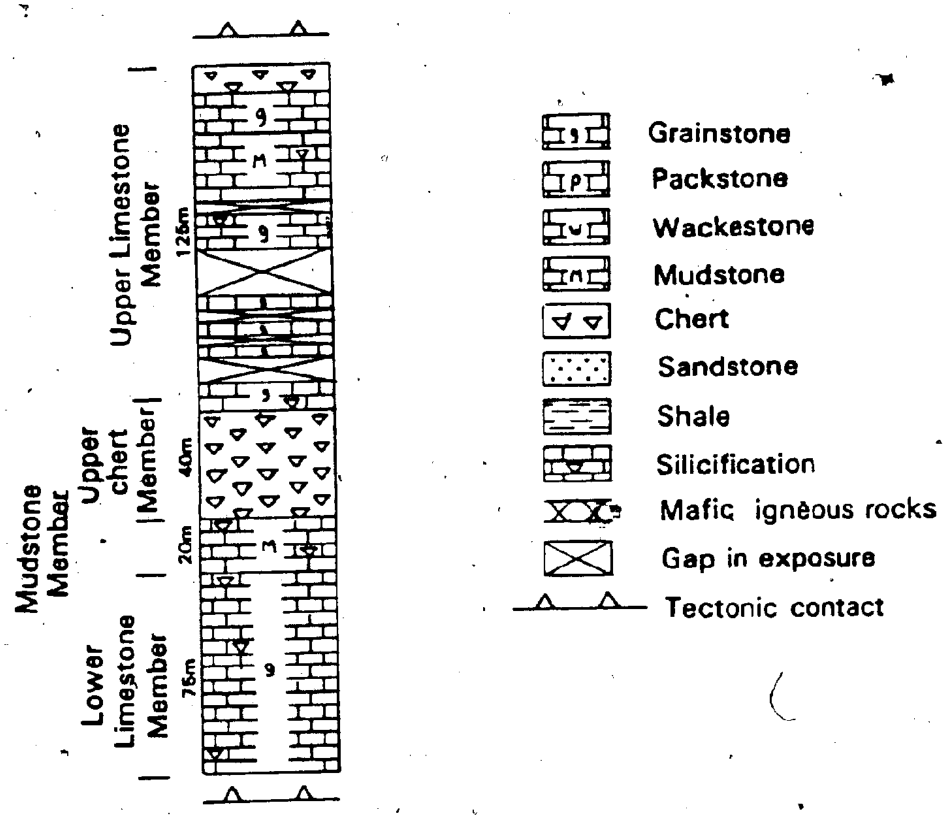


Figure 3-16: Stratigraphic section of the Wahrah Formation (modified after Glennie et al., 1974). The symbols also apply to figures 3-17 and 3-19

The difficulty in distinguishing the Mudstone from the Chert Member and the degree of imbrication of these units, did not allow the writer to confirm the assignment of the dark grainstone unit (sequence 4) to the upper Wahrah Formation on a stratigraphical basis.

3.2.3 The Al Ayn Formation

The Al Ayn Formation only occurs in an isolated outcrop area less than one kilometer east of the northern Hamrat Duru belt. The lithologies are mostly centimeter- to decimeter-bedded, calc-arenites and calc-siltites interbedded with minor calcareous shales and marls. Locally, these rocks are intruded by mafic igneous sills. These lithologies are believed to correlate with the upper part of the type-section of the Al Ayn formation (figure 3-17).

3.2.4 The Haliw Formation

The Haliw Formation is exposed north of the Sufrat ad Dawh Range, in an area lying between the erosional front of the Semail ophiolite nappe and the northern Hamrat Duru belt. This formation is mainly represented by centimeter-bedded sequences of red radiolarian cherts (figure 3-18), but also comprises centimeter- to decimeter-bedded, oolitic grainstones, light-coloured marlstones, white reefal lithoclasts attaining several meters in size and fine- to medium-grained altered mafic igneous fragments. Figure 3-19 is a stratigraphical section of this formation measured in the study area by Glennie et al. (1974).

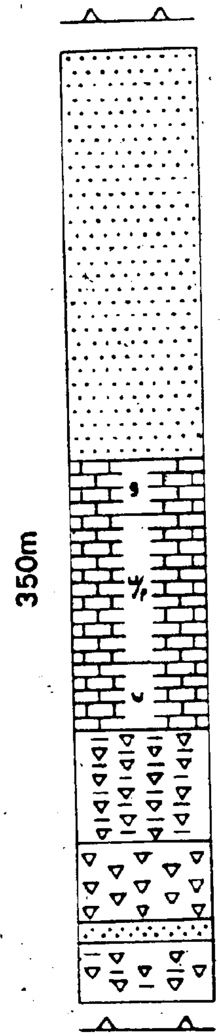


Figure 3-17: Stratigraphic section of the Al Ayn Formation (modified after Glennie *et al.*, 1974). See figure 3-16 for legend.

Figure 3-18: Contorted red radiolarian cherts of the Haliw Formation.

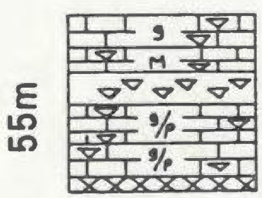


Figure 3-19: Stratigraphic section of the Haliw Formation (modified after Glennie et al., 1974). See figure 3-16 for legend.

3.3 The Semail ophiolite and the underlying metamorphic rocks

3.3.1 The Semail ophiolite

The Semail ophiolite is continuously exposed along the northern margin of the study area where it forms a series of rugged ridges averaging 50 meters in height, and of a distinct dark brown colour (figure 3-20). The lithologies consist predominantly of medium- to coarse-grained, highly serpentinized peridotites and dunites, and fine- to coarse-grained gabbroic rocks.

Figure 3-20: Rocks of the Semail Ophiolite in the background, and the Hawasina Complex in the foreground.

3.3.2 The metamorphic rocks

Metamorphic rocks outcrop in the area lying between the erosional front of the Semail nappe and the northern Hamrat Duru belt. They are poorly exposed, and are characterized by a light blueish colour, altering to white. They consist mainly of quartz-rich mica schists and metaconglomerates, and display a well-developed schistosity. They are assumed to belong to the Haybi Complex (Searle, 1980).

Chapter 4

STRUCTURE OF THE HAWASINA COMPLEX IN THE SUFRAT AD DAWH RANGE

4.1 Introduction

In this chapter, a detailed analysis of the macroscopic structure of the Sufrat ad Dawh Range is presented. For the purpose of this analysis, the Sufrat ad Dawh Range is divided into four structural domains: the northern area, the northern Hamrat Duru belt, the Central Sufrat ad Dawh area and the southern Hamrat Duru belt. The location of these domains is indicated in figure 4-1.

The northern area is underlain by units of the Haliw and the Al Ayn Formations, metamorphic rocks of the Haybi Complex, and ultramafic and mafic plutonic rocks of the Semail ophiolite. The area is poorly exposed and was mapped at a scale of 1:50 000.

The northern Hamrat Duru belt was mapped in considerably more detail, at a scale of 1:20 000. This was done to optimize the understanding of the internal geometry of the belt and its northern and southern contact relationship with the Wahrah Formation. The Hamrat Duru lithologies in this area, moreover, are better exposed than the other Hawasina units and are more intricately deformed.

The central Sufrat ad Dawh Range extends from the northern to the southern Hamrat Duru belt. The structure in this area was found to be relatively simple and, consequently, it was mapped at a scale of 1:50 000.

Finally, for the same reasons mentioned for the northern Hamrat Duru belt, the central part of the southern Hamrat Duru belt was mapped at a scale of 1:20 000, thus completing a structural transect of the Sufrat ad Dawh Range.

The geological maps of the northern Hamrat Duru belt and the central part of the southern Hamrat Duru belt, correspond to inset A and B, respectively, included with this thesis. Inset C is a compilation of the structure of the entire study area at the scale of 1:50 000 (figure 4-1).

In insets A, B and C, the areas lying within the limits of outcrop (represented by a dotted line) are exposed at 90% and more, depending on the amount of talus slope and small wadis. The areas lying outside these limits are overlain by wadi gravel and sands. In the areas underlain by lithologies of the Hamrat Duru Group, a "defined" symbol (solid line) indicates that the structural element represented by this symbol can be traced out within the outcrop limits along most of its length. An "assumed" symbol (dashed line) is used when this element is interpreted to exist outside the outcrop limits, or to indicate that evidence for the existence of this element ends within these limits. As explained later in the text, "assumed" and "approximate" thrust symbols were also used in

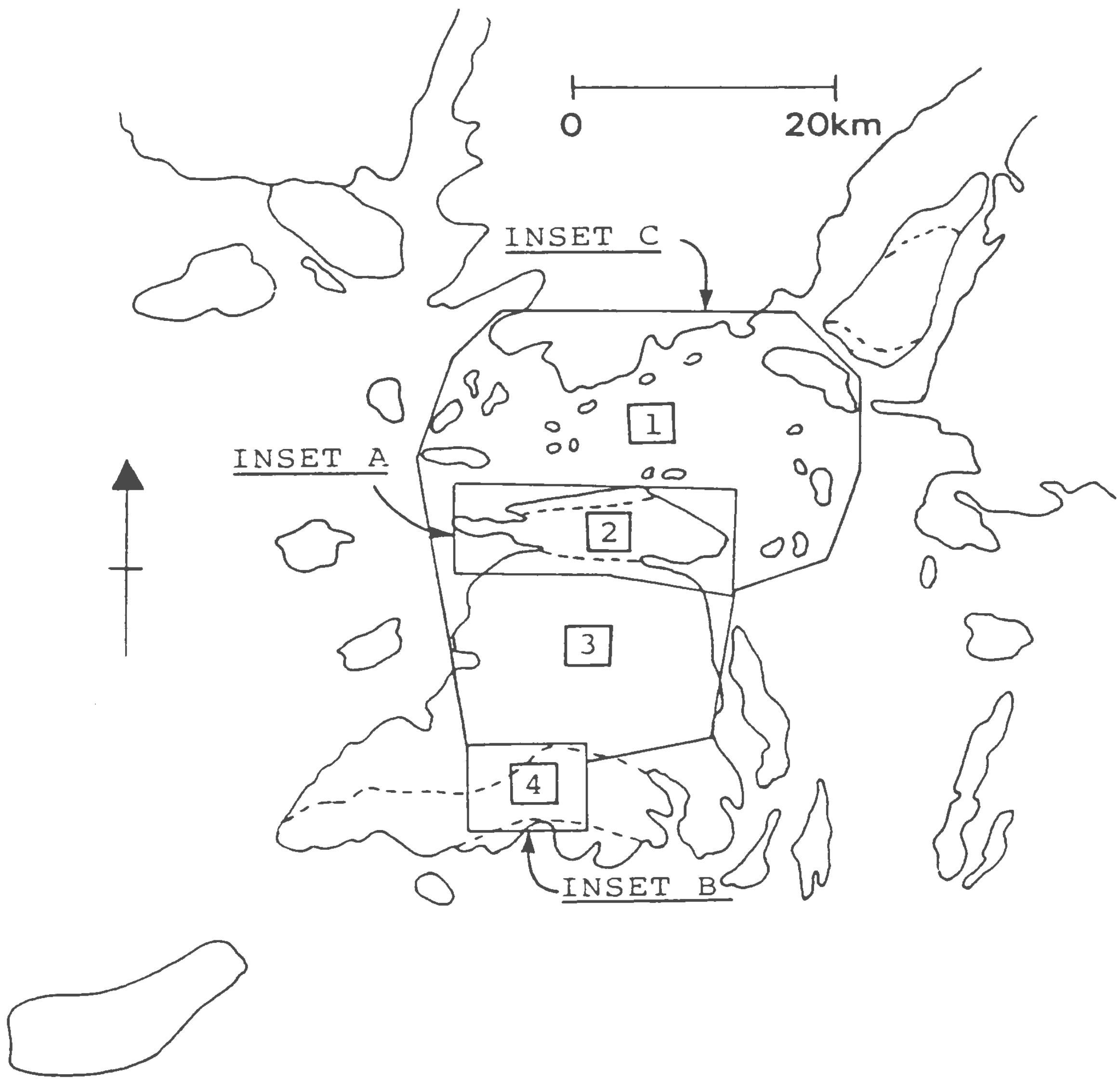


Figure 4-1: Location and extent of the four structural domains and insets A, B and C, in the Sufrat ad Dawh Range; 1: Northern area, 2: Northern Hamrat Duru belt, 3: Central Sufrat ad Dawh Range, 4: Central part of the southern Hamrat Duru belt.

the central Sufrat ad Dawh Range where the nature of many of the lithological boundaries is uncertain. In this chapter, a description of the macroscopic structure will be provided, first, for each of the four structural domains, and will be followed by a discussion on the significance and spatial relationships of these structures. This approach is used with the aim of emphasizing the difference in what is considered as factual data, and the interpretation of the structure in poorly exposed areas, at depth and above the erosional surface.

The stereoplots presented in this chapter to supplement the description of the structures, are equal area, lower hemisphere projections. The terminology used is from Dahlstrom (1970), Boyer and Elliott (1982) and Butler (1982).

4.2 The northern area (inset C)

4.2.1 Description of the structure

In the northern area, outcrops of the Haliw and the Al Ayn Formations, the Haybi Complex, and the Semail ophiolite stand up as isolated clusters of hills above the gravel plain.

Measurements of the orientation of bedding planes in the Haliw Formation are represented in figure 4-2. The pattern obtained indicates that these lithologies are generally slightly to moderately inclined, with a higher concentration of the dips towards the north-east. The orientation of the schistosity in the metamorphic rocks was also plotted on a stereogram (figure 4-3), and indicates that planar fabrics in the metamorphic rocks, on average, dip moderately towards the north-west.

The Haliw lithologies are locally underlying the metamorphic rocks in outcrop (figure 4-4). In places, where the Semail, the metamorphic and the Haliw lithologies outcrop adjacent to each others, the Haliw Formation is separated from the rocks of the Semail ophiolite by the metamorphic rocks (see north-central part of the study area in inset C), while consistently dipping towards them. Elsewhere, the rocks of the Haybi Complex do not outcrop between the units of the Semail ophiolite and the Haliw Formation. A tectonic klippe of the metamorphic rocks, and a window of the Haliw Formation, occur in the west and the east, respectively, of the northern area.

Less than one kilometer east of the northern Hamrat Duru belt, units belonging to the Al Ayn Formation are exposed in a semi-circular outcrop pattern. The form-surface trace of bedding defines a moderately east-plunging, upright anticline (see figure 4-5 and 4-6). The cylindrical nature of this fold is indicated by the fact that the poles to the bedding planes plot along a great circle, representing the AC or profile plane. The attitude of the fold axis of this structure is represented by the pole to this great circle. Outcrops of the Semail ophiolite occurring further eastward follow the arcuate pattern of the Al Ayn lithologies,

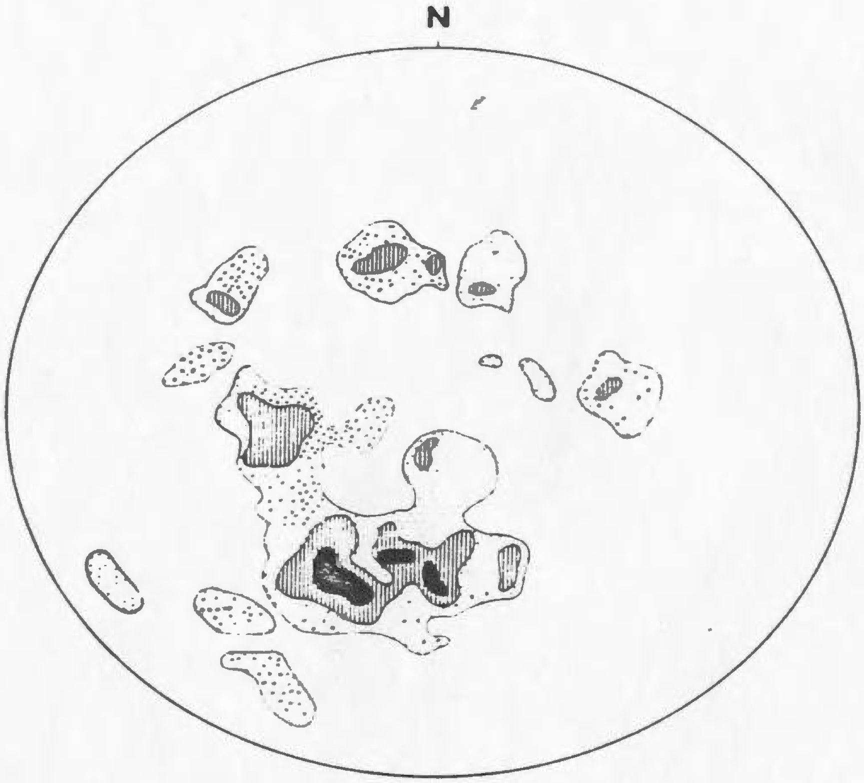


Figure 4-2: Poles to bedding of the Haliw lithologies exposed in the northern area (n=46, contours: 8,6,4% per 1% area).

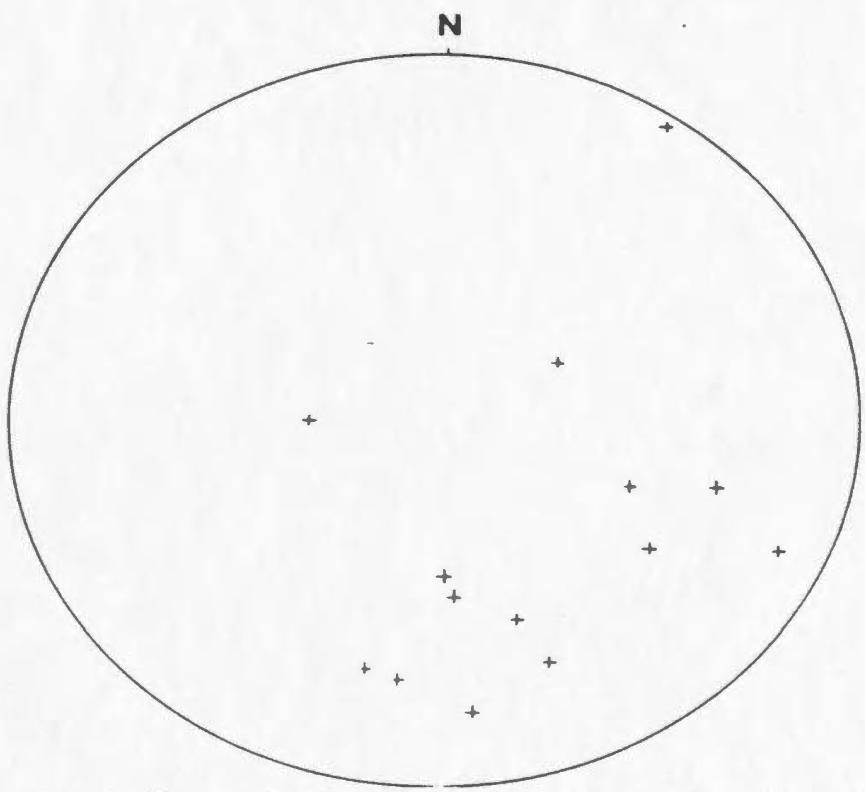


Figure 4-3: Poles to the schistosity in the metamorphic rocks of the Haybi Complex

Figure 4-4: Tectonic superposition of the metamorphic rocks of the Haybi Complex (Mt) over the cherts of the Haliw lithologies (Ha).

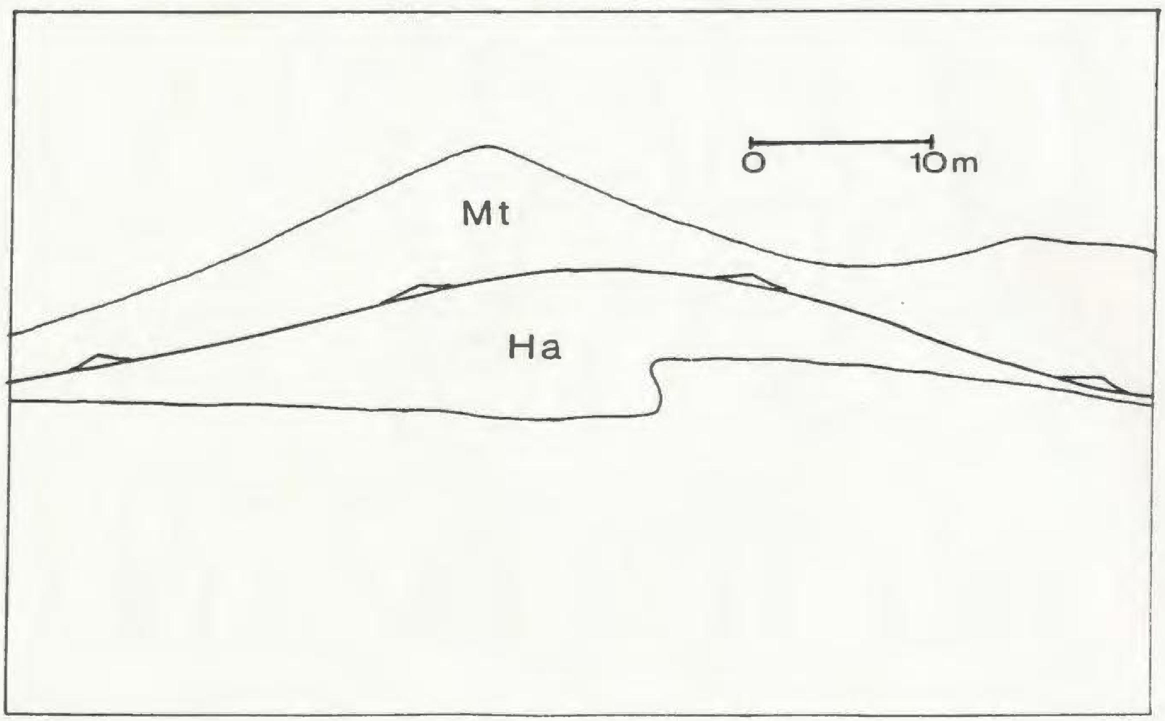
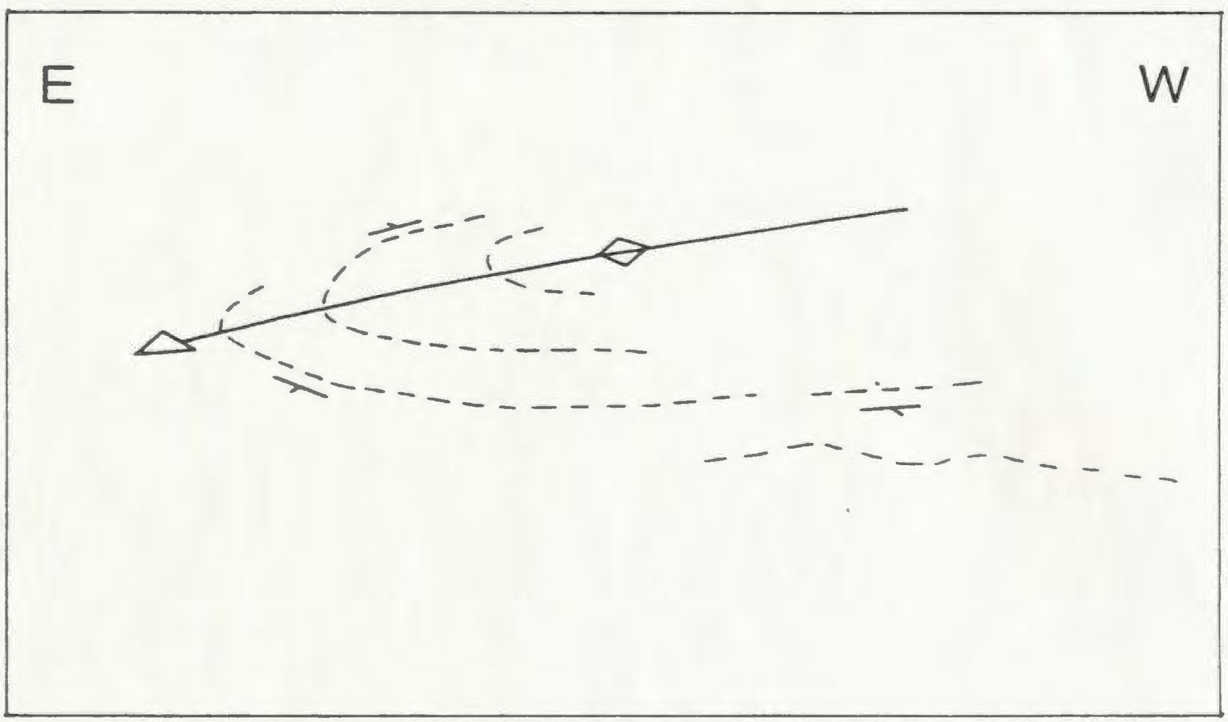


Figure 4-5: Semi-circular outcrop pattern of the lithologies belonging to the Al Ayn Formation, east of the northern Hamrat Duru belt, defining the form surface trace of an easterly plunging anticline.



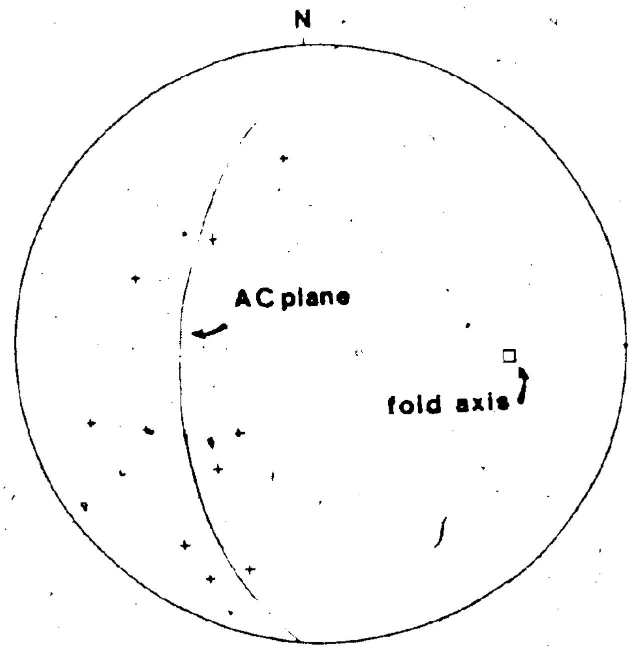


Figure 4-6: Poles to bedding of the Al Ayn lithologies, defining an easterly plunging cylindrical fold.

indicating that the Semail nappe is also folded along this structure.

A major NE-SW trending, high-angle fault accounts for a 10 kilometers apparent right-lateral offset of the surface trace of the Semail sole thrust. The dip attitude of the fault and its displacement vector could not be determined.

4.2.2 Discussion

The interpretation of the tectonostratigraphic relationships of the Haliw and the Al Ayn Formations, the metamorphic rocks of the Haybi Complex, and the Semail ophiolite is illustrated in figure 4-7. The Semail ophiolite is thought to overlie the Haybi Complex, the Haliw and the Al Ayn Formations. The Haybi Complex overlies the

Haliw Formation, but its tectonic position with respect to the Al Ayn Formation cannot be determined in the study area. Similarly, the relationship of the Haliw Formation and the Al Ayn Formation is not exposed.

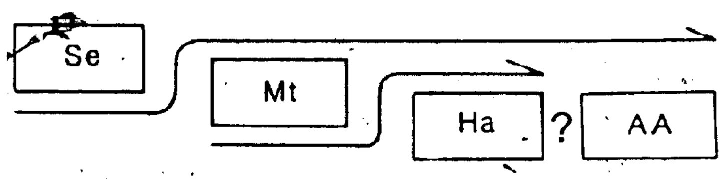


Figure 4-7: Tectonostratigraphical relationships of the Semail ophiolite, the Haybi metamorphic rocks and the Haliw and Al Ayn Formations.

With the exception of the Al Ayn Formation, all other units in this area appear to have consistent north-westerly to north-easterly dips of planar fabric elements. Local warping accounts for the occurrence of a tectonic klippe of the metamorphic rocks in the west, and of a window of the Haliw unit in the east of the northern area.

The structure in the northern area thus consists of a regular, north-dipping stack of Haliw sedimentary and Haybi metamorphic rocks overlain by the Semail ophiolite. Poor outcrop does not allow a more detailed appraisal of the internal geometry of these units.

4.3 The northern Hamrat Duru belt (inset A)

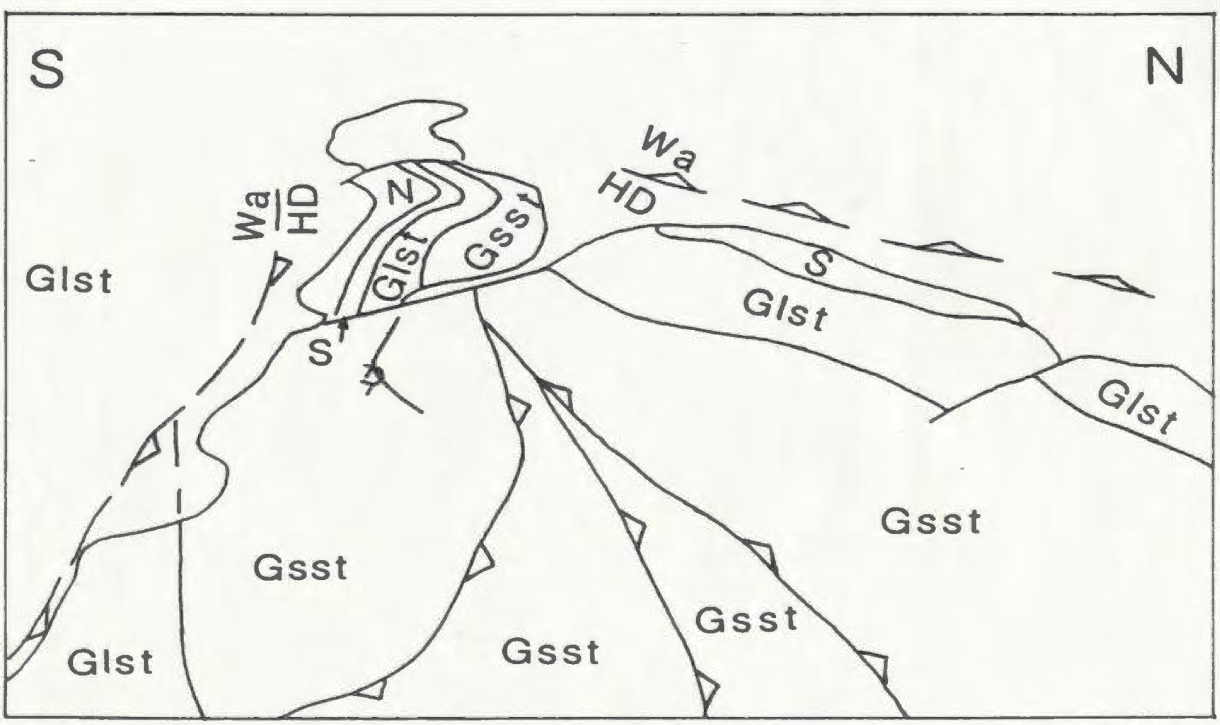
4.3.1 Description of the structure

The structure displayed in the northern Hamrat Duru belt defines two en-echelon anticlines trending in an east-west direction.

The western hinge of the anticline in the eastern part of the belt is plunging towards the west. The eastern hinge of the western anticline is plunging towards the east. This geometry defines a zig-zag pattern of left-hand, en-echelon folding (Campbell, 1958). The anticlines fold imbricate fault planes that occur within the Sandstone Member of the Guwayza Formation. This accounts for the predominance of this member in the study area (figures 4-8 and 4-9).

Along the northern limb of the eastern and the western anticlines, the Limestone Member of the Guwayza Formation, and the Sid'r and Nayid Formations occur in a conformable succession above the Sandstone Member. These units extend across most of the northern part of the Hamrat Duru belt (figure 3-2; see also section BB', inset A). In the west, these units are folded in the form of a boxfold-style syncline that plunges shallowly towards the east (figure 4-10). Further to the east, these units are dipping and younging consistently towards the north (section BB', CC' and DD'). The box-fold style syncline abuts at its western and eastern end against units of the Guwayza Sandstone Member. These lithologies extend easterly to the other

Figure 4-8: Oblique aerial view of the western anticline in the northern Hamrat Duru belt (see inset A). The Sandstone Member of the Guwayza Formation (Gsst) is imbricated in the core of the anticline, and is overlain by the Limestone Member (Glst) along the northern and the southern limb of this structure.



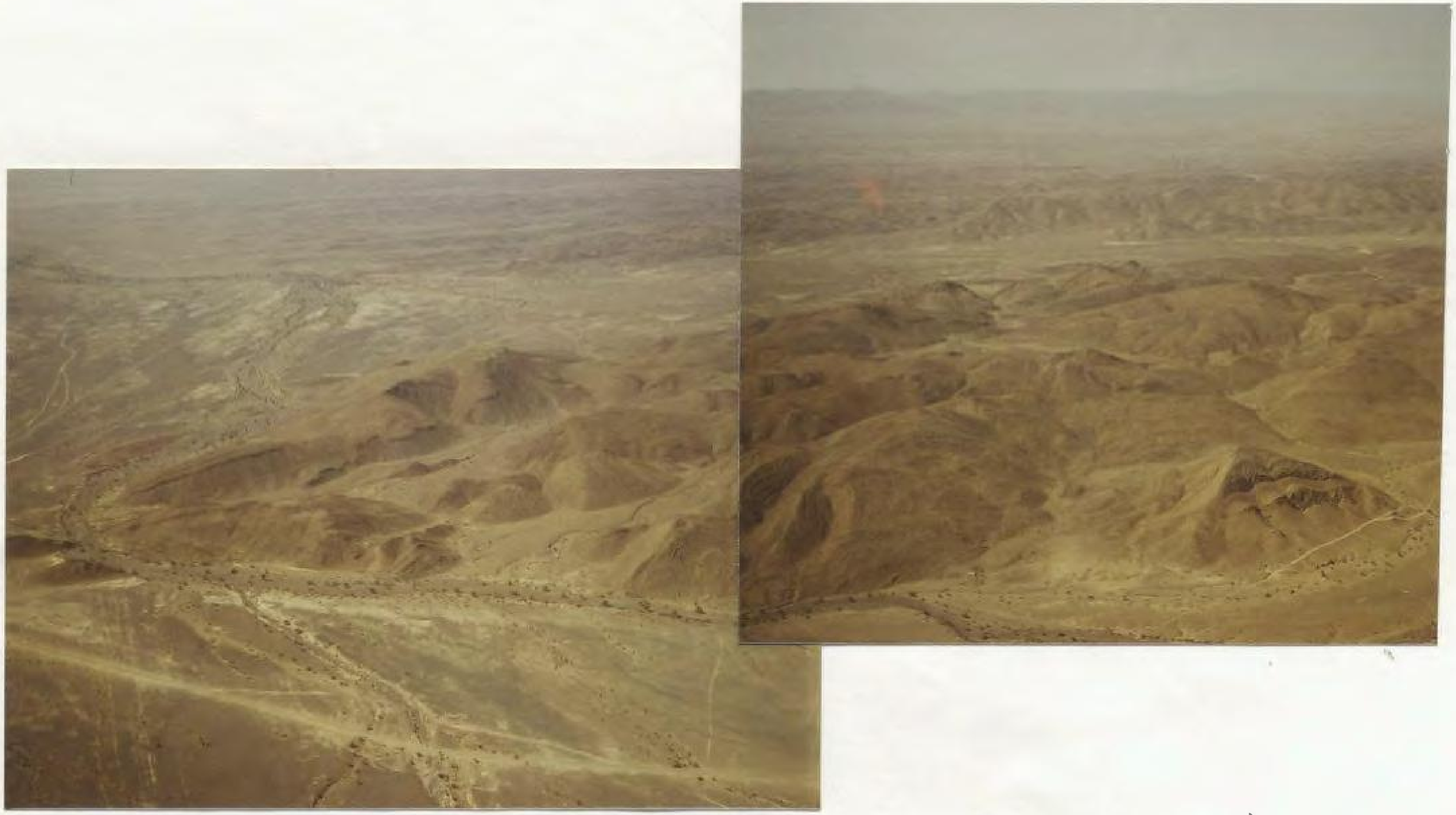


Figure 4-9: Oblique aerial view towards the south-west, of the eastern antiform in the northern Hamrat Duru belt. In the background lies the central Sufrat ad Dawh Range and the southern Hamrat Duru belt.

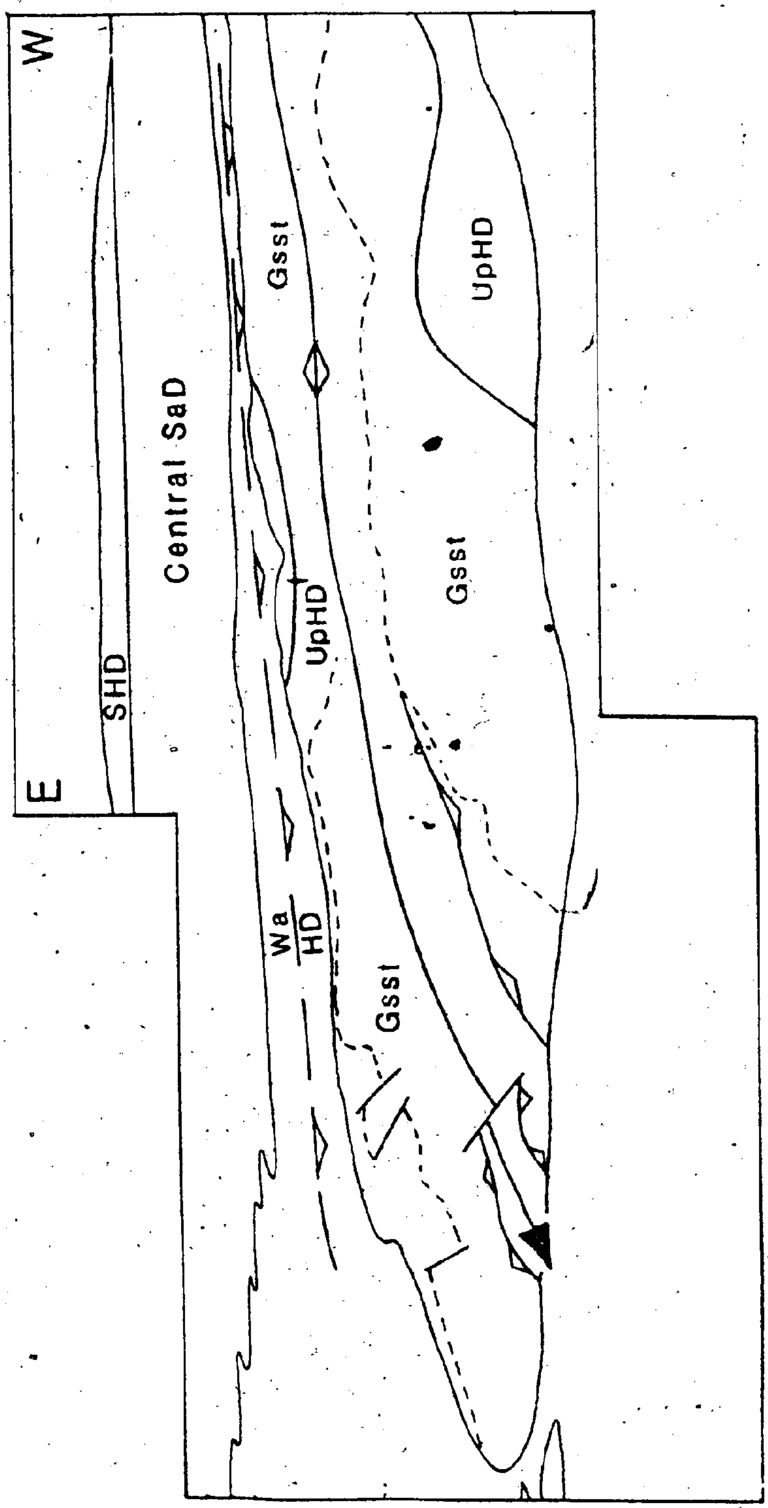
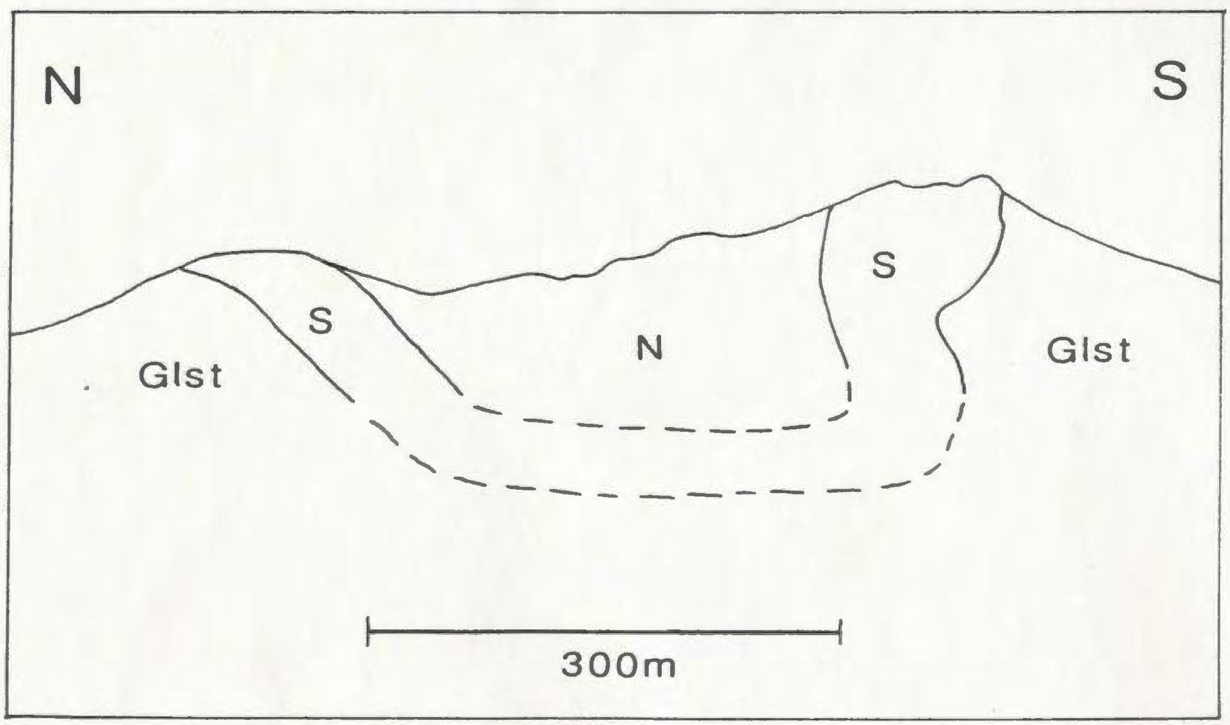

W
E
SHD
Central SaD
Gsst
UpHD
Gsst
UpHD
Gsst
Wa
HD

Figure 4-10: Box-fold style syncline in the north-western part of northern Hamrat Duru belt.



extremity of the study area, tectonically overlying the Nayid Formation, and dipping and younging towards the north.

The Sid'r and the Nayid Formations occur also conformably on top of the Guwayza Formation along the southern limb of the two anticlines and are dipping and younging towards the south. In the east, they define a shallow, easterly plunging syncline adjacent to a shallow easterly plunging syncline in the Wahrah imbricates further to the south (section DD'). Units of the Guwayza Formation are scarcely exposed to the south of these sequences. They are steeply dipping to overturned and young southwards.

The eastern anticline is doubly plunging. In the east, a north-south trending dip-slip fault with a minor strike-slip component, occurs.

The western anticline is transected by a NW-SE striking fault (section BB' and CC') that runs to the east in an area of no exposure. To the north-west; this fault merges with the thrust fault superposing the Sandstone Member of the Guwayza Formation over the Nayid Formation. The fault has a large, apparent strike-slip offset.

A number of high-angle, NW-SE to NE-SW trending faults offset laterally the upper Hamrat Duru lithostratigraphy along the northern and the southern limbs of the anticlines.

The Wahrah lithologies occurring to the north of the Hamrat Duru belt are steeply north-dipping to overturned, and are younging northwards. They are structurally repeated by east-west trending imbricate faults and NE-SW trending splay faults. To the north, the Wahrah imbricates are overlain by the footwall of the Haliw and Semail nappes. The floor thrust of the Wahrah imbricates, in turn, defines the northern boundary of the Hamrat Duru belt. Part of its surface trace coincides with a zone, more than a hundred meters wide, of strongly sheared light-coloured mudstones and cherts with steeply northward-dipping foliation and southward-verging, asymmetrical folds (figure 4-11).

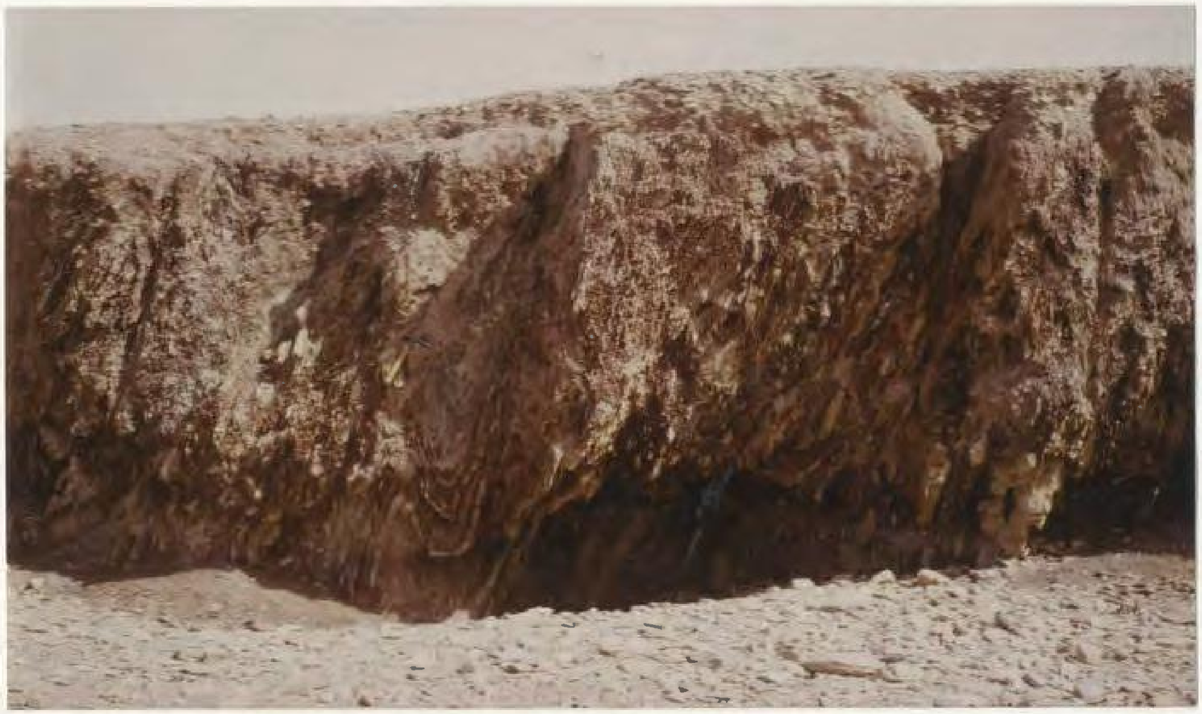


Figure 4-11: Sheared mudstone and chert lithologies along the southern margin of the northern Wahrah imbricates, displaying southward-verging, asymmetrical folds (beneath the hammer).

The Wahrah Formation to the south of the study area is represented by a regular, E-W oriented imbricate stack that is dipping and facing towards the north.

The contact between the Hamrat Duru belt and the southern Wahrah imbricates lies in an east-west trending belt of very poor exposure. Wide zones of intensely sheared cherts and marlstones similar to the rocks observed along the northern margin of the Hamrat Duru belt occur in the eastern part of this poorly exposed area.

4.3.2 Discussion

Figure 4-12 shows the projection of the map structures and the geometrical configuration of the Hamrat Duru belt at depth and above the erosional surface on the four structural cross-sections drawn through the study area. The reader is referred to the cross-sections of the surface data presented on inset A, for comparaison. The macroscopic structure displayed in this domain represents an E-W trending culmination, that consists of two en-echelon arranged anticlines folding a pre-existing Hamrat Duru imbricate stack. This structure is transected by three steeply dipping reverse faults (faults 1,2 and 3). While faults 1 and 2 are exposed, the existence of fault 3, as discussed later, is inferred. The geometrical relationships between folds and faults indicate that fault 1 is either an out-of-the-syncline thrust or a backlimb thrust; faults 2 and 3 are forelimb thrusts (Dahlstrom, 1970).

The boxfold syncline in the north-western part, and the other syncline in the south-eastern part of the belt, are parasitic to the large-scale anticlinal structures (figure 4-12, sections BB' and DD', respectively).

The northern limb of the boxfold syncline is truncated

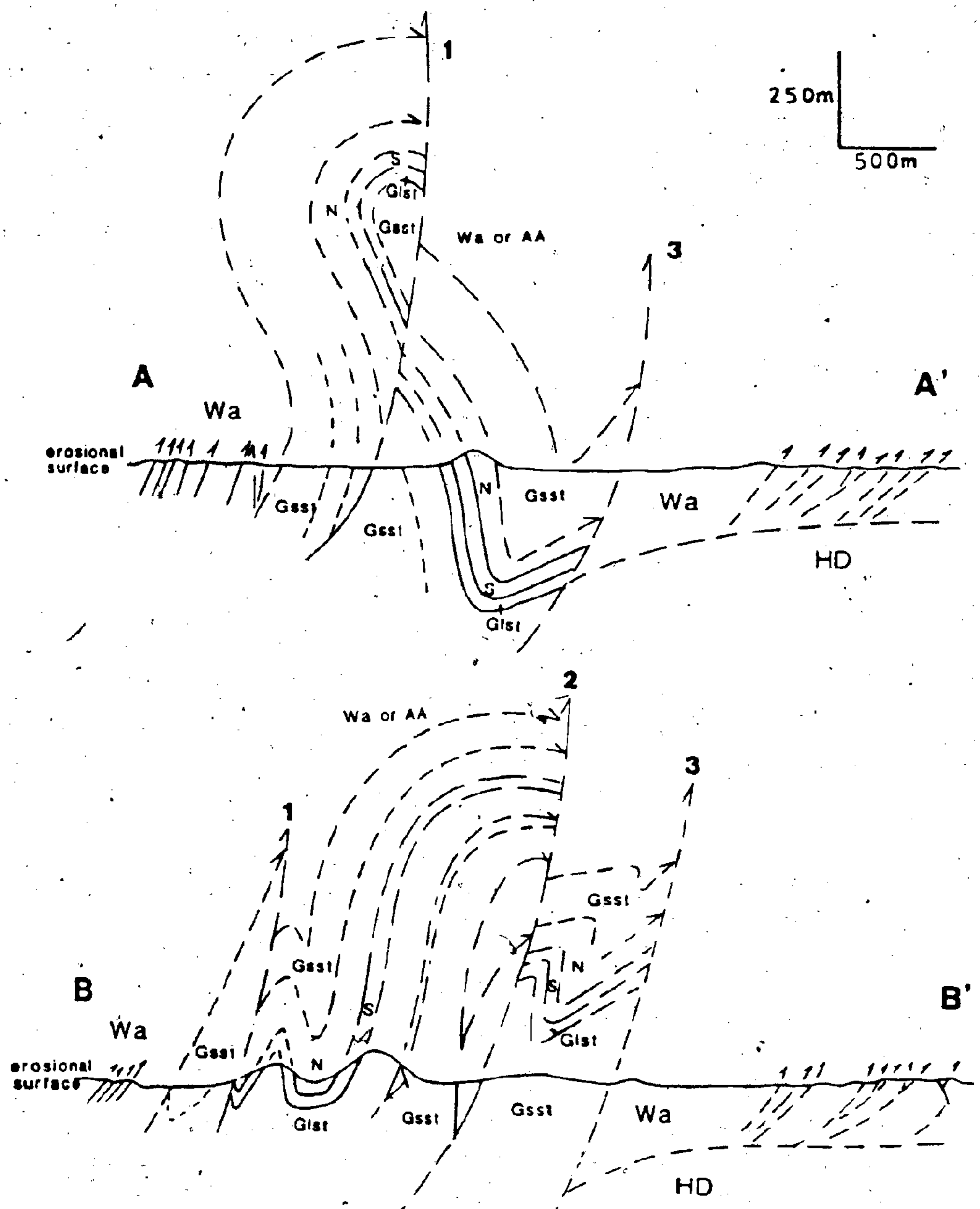


Figure 4-12: Projection of the map structures and interpretation of the geometrical configuration of the northern Hamrat Duru belt at depth and above the erosional surface on each of the four structural cross-sections drawn through this area

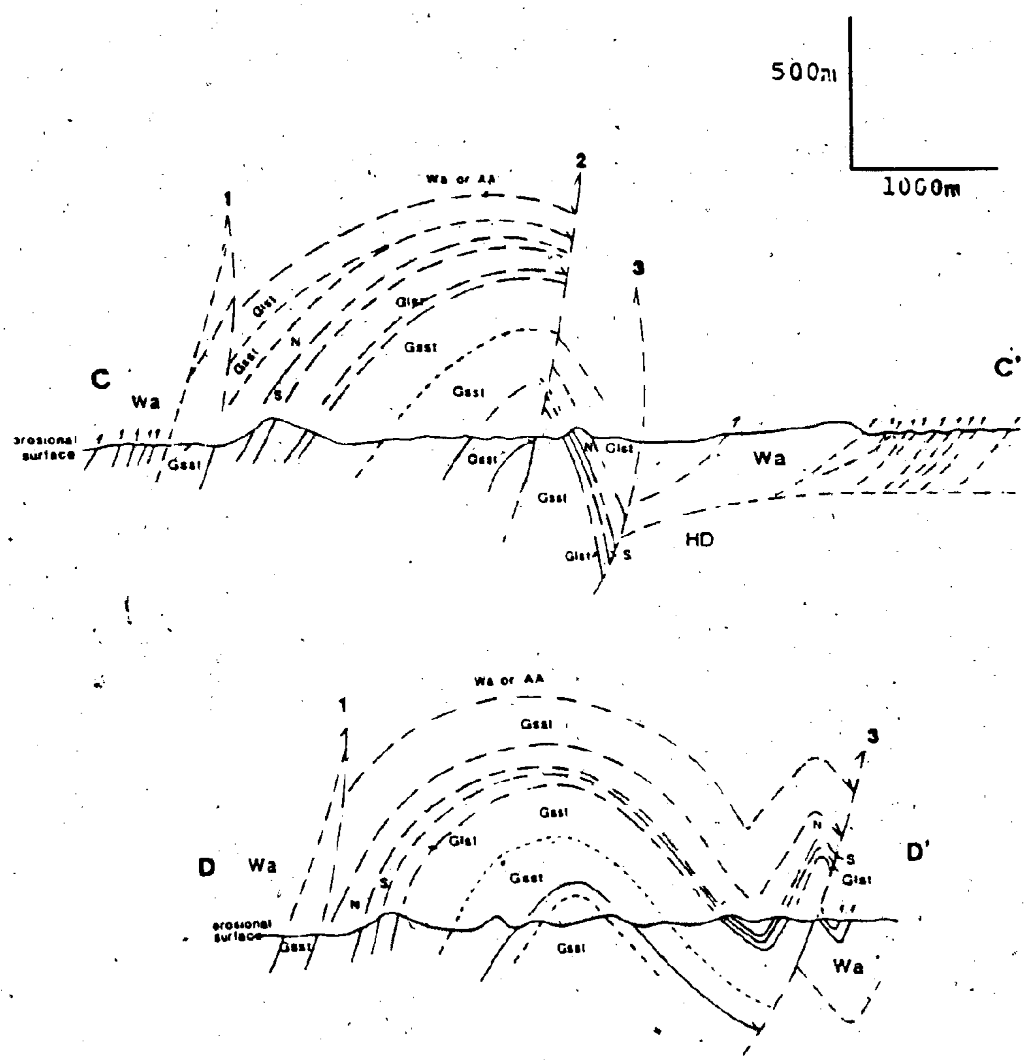


Figure 4-12, continued.

along strike to the east by fault 1 (figure 4-12, sections BB' and CC'). To the west, fault 1 truncates both limbs of the syncline along what is interpreted as a westerly dipping lateral ramp. It is cutting laterally down-section in the Hamrat Duru succession at a shallower dip than the bedding. This accounts for the absence of the Limestone Member of the Guwayza Formation, the Sid'r and the Nayid Formations at the erosional surface, along the northern limb of the western anticline (figure 4-12, section AA').

Fault 2 transects the southern limb of the western anticline to the east, as it merges with fault 3. To the west, fault 2 merges with fault 1. Fault 2 thus represents of a major connecting splay fault (Boyer and Elliott, 1982, figure 7).

To the north, the Hamrat Duru nappe is overlain by an imbricate stack of the Wahrah Formation. To the south, the Hamrat Duru imbricates must overlie the southern Wahrah imbricates. This is shown by the fact that there is not enough room to bring the Wahrah imbricates, which are consistently dipping and facing northwards (see section AA', BB' and CC', inset A and figure 4-12) over the Hamrat Duru nappe along a synformal hinge. A steeply north-dipping, east-west trending fault contact (fault 3) is thus inferred, superposing the folded imbricate stack of the Hamrat Duru Group over a more regular imbricate stack of the Wahrah Formation situated to the south. The Hamrat Duru imbricates are assumed to extend, south of fault 3, beneath the Wahrah imbricates of the central Sufrat ad Dawh Range (as shown in section AA', BB' and CC' of figure 4-12). Extensive shearing observed in a few outcrops near the inferred position of fault 3 lends further support to the presence of this fault along the southern margin of the Hamrat Duru belt. Similar shearing along the floor thrust of the Wahrah nappe north of the Hamrat Duru belt is also attributed to movement along this thrust surface.

The anticline of Al Ayn Formation shares the same axial trend as the eastern anticline in the Hamrat Duru belt (see inset C). Thus, the Al Ayn Formation is thought to be folded along the same anticlinal structure, while overlying the units of the Hamrat Duru Group in the east. Furthermore, the trace of the sole thrust of the Semail ophiolite appears to follow the same trend as the units of the Al Ayn Formation. Hence, this sole thrust is also considered to be folded along the same structure, while lying above the Al Ayn lithologies. It is not known if the Al Ayn Formation also occupies the hinge of the antiform, above the Hamrat Duru imbricates, along the plane of sections AA', BB', CC' and DD'.

In summary, the northern Hamrat Duru belt defines a structural culmination consisting of two en-echelon arranged anticlines, folding an already established set of imbrication faults. These folds are truncated by three major high-angle reverse faults resulting in the re-imbrication of the early imbricate systems. The southernmost fault thrusts the Hamrat Duru imbricates southwards over the imbricate stack of the Wahrah Formation. The normal Hawasina stacking order is only preserved along the northern margin of the culmination.

4.4 The Wahrah nappe in the Central Sufrat ad Dawh Range (inset C)

4.4.1 Description of the structure

The central Sufrat ad Dawh Range consistently displays a high degree of imbrication. This is shown by the intense repetition of the Wahrah lithostratigraphy, and consistent northward dips and younging directions. As discussed in 3.2.2, this area comprises 3 distinct lithostratigraphic assemblages, arranged in 3 E-W trending belts. Each of these belts consists of a complex array of connecting, rejoining and diverging splays (Boyer and Elliott, 1982), resulting in an impressive pattern of interfingering tectonic slivers. Since evidence of shearing along the trace of individual thrust faults was rarely observed, these faults were identified mainly on the basis of their cross-cutting relationships with the lithologies.

Tectonic and stratigraphic contacts were not distinguished. It was found that the imbrication in this area commonly lead to an anomalous succession of the Wahrah Members, i.e. that the normal stratigraphic order is often not preserved. For instance, in assemblage B, the units of the Lower Limestone Member may directly overlie units of the

Mudstone Member, or are overlain by units of the Chert Member. In assemblage C, units of the Upper Limestone Member may overlie directly units of the Mudstone Member, or are overlain by units of the Chert or the Mudstone members. The exact location of the thrust surfaces within these successions is uncertain. The lithological boundaries were not studied systematically, but it is suspected that most of the lithological boundaries are tectonic, pointing to the intensity of the imbrication. Hence, in insets A and B, "assumed" thrust symbols were assigned to the lithological boundaries of the units of the Wahrah Formation. Similarly, in inset C, the exact location of the thrust surfaces in the imbricate stack of the central Sufrat ad Dawh area could not be ascertain and "approximate" thrust symbols were used to indicate the pattern of the imbrication along the erosional surface.

The structure displayed by the lithostratigraphical assemblages A and B (as defined in section 3.4) consists of a regular arrangement of E-W trending imbricates, in which the bedding planes are in general moderately north-dipping (figure 4-13). Since the imbricate faults run parallel to the bedding along most of their length, this stereoplot is also believed to illustrate the attitude of the imbricate thrust faults. Folds of bedding planes are common within the individual imbricates. These folds do not appear to affect the thrust surfaces that contain the rocks in which they are developed. The folds have sub-horizontal, E-W trending fold axes and north-dipping axial planes, and their profile is angular and usually asymmetric with a southward vergence (figure 4-14).

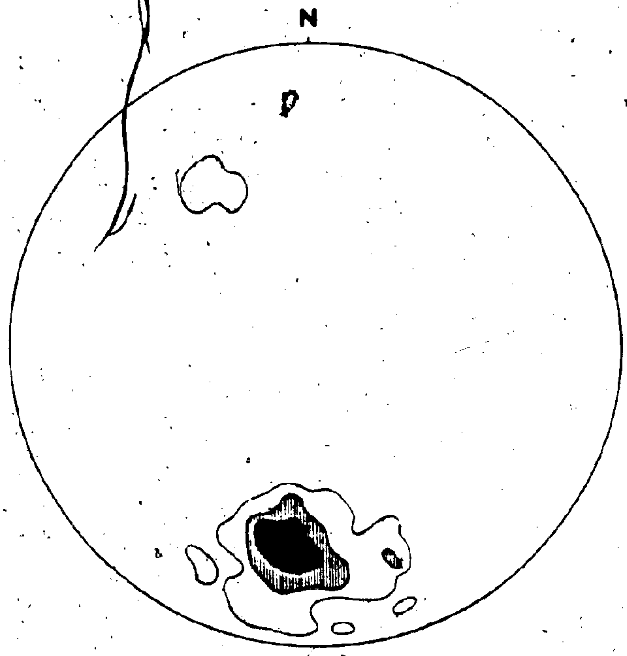
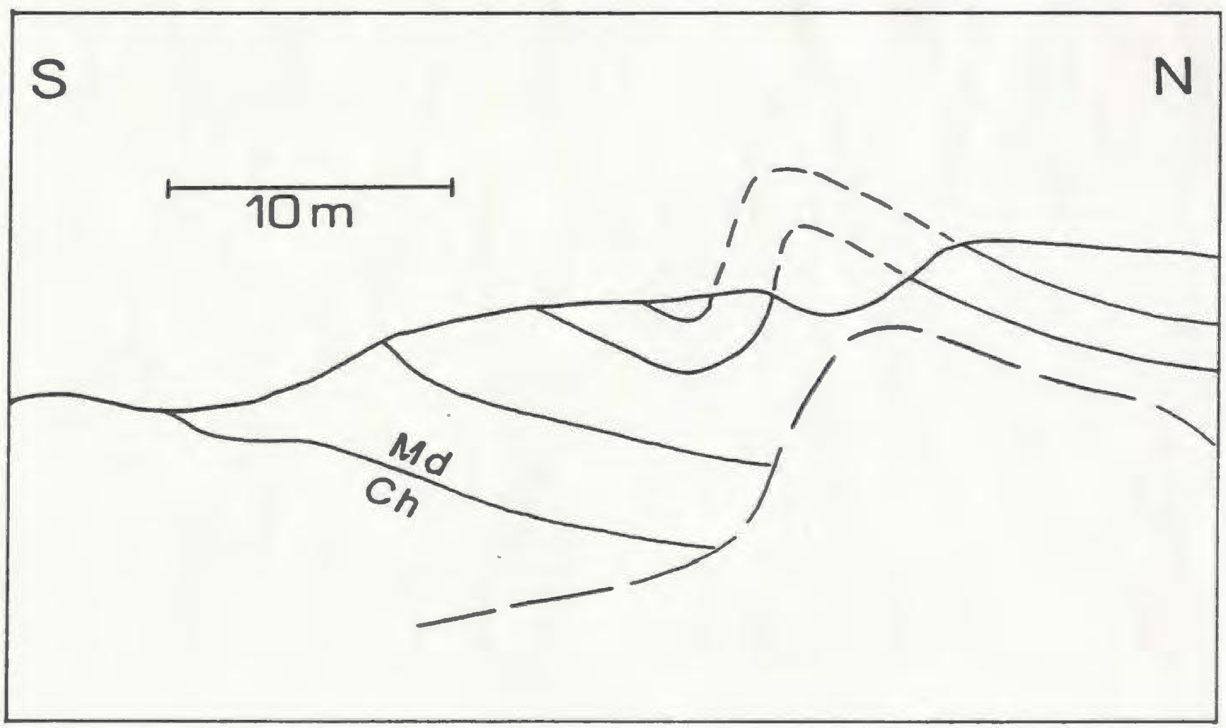


Figure 4-13: Poles to bedding in assemblages A and B in the central Sufrat ad Dawh Range, indicating that the lithologies are generally dipping towards the north. The smaller cluster represents the southern limbs of the occasional folds occurring in the area (n=66, contours: 15, 10 and 5% per 1% area).

In the north-eastern corner of this area (see also inset A), Wahrah imbricates are tightly folded along steeply west-plunging axes, with steeply north-dipping axial planes. These folds are transected by a N-S trending high-angle fault. The folds in these assemblages vary in wavelength from a few meters to more than 500 meters.

In the central part of the study area, a large-scale, tight to isoclinal antiform is developed. The general

Figure 4-14: Southward verging, asymmetrical fold in the Mudstone Member of thé Wahrah Formation, central Sufrat ad Dawh Range.



attitude of the bedding along the northern and southern limbs of this antiform suggests that the axial plane of the structure is dipping steeply towards the north; the fold faces southwards and plunges moderately to the west. It has a minimum wavelength of five kilometers and a minimum amplitude of twelve kilometers. It folds assemblage C of the Wahrah imbricate stacks, and contains in its hinge area a number of tight parasitic folds less than one kilometer in wavelength, and not exceeding two kilometers in amplitude. These folds are plunging towards the south-west, the west and the north-west. Also included along its northern limb is a westerly plunging "z" fold, a few hundred meters in wavelength and amplitude, and an E-W trending doubly plunging antiform of approximately the same scale. The southern limb of this antiform is transected by an E-W trending fault that extends across the entire mapping area. Other minor high-angle faults of various trends occur in the core of the antiform.

This large scale antiformal structure and the fault transecting its southern limb are folded openly along a N-S striking axial plane. Poles to the bedding along the trace of the fold hinge are plotted on a stereogram (figure 4-15). Plane P represents the orientation of the axial plane of this open fold, as approximated from the map pattern. An easterly dip of this axial plane is inferred on the basis of the pole distribution.

The imbricates lying to the south of the major transecting

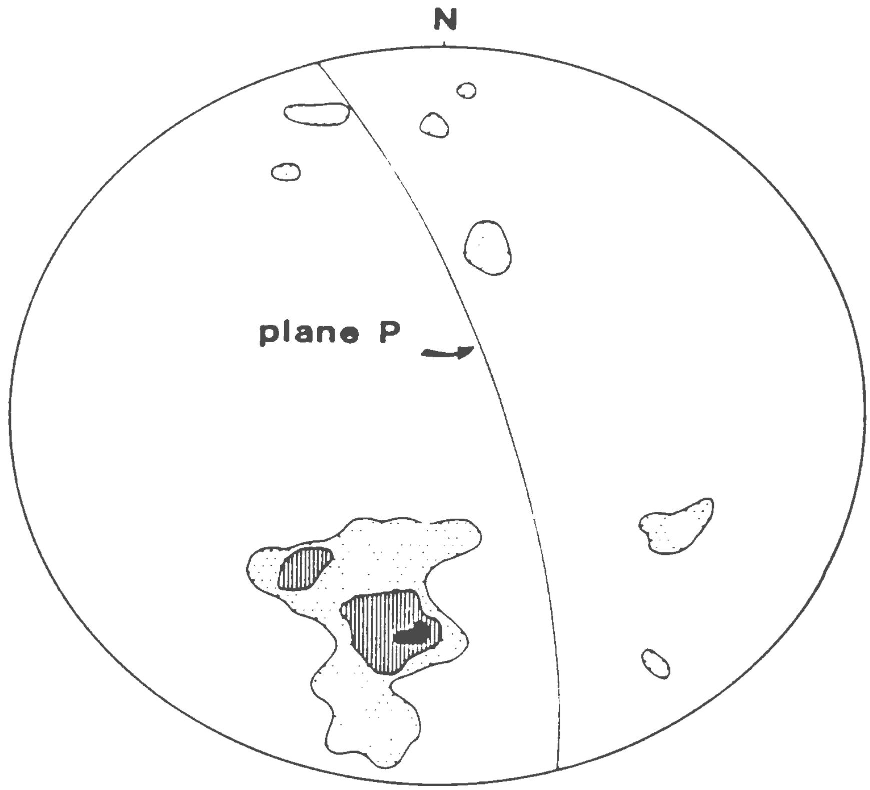


Figure 4-15: Poles to bedding along the surface trace of the large-scale antiform in the central Sufrat ad Dawh Range (n=67, contours: 9, 6, and 3% per 1% area). Plane P is the axial plane of the late open fold.

fault are only slightly warped along N-S trending axial planes. The facing direction is consistently northwards, and dip directions of the bedding planes are also predominantly northwards. Occasionally, folds of bedding are developed within the imbricates. These folds are mesoscopic, plunge gently towards the west or east. They are generally asymmetrical with a southwards vergence.

4.4.2 Discussion

A simplified version of the imbrication pattern of the Wahrah Formation in the central Sufrat ad Dawh Range is illustrated in figure 4-16. This diagram illustrates the imbricates before later large-scale folding along a N-S striking axial plane.

Three models for the geometrical configuration of the Wahrah imbricate stack are considered to account for the occurrence of the lithostratigraphic assemblages in the study area.

In the first model, the Wahrah imbricate stack is viewed as an imbricate fan system, whereby all thrust surfaces curve asymptotically downwards and join a common horizon at depth. The thrust faults cause the structural repetition of the Wahrah lithologies (see figure 4-17). This is a classical thrust geometry in fold and thrust belts (Coney, 1973; Boyer and Elliott, 1982). In this model, the absence of the Lower and the Upper Limestone members in the south and the north, respectively, of the study area is purely an artifact of the way the erosional surface is cutting through the imbricate stack. The occurrence of three distinct types of lithological assemblages, as shown by the surface geology in this area (figure 3-12), is possible if the floor thrust of the Wahrah imbricate fan dips towards the south at an angle θ with respect to the erosional surface (figure 4-17b). Considering that the Wahrah floor thrust dips towards the north as it overlies the southern Hamrat Duru

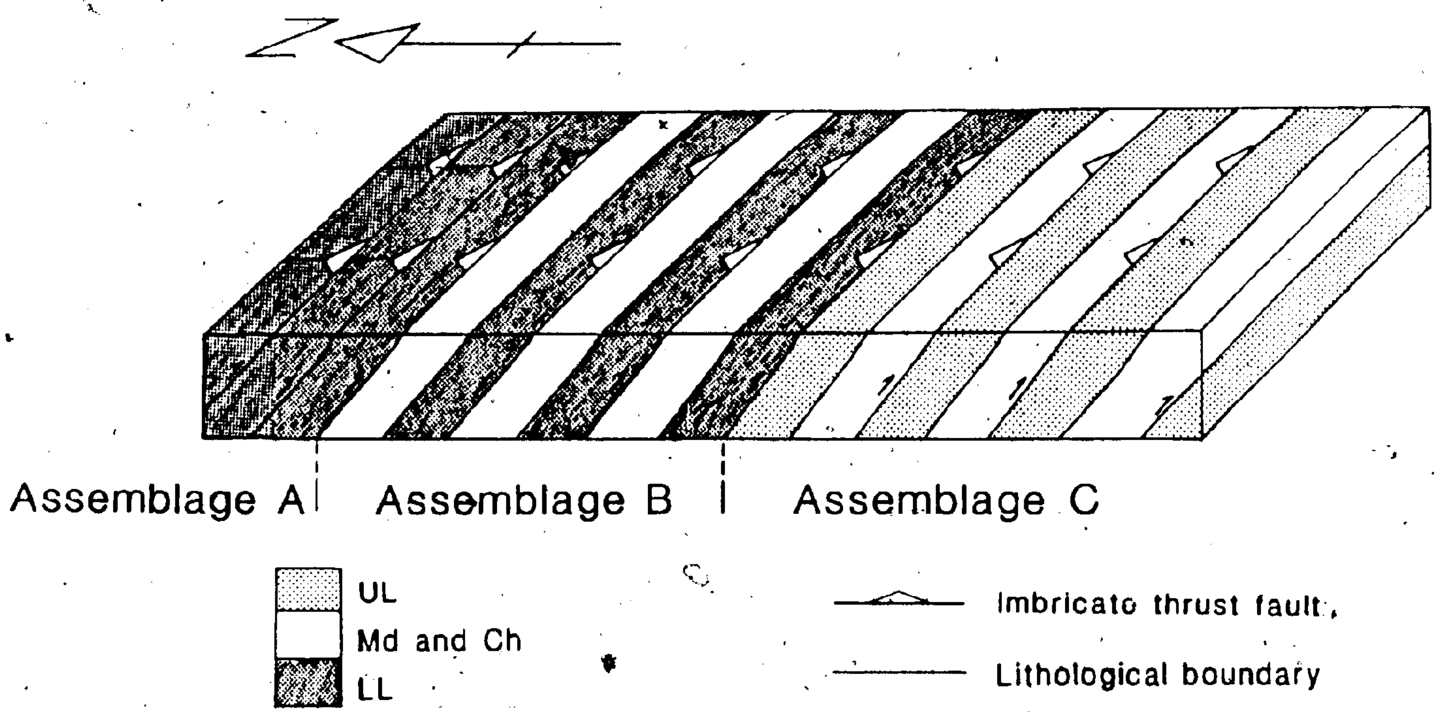


Figure 4-16: Simplified version of the lithological distribution in the Wahrah imbricate stack of the central Sufrat ad Dawh Range.

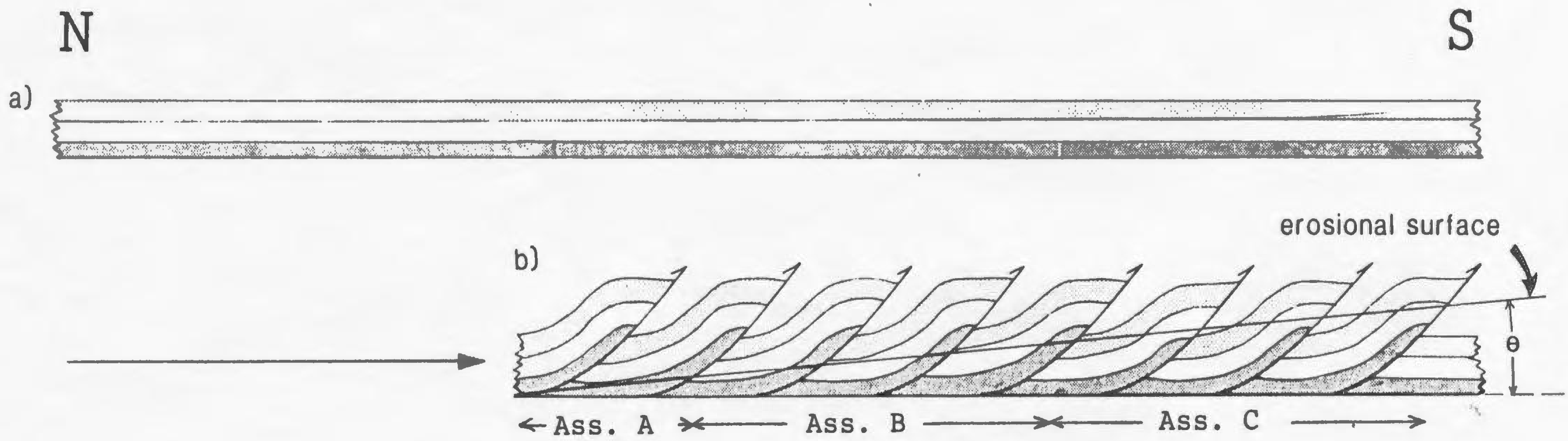


Figure 4-17: a) Conformable succession of the Wahrah Formation (the lithological symbols are the same as in figure 4-16),
b) imbrication (based on the model of Boyer and Elliott, 1982) and present geometrical configuration of the Wahrah imbricate stack in the central Sufrat ad Dawh Range.

belt (see cross-section in inset C), the Wahrah imbricate stack, according to the model presented in figure 4-17, would have to form a broad, upright, synformal flexure at depth, in the south of the central Sufrat ad Dawh Range.

The displacement along each of the imbricate thrust faults in this model is ideally assumed to remain the same. Following a slightly modified scheme, the same pattern would be achieved along the erosional surface if the displacement along these faults would increase progressively towards the north.

The middle part of this imbricate stack, however, is folded by a large-scale antiform (section BC in inset C). Therefore, the ideal circumstances required by the model of figure 4-17, whereby the erosional surface is at a constant angle θ with respect to the base of the imbricate stack, do not hold in the vicinity of the fold. This model is therefore, not entirely satisfactory.

In the second model, the lithostratigraphical distribution in this area reflects substantial diachronous facies variations in the Wahrah Formation. This is illustrated in figure 4-18a. The Lower Limestone Member, dominant in the north, pinches out towards the south, while the Upper Limestone Member follows the opposite trend. Structural telescoping of these lithologies along a common décollement horizon at depth, as depicted in figure 4-18b, would result in the observed distribution pattern.

Glennie et al. (1974, p.215-218) have documented

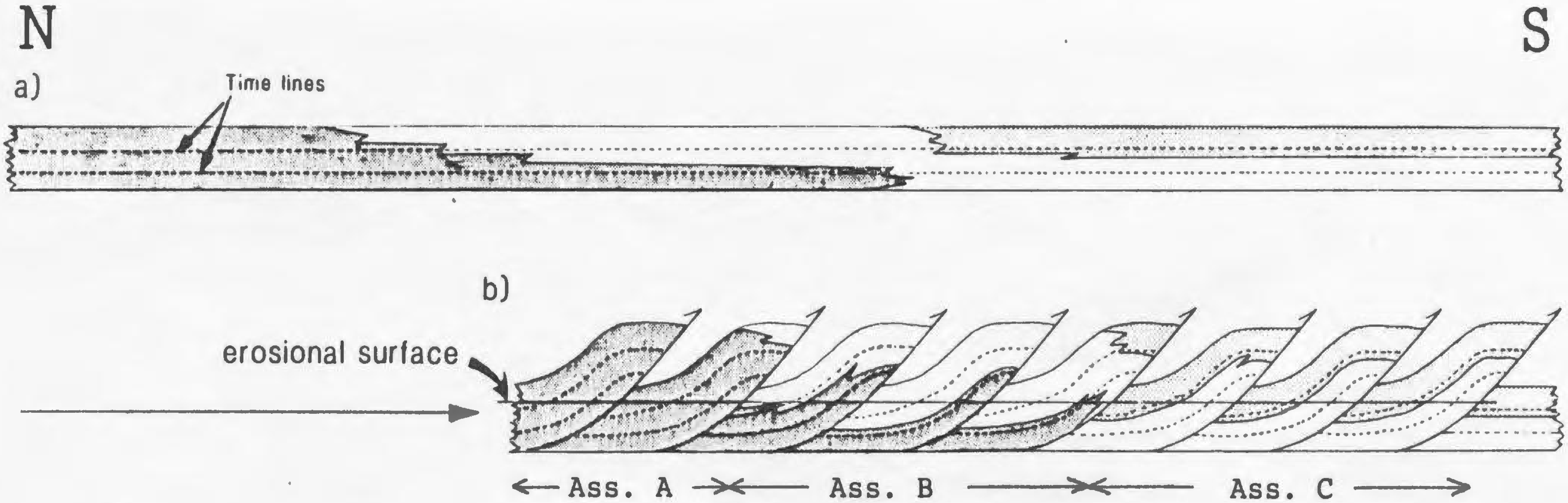


Figure 4-18: Alternative model for the distribution of the Wahrah lithologies in the central Sufrat ad Dawh Range; a) conformable succession of the Wahrah Formation displaying north-south diachronous facies variations, b) imbrication and formation of a regular imbricate stack.

considerable regional facies variation in the Wahrah Formation. This consists of the thinning-out of the two limestone members towards the north-east and the east, grading into more distal lithologies. Hence, the variation in facies of the Upper Limestone Member, as proposed for the Sufrat ad Dawh Range, is in agreement with the regional trends. On the other hand, the variation in facies of the Lower Limestone Member is incompatible with these trends.

The difference in stratigraphical thickness of the Guwayza Formation in the northern and the southern Hamrat Duru belt may indicate, as discussed in section 3.2., that this formation becomes more distal in facies towards the south. This is also in contradiction with the local variations in facies of the Hamrat Duru Group documented by Glennie et al. (1974). Hence, it is thought that until further stratigraphical work is done, one may not dismiss the possibility that the Lower Limestone Member of the Wahrah Formation, which is correlatable with the Guwayza Formation, follows the same trend in facies variation as the Guwayza Formation.

A major argument against the model presented in figure 4-18 can be put forward. The stratigraphical thickness of the Lower Limestone Member would be expected to be substantially greater in the northernmost imbricates and gradually diminish in the more southerly imbricates. This was not observed. The poorly exposed nature of the Upper Limestone Member precluded a similar evaluation of the variation in thickness of this member.

The models presented in figure 4-17 and 4-18 assume that the Wahrah Formation in the Central Sufrat ad Dawh Range forms an imbricate fan. However, the limited topographic relief, characteristic of the central Sufrat ad Dawh Range, provides little indication for the morphology of the Wahrah imbricates in cross-section. The thrust system could also have consisted of a duplex whose roof thrust was once lying above the present surface of erosion. This thrust would, in turn, have formed the floor thrust of another thrust system, consisting either of the Wahrah Formation, or of another type of rock unit.

It is conceivable that the geometrical arrangement of the imbricates in the central Sufrat ad Dawh Range is more complex than what is depicted in the previous models. Thus, a third explanation may be invoked for the distribution of the Wahrah lithostratigraphy in this area. Assuming that, before imbrication, the Wahrah Formation was uniformly represented by all four of its members (i.e. assuming that no significant facies variations existed), it is possible that each lithostratigraphical assemblage represents a distinct duplex, whose floor and roof thrust enclose only part of the Wahrah stratigraphy. Assemblage A is contained in a duplex whose floor and roof thrust lie at the base and the top, respectively, of the Lower Limestone Member. Assemblage B lies within a duplex enclosing the Mudstone, the Chert and the Lower Limestone Members. Assemblage C lies within a duplex whose floor thrust remains above the

Lower Limestone Member. Figure 4-19 illustrates how this geometry may be achieved. The sequence of development of the duplexes in this figure is based on a measured graphical experiment conceptualized by Boyer (1978) and Boyer and Elliott (1982). In figure 4-19(a), a décollement develops at the base of the Wahrah Formation, and ramps to the top of the Lower Limestone Member. Imbrication of this member proceeds, thus forming assemblage A (figure 4-19(b)). The décollement then steps on top of the Mudstone and the Chert Members, leading, as shown in (c), to the imbrication of these members and the Lower Limestone Member, thus forming assemblage B. In (d), from the base of the Wahrah Formation, the décollement ramps to the top of the Lower Limestone Member, and migrates further south on top of the Upper Limestone Member, resulting as shown in (e), in the imbrication of the Mudstone, the Chert and the Upper Limestone Members; this leads to the formation of assemblage C; figure 4-19(f) represents the final geometrical configuration of the Wahrah duplex. Note that, from (a) to (f), the floor thrust of the Wahrah imbricate stack climbs up-section southwards, in the direction of transport of the imbricates.

The process of imbrication illustrated in figure 4-19 is thought to be equivalent to what Glennie et al. (1974, p.344) briefly referred to as "intra-formational slippage" to account for this peculiar distribution of the Wahrah lithologies.

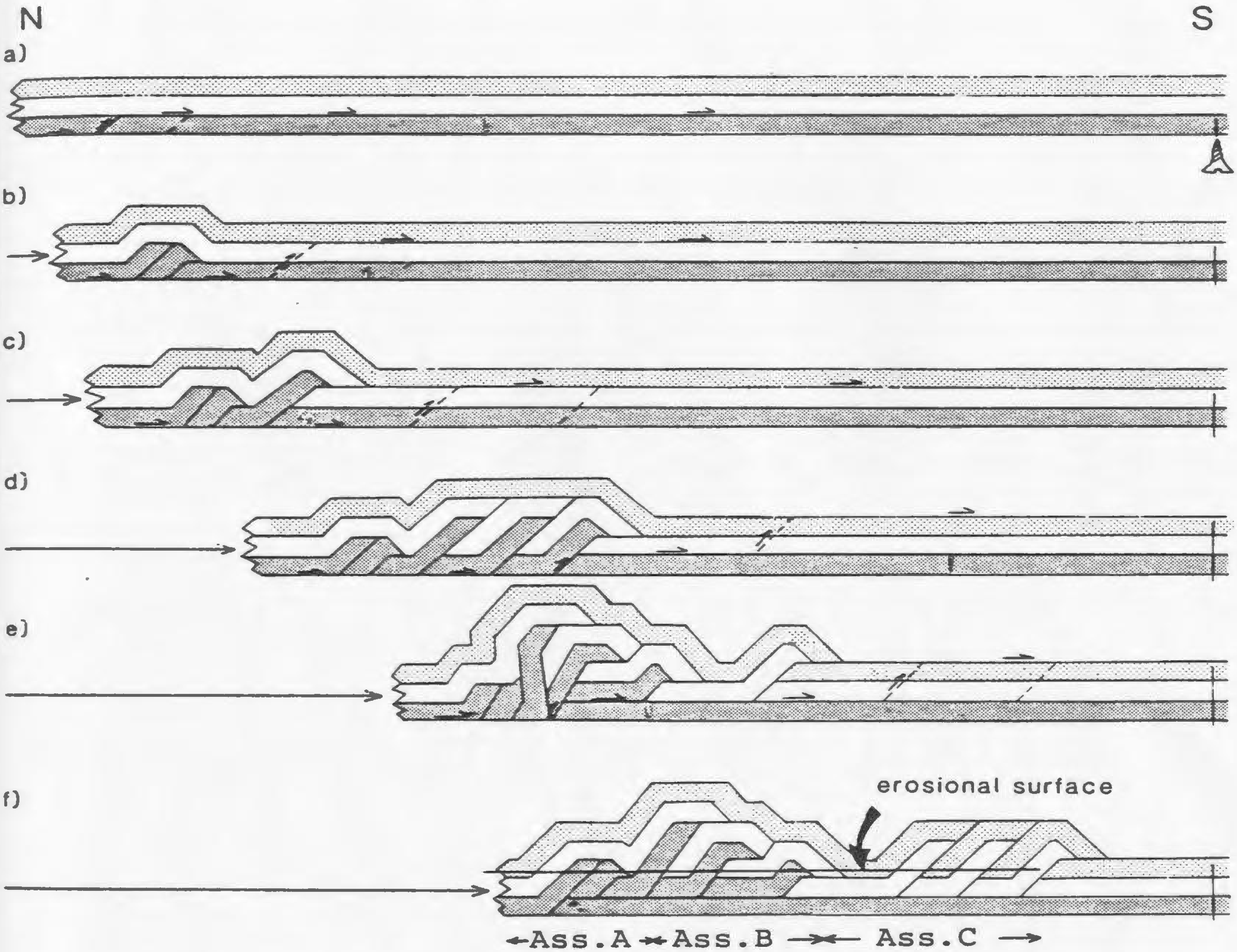


Figure 4-19: Third model for the lithological distribution of the Wahrah Formation in the central Sufrat ad Dawh Range (see text for discussion).

According to this third model, however, the Upper Limestone, the Chert and the Mudstone members would be expected to appear above assemblage A, along the erosional surface, in the north of the Sufrat ad Dawh Range. This does not seem to be the case.

In conclusion, the three models, presented here, are highly idealized. It is thought that, although slightly inconsistent with the field evidence, all three, or a combination of 2 or 3, may be equally valid. With the data presently at hand, however, there is no way of determining which alternative is the most applicable in the study area.

The geometrical relationship, shown by the large-scale antiformal structure and the E-W trending fault truncating its southern limb allows the designation of this fault as a forelimb fault (Dahlstrom, 1970). The fault causes the structural repetition of assemblage C in the southern part of the study area. The high-angle faults occurring in the core of the antiform probably correspond to structural complications resulting from room problems that developed during folding at deeper levels in the fold core.

The origin of the westerly plunging "z" fold on the northern limb of the large-scale antiform, according to the Pumpellyan rule on the geometrical relationship of parasitic folds (De Sitter, 1964), is unrelated to the development of this antiform. The occurrence of a doubly plunging fold along the same limb of this structure hints, however, at the doubly-plunging nature of the large-scale antiform. Hence, the "z" fold, although plunging in the opposite direction, may be related to an easterly plunging antiformal hinge situated in the gravel plain east of the study area, if the hinge line of the parasitic fold was rotated during folding from an easterly to a westerly plunge.

4.5 The southern Hamrat Duru belt (inset B)

4.5.1 Description of the structure

The structure of the southern Hamrat Duru belt is dominated by a series of imbricates that are facing and moderately dipping towards the north (see sections AA', BB' and CC' on inset B). These imbricates trend in an E-W direction in the central part of the belt, but their trend becomes progressively oriented to a NE-SW direction westwards (see insets A and C). They range in thickness from several meters (at the scale of the outcrop) to a kilometer, and generally involve all three formations of the Hamrat Duru Group.

One major set of folds is recognized. They are generally open to tight, and have shallowly plunging fold axes that trend in a NE-SW orientation in the central part of the belt and become reoriented to an easterly orientation in the east. Thus, they parallel the change in strike of the imbricates (figure 4-20). The folds are often asymmetrical, verging southwards, and either fold the thrust planes or are truncated by them. They are recognized at the scale of the outcrop and may reach up to a kilometer in wavelength and 200-300 meters in amplitude.

N-S trending, high-angle faults are common in the area of inset B. They may be traced for more than three kilometers along strike. Some offset the Hamrat Duru imbricate thrust faults, as well as the contact of the Wahrah and Hamrat Duru units to the north. Others terminate against the imbricate faults. E-W oriented, high-angle, dip-slip faults also occur, but do not affect the thrust faults. The attitude of these faults could not be determined.

Lithologies of the Chert and the Upper Limestone Members of the Wahrah Formation occur in a poorly exposed area enclosed within the Hamrat Duru belt (figure 4-21).

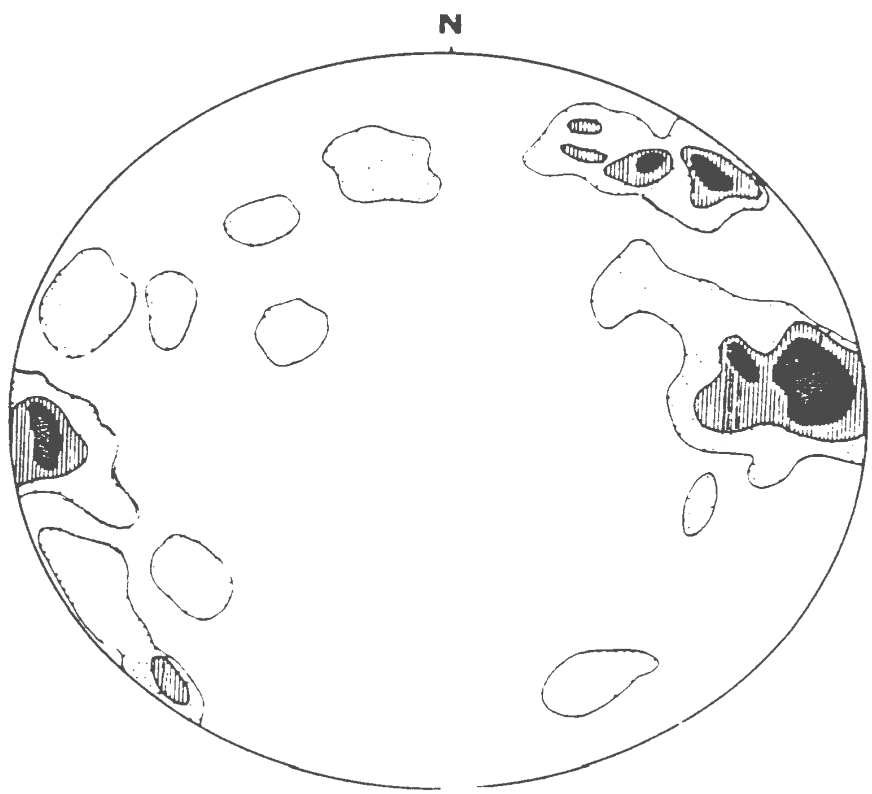
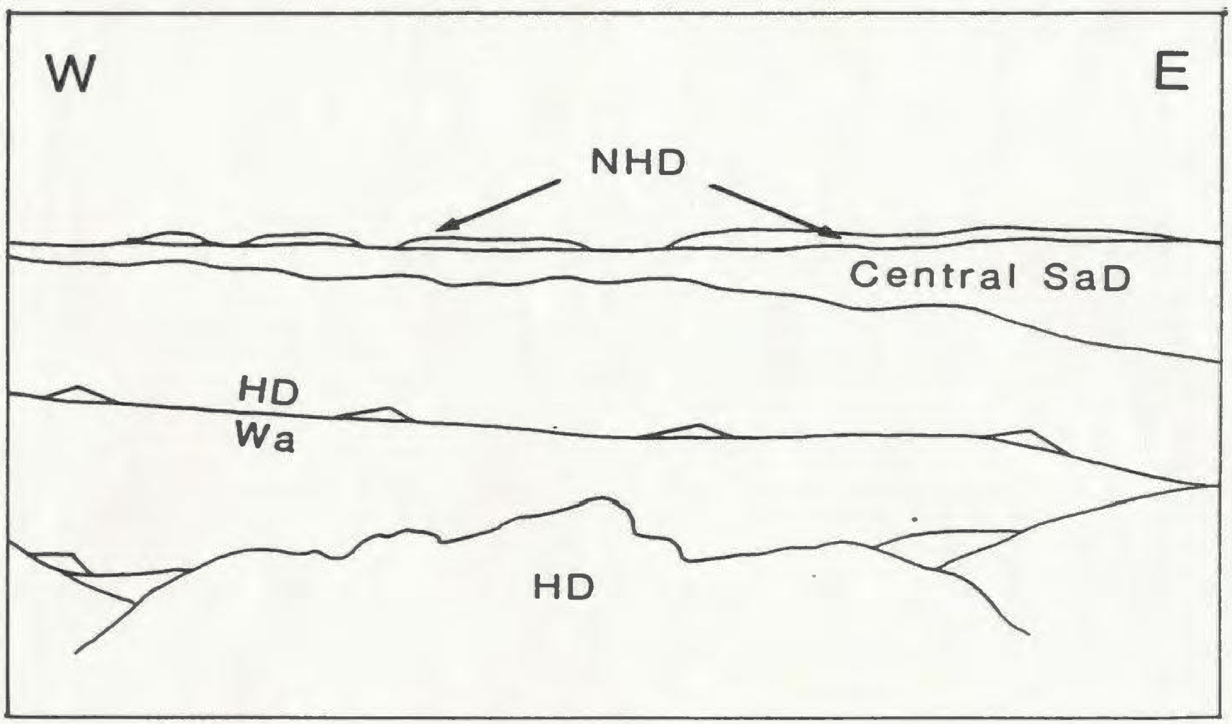


Figure 4-20: Fold axes measured in the map area of inset B (n=75, contours: 8, 6 and 4% per 1% area).

These units are dipping and younging towards the north. The northern limit of these units has a strike length of two

Figure 4-21: Area of poor exposure, lying within the southern Hamrat Duru belt (east-central part of inset C) and containing units of the Wahrah Formation. Note the Wahrah imbricates of the central Sufrat ad Dawh Range in the background.



kilometers. The southern boundary merges towards the west with the northern boundary. A reconnaissance survey in the east of the poorly exposed area has shown that these lithologies are juxtaposed against units of the Hamrat Duru Group by a N-S oriented fault (see inset C). Therefore, this domain of Wahrah lithologies is enclosed entirely within the southern Hamrat Duru belt.

The structure in the Wahrah unit fringing the southern margin of the Hamrat Duru belt consists of a regular E-W trending imbricate stack with north-dipping thrust faults. Minor angular, south-verging asymmetrical folds with sub-horizontal east-west trending axes occur. The relationships of these folds with the thrust surfaces is uncertain.

4.5.2 Discussion

The Wahrah nappe overlies tectonically the Hamrat Duru nappe along the northern boundary of the southern Hamrat Duru belt (figure 4-22). This is thought to represent the conventional, regional tectonostatigraphic stacking order of these nappes (see section 2.3). The opposite relationship occurs along the southern boundary of the belt, where the Hamrat Duru imbricates overlie the narrow belt of Wahrah imbricates (figure 4-23). These tectonic relationships are suggested by the consistent northerly dips and facing directions of the Hamrat Duru and the Wahrah imbricates in this part of the study area.

Figure 4-22: Structures in the upper Hamrat Duru Group are depicted in the foreground. The Wahrah imbricates in the background structurally overlie the southern Hamrat Duru belt along the northern boundary of this belt. Note the trace of a N-S trending fault displacing the roof thrust of the Hamrat Duru imbricates.

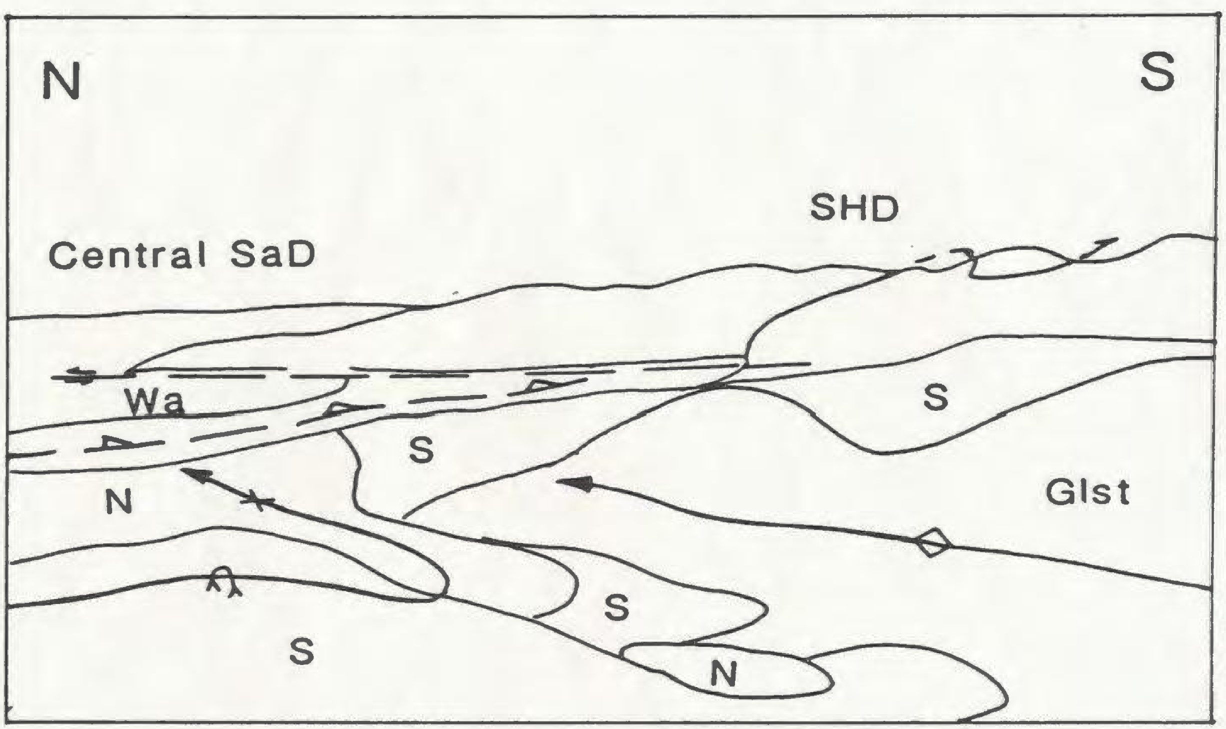
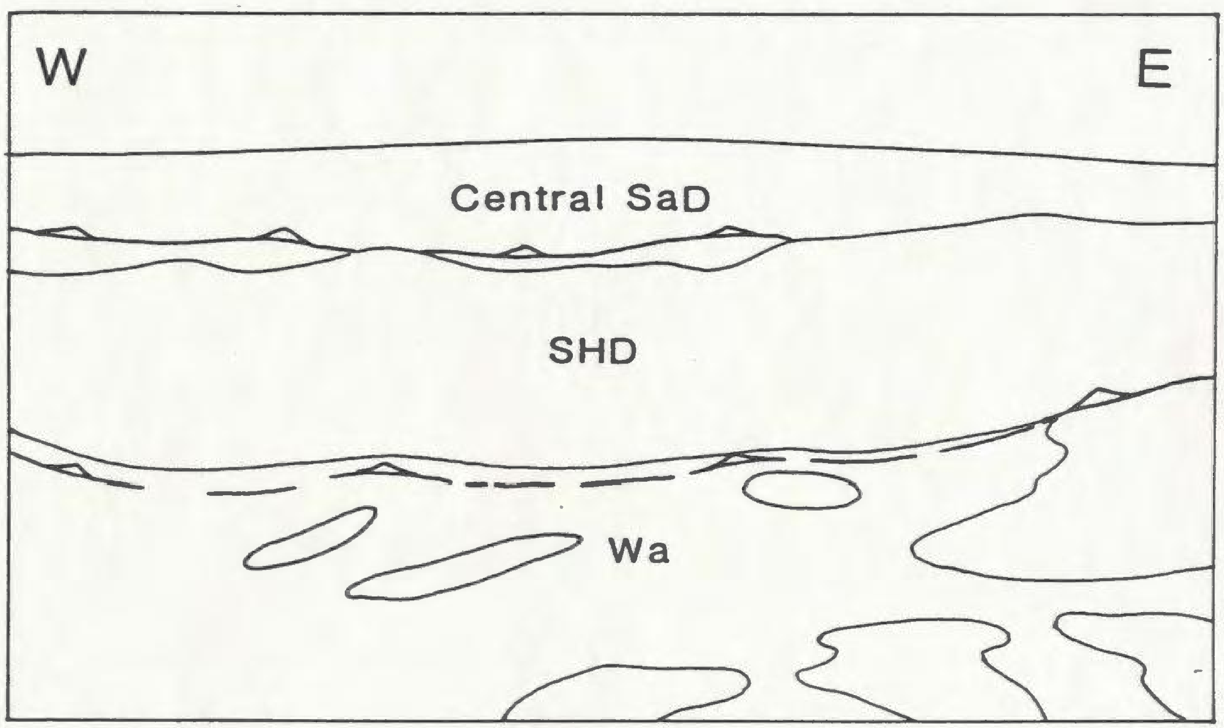


Figure 4-23: Tectonic setting of the southern Hamrat Duru belt, clearly displaying the superposition of the southern Hamrat Duru belt over the southern Wahrah imbricates, exposed in the foreground.



The Wahrah lithologies enclosed within the Hamrat Duru belt are interpreted to belong to one or more E-W trending Wahrah imbricates structurally bounded to the north and the south by Hamrat Duru imbricates.

Figure 4-24 is a diagramatic representation, in plan view and in cross-section, of the central part of the southern Hamrat Duru belt, comprising part of the structurally enclosed Wahrah lithologies. This geometry is best interpreted in terms of the tectonic repetition of the Wahrah and the Hamrat Duru imbricated nappes. Hence, fault 1 represents the floor thrust and the roof thrust of the Wahrah and the Hamrat Duru nappes, respectively. This fault corresponds to the original stacking order of the Wahrah imbricates overlying the Hamrat Duru imbricates. It is divided into three sections. Fault 1a marks the northern limit of the Hamrat Duru belt. Fault 1b forms the southern boundary of the enclosed Wahrah lithologies, and merges with fault 2 at depth and along its western extension. Fault 1c is not observed in the study area but is assumed to underlie the Wahrah imbricates occurring to the south of the Hamrat Duru belt. Faults 2 and 3 are interpreted as two re-imbrication faults, tectonically repeating the local tectonostratigraphy.

This interpretation is corroborated by localized cross-cutting relationships, observed in the Hamrat Duru belt, whereby thrust surfaces are folded and abut against unfolded thrust surfaces. Some of these relationships are

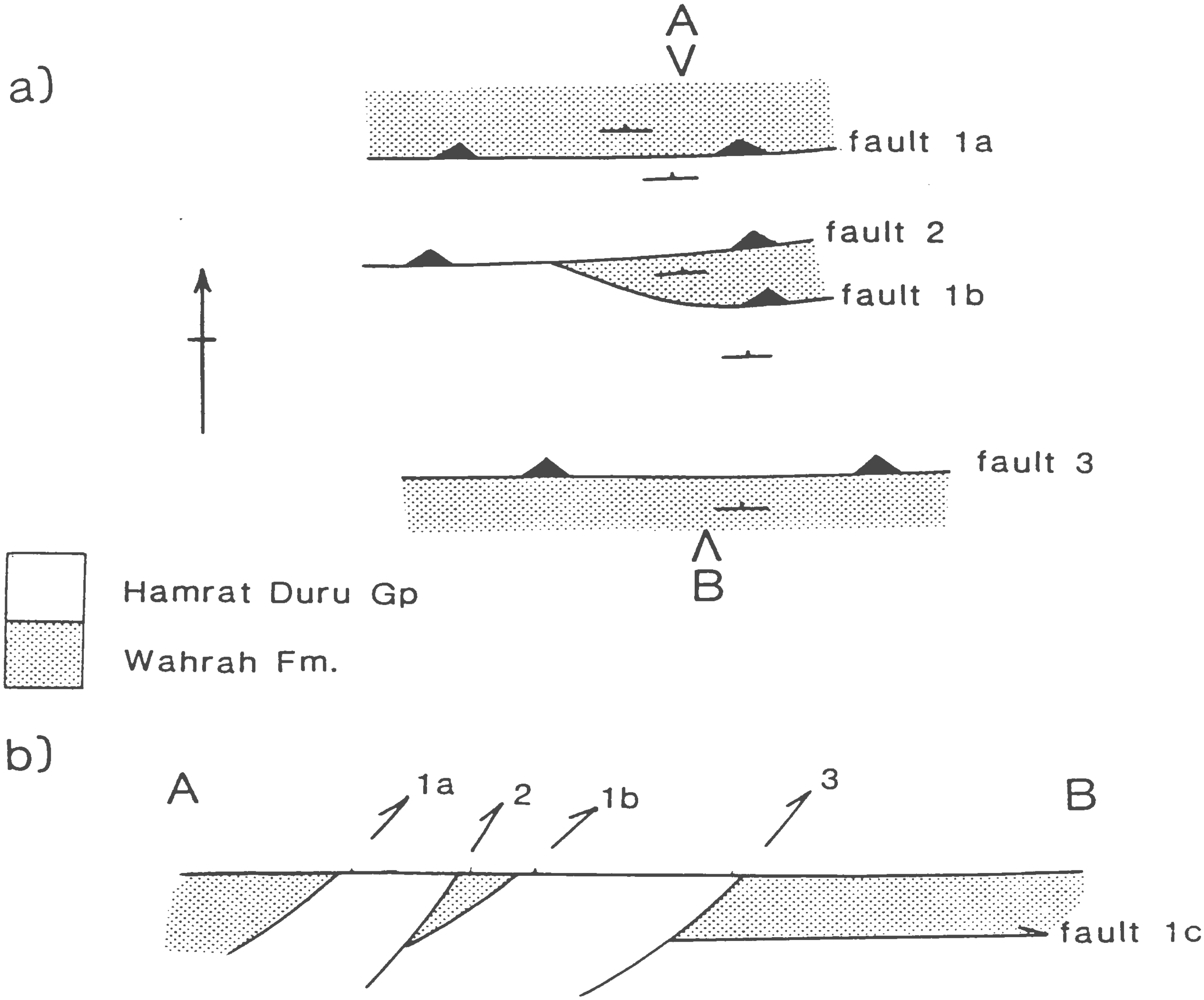


Figure 4-24: Schematic representation in plan view (a) and in cross-section (b) of the southern Hamrat Duru belt.

shown in inset B, and are outlined in figure 4-25. They indicate that there are at least two distinct generations of thrust surfaces.

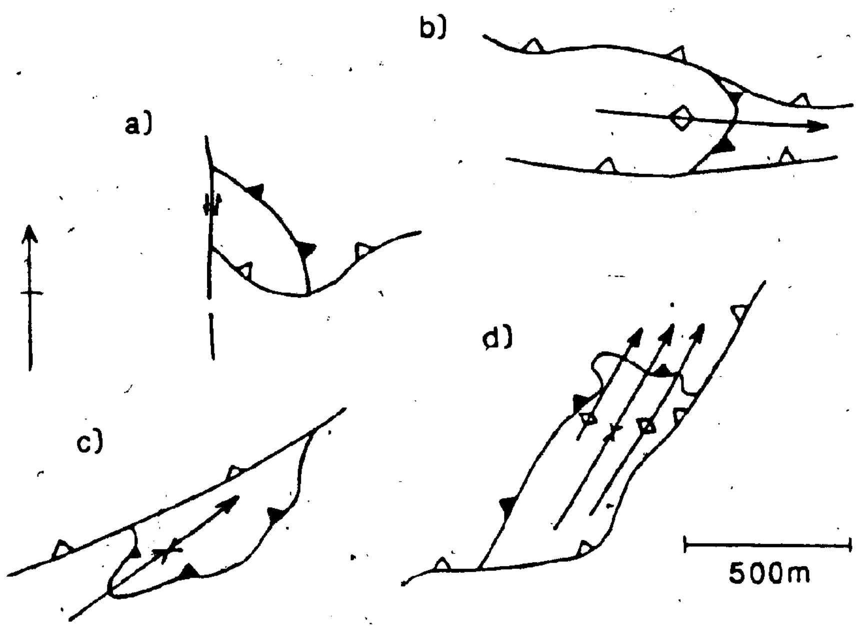


Figure 4-25: Cross-cutting relationships of thrust surfaces in the southern Hamrat Duru belt, as shown in inset B (filled teeth: early thrust, open teeth: late thrust).

The cross-cutting relationships are, however, scarce. They are shown unambiguously only when the hinge of a plunging fold affecting an early thrust is transected by a later thrust (see all four patterns in figure 4-25). This suggests that the later set of thrust surfaces developed essentially parallel to the early set. Consequently, it is generally not possible to assign any of the thrust surfaces to one generation or the other.

Moreover, there is no evidence indicating that the north-easterly to easterly trending folds, although sharing the same style and orientation, do necessarily belong to a single generation. An interference pattern of shallowly plunging folds sharing these characteristics is not likely to emerge on the map pattern. Hence, the folds may not be used to help determine to what generation a thrust fault belongs.

The re-orientation of the imbricate thrust faults and the fold axes from an E-W to an NE-SW trend defines a large-scale fold with a roughly N-S oriented axial plane. It represents minor shortening of the Hamrat Duru imbricates in the E-W direction.

4.6 Structure of the Sufrat ad Dawh Range

4.6.1 Tectonostratigraphy

Four tectonostratigraphic units of the Hawasina complex are recognized in the Sufrat ad Dawh Range, in addition to the Semail ophiolite nappe and the metamorphic rocks of the Haybi Complex. The tectonic stacking order of these nappes is summarized in figure 4-26.

The Semail ophiolite overlies directly the metamorphic rocks of the Haybi Complex, the Haliw, the Wahrah and the Al Ayn nappes. The tectonic relationship of the Wahrah nappe with respect to the Al Ayn nappe is not displayed in the study area. Only the Wahrah nappe is exposed below the floor thrust of the Haliw nappe. The relationship of the

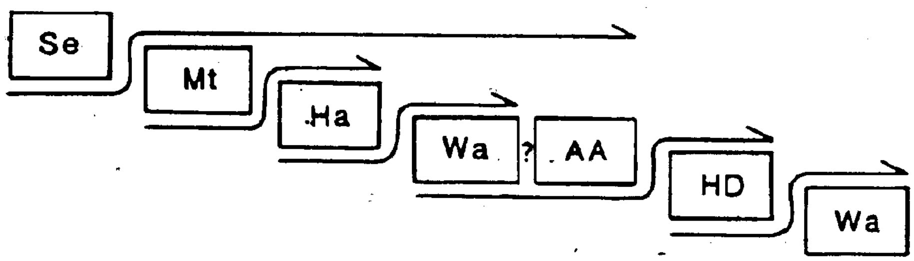


Figure 4-26: Tectonostratigraphy of the Sufrat ad Dawh Range.

Haliw and the Al Ayn nappes is not known. The Hamrat Duru nappe is overlain by the Wahrah and the Al Ayn nappes. On the other hand, the Hamrat Duru nappe in turn overlies different segments of the Wahrah thrust system.

These observations are largely in agreement with the regular regional stacking order of these nappes in other parts of the Oman Mountains (Glennie _et al_., 1973, 1974). One major difference is the reversal in the tectonostratigraphy displayed in the Sufrat ad Dawh Range by the Wahrah and the Hamrat Duru nappes, thus confirming the observation made in the south part of the Sufrat ad Dawh Range by these workers (see Glennie _et al_. (1974) section 9, enclosure 5). This study further demonstrates that this reversal in tectonostratigraphy is not exceptional, but occurs systematically across the strike of the Hawasina Complex in the Sufrat ad Dawh Range.

4.6.2 Synopsis of the structure

The structural grain of the Hawasina nappes in the Sufrat ad Dawh Range maintains a consistent E-W trend, and parallels the regional tectonic strike of the Late Cretaceous allochthons in the Oman Mountains. The results of the detailed geometrical analysis presented in this chapter are summarized in a composite N-S trending structural section drawn across the Sufrat ad Dawh Range (figure 4-27).

The structure in the northern and southern Hamrat Duru belts and in the central part of the Sufrat ad Dawh Range, is dominated by a regular hinterland-facing imbrication, with E-W striking thrust surfaces. A salient characteristic of the deformational style in these areas is the occurrence of two geometrically distinct types of reverse faults. The faults belonging to the prevailing set (dashed thrust lines in figure 4-27) generally lie parallel to the bedding. In the northern and southern Hamrat Duru belts, these faults define a duplex, whose roof thrust lies along the northern margins of these belts, and also constitutes the floor thrust of the overlying Wahrah imbricates. The floor thrust of the Hamrat Duru duplexes is assumed to lie in the subsurface, at an undetermined depth. In the central part of the Sufrat ad Dawh Range, the main set of faults is responsible for the intense imbrication of the Wahrah Formation. The thrust surfaces may merge, as shown in figure 4-27, along a common décollement, which would form

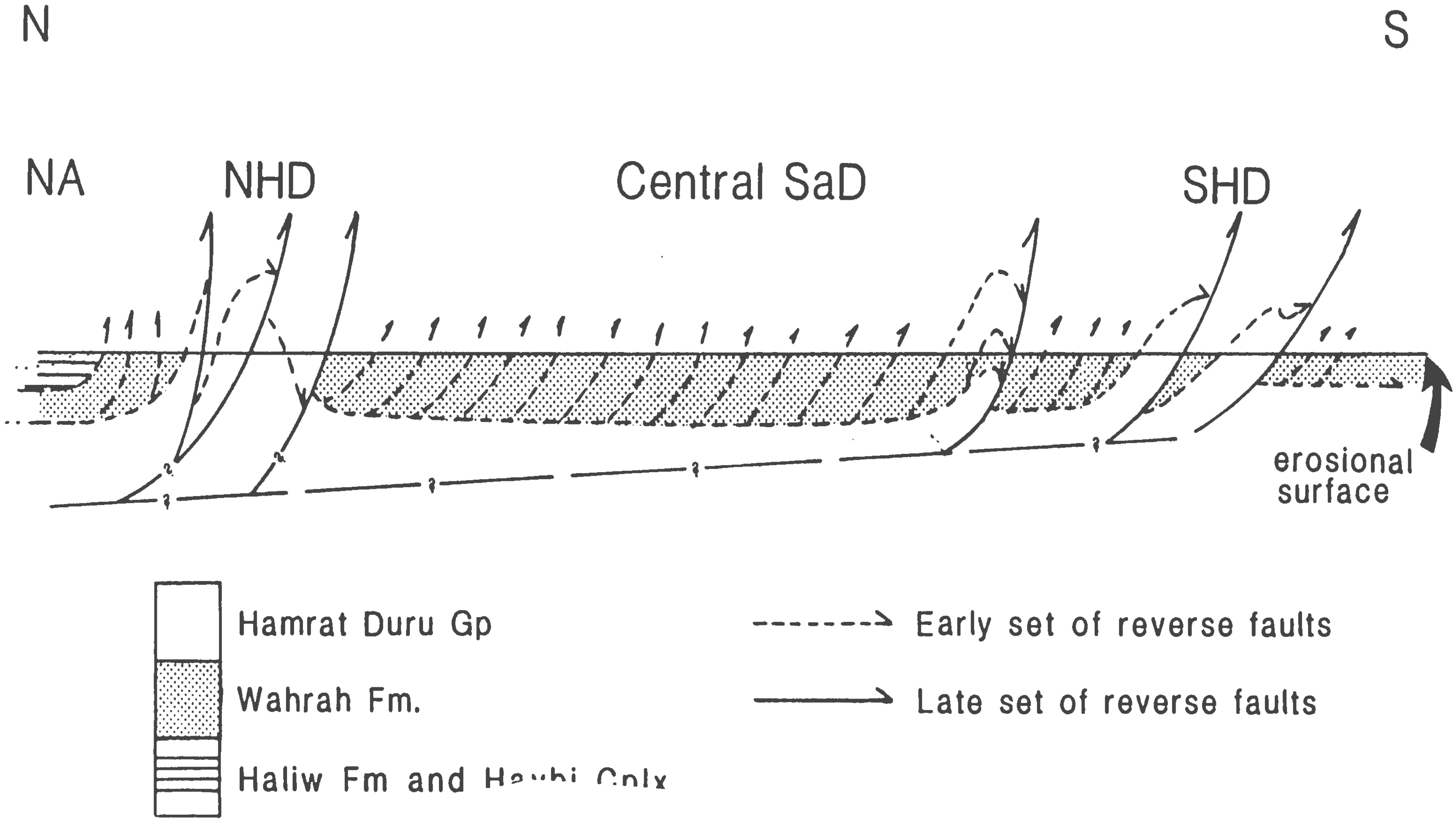


Figure 4-27: Schematic representation of the macroscopic structure of the Sufrat ad Dawh Range.

the floor thrust of the Wahrah nappe (figures 4-17b and 4-18b). Alternatively, they may define a thrust system composed of three major duplexes (figure 4-19f).

In the northern Hamrat Duru belt, the lithologies and the first set of reverse faults are folded along an E-W trending antiformal culmination. This culmination is transected by the second set of reverse faults (solid thrust lines in figure 4-27). The steeply dipping nature of these faults controls the attitude of the Hamrat Duru and the Wahrah nappes in this area, which contrasts with the regular, moderate northerly dip of the rock sequences in the northern area (see cross-section AB, inset C). They breach the Hamrat Duru roof thrust and allow the Hamrat Duru duplex to overlie tectonically the Wahrah imbricates to the south. The Wahrah imbricates to the north of this belt represent the trailing edge of the Wahrah nappe.

A similar geometry may be present in the central Sufrat ad Dawh Range, but there the Hamrat Duru nappe does not occur at the erosional level. This suggests that either the displacement along the secondary faults is less than in the northern Hamrat Duru belt (as shown in figure 4-27), or that this fault does not reach the Hamrat Duru nappe at depth (figure 4-28). It is also conceivable that the Hamrat Duru nappe is altogether absent from the subsurface.

In the southern Hamrat Duru belt, the lithologies and the main set of faults are also folded. These folds, however, are more angular and smaller in amplitude and in wavelength,

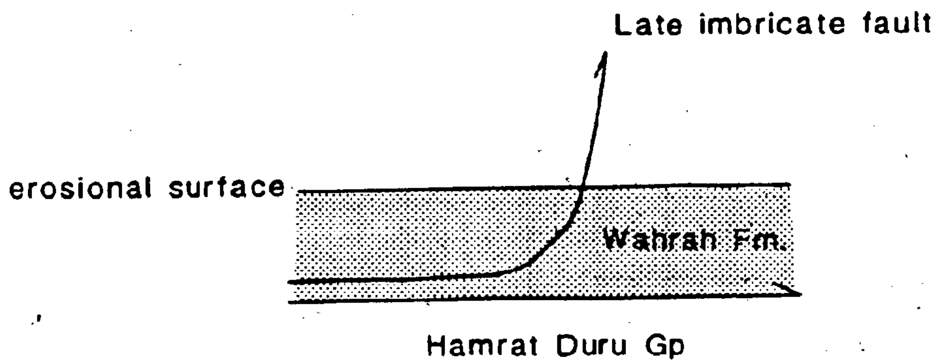


Figure 4-28: Alternative to figure 4-27 illustrating why the large-scale fold and forelimb fault structure in the central Sufrat ad Dawh Range does not allow units of the Hamrat Duru nappe to be exposed at the erosional surface.

than in the northern Hamrat Duru belt. The second set of reverse faults in this area also causes the imbrication of the Wahrah and the Hamrat Duru nappes. Apart from localised exceptions, these faults do not truncate at a high angle the lithologies and the main set of faults as in the northern Hamrat Duru belt, but generally lie parallel to them. This results in an intensification of the imbrication of the Hamrat Duru Group already established by the first set of reverse faults.

The disparity in geometrical configuration that exists between the northern and southern Hamrat Duru belts may originate from the difference in the thickness of the units involved in the late imbrication. In the northern belt, the

Hamrat Duru Group is stratigraphically much thicker than in the south. It is thought that the thinness of the group in the southern belt enhanced thrusting instead of folding as a main mechanism of shortening. Furthermore, folds developed in a thinner sequence of rocks would be expected to be more angular and of a smaller wavelength than in a thicker sequence (Ramsay, 1967).

The second set of reverse faults, although not as intense as the first set, affects the Hawasina nappes in a systematic fashion. Hence, as shown in figure 4-27, this set is thought to represent a large-scale imbrication system linked to a regional décollement that lies beneath the floor thrust of the Wahrah nappe, but whose depth is otherwise unknown.

High-angle faults trending in an NW-SE to SW-NE orientation are common throughout the study area. Because these faults usually offset inclined planar structural elements, the displacement along their surfaces is ambiguous. Dip-slip and strike-slip movements could yield the same apparent offsets on the map.

Finally, the central and the southern part of the Sufrat ad Dawh Range record a large-scale open fold with a N-S striking axial plane, causing the trend of all structural elements in these areas to deviate from a NE-SW orientation eastwards to an E-W orientation.

Chapter 5

DEFORMATIONAL HISTORY OF THE HAWASINA COMPLEX IN THE SUFRAT AD DAWH RANGE AND REGIONAL IMPLICATIONS

5.1 Introduction

The purpose of this chapter is to discuss the kinematic evolution of the Hawasina nappes in the Sufrat ad Dawh Range, and to examine the implications for the deformational history of the western foothills.

5.2 Deformational history of the Hawasina nappes

This section outlines the deformational history of the northern Hamrat Duru belt, the central Sufrat ad Dawh Range and the southern Hamrat Duru belt, derived from the detailed geometrical analysis of these domains presented in the previous chapter. Due to the poorly exposed nature of the northern area, the deformational history of this domain cannot be assessed adequately. However, the nappes occurring in this area are believed to be relatively undeformed.

5.2.1 The northern Hamrat Duru belt

The deformational history of the northern Hamrat Duru belt comprises the following events:

1. Imbrication of the Hamrat Duru Group along northward dipping thrust planes, leading to the formation of the Hamrat Duru nappe. This imbrication may have preceeded, accompanied or followed the imbrication of the Wahrah Formation and the superposition of the Hawasina, Haybi and Semail nappes.

2. Large-scale folding of the Hamrat Duru nappe along two en-echelon arranged anticlines and parasitic synclines with E-W oriented axes. This event also affected the Al Ayn and the Semail ophiolitic nappes. It is not known how far south the Haliw, the Al Ayn, the Haybi and the Semail nappes extended with respect to the position of these fold structures.

3. Reverse faulting along the limbs of the large-scale antiform breaching the roof thrust of the Hamrat Duru nappe. This resulted in the southward emplacement of this nappe over the Wahrah nappe.

5.2.2 The central Sufrat ad Dawh Range

Four deformational events are recognized in this area:

1. Imbrication of the Wahrah Formation along northward-dipping thrust faults, preceeded or accompanied by asymmetrical folding affecting the lithologies of the individual imbricates. The process of imbrication is discussed and illustrated in section 4.4.2.

2. Folding of the Wahrah imbricates, producing a large-scale westerly-plunging antiform, inclined towards the north.

3. Reverse faulting along the southern limb of the large-scale antiform.

4. Open folding of all pre-existing structures in the southern part of the central Sufrat ad Dawh Range, along a N-S trending axial plane.

5.2.3 The southern Hamrat Duru belt

Four deformational events are recorded in this area:

1. Imbrication of the Hamrat Duru Group along thrust surfaces dipping towards the north. This event preceeded or was accompanied by E-W trending south-verging asymmetrical folding. It either preceeded, accompanied or followed the imbrication and the tectonic superposition of the Wahrah nappe on the Hamrat Duru nappe.
2. E-W trending asymmetrical folding of the imbricates with a southward vergence.
3. Imbrication of the Wahrah and the Hamrat Duru nappes along northward dipping thrust faults.
4. Open folding along a N-S striking axial plane.

5.2.4 The deformational history of the Sufrat ad Dawh Range

Three major deformational events are recorded in the northern, central and southern Sufrat ad Dawh Range. These consist of two distinct episodes of imbrication separated by a phase of folding on E-W trending axes. The first episode of imbrication caused the repetition and consequent structural thickening of the Hamrat Duru and the Wahrah lithostratigraphic sequences, and thus led to the formation of two distinct thrust systems, or nappes. In the Central Sufrat ad Dawh Range and possibly in the southern Hamrat Duru belt, this event was preceeded or accompanied by E-W trending, sub-horizontal, asymmetrical folding with a southward vergence, suggesting that the nappes were telescoped towards the foreland of the mountain belt.

The second deformational event is represented by folding of the Hamrat Duru and the Wahrah nappes and, in the north, the Al Ayn and the Semail nappes, along E-W trending fold axes. This indicates that this event occurred after the tectonic superposition of the allochthons.

The latest episode of imbrication is thought to have initiated in the core of these folds to accomodate for the space problems arisen during the formation of these folds. Increased shortening resulted in brittle failure along the limbs of these structures, causing the re-imbrication of the Hamrat Duru and the Wahrah nappes, in the northern and the southern parts of the Sufrat ad Dawh Range, and possibly in the central Sufrat ad Dawh Range.

These deformational events are believed to be related to a phase, or phases, of horizontal shortening in a N-S direction. A southward polarity associated with this event is inferred on the basis of the south vergence of the second generation folds, and the northerly dip of the re-imbrication fault surfaces. In addition, the central and the southern parts of the study area record subsequent large-scale open folding along a N-S striking axial plane.

The displacement along the high-angle faults, which generally trend in a N-S direction and occur uniformly throughout the study area, is interpreted to be predominantly strike-slip, resulting from a variation along strike in the amount of movement during the displacement of the nappes. These are referred to as "tear faults", and are a common component in fold and thrust belts (Dahlstrom, 1970; Laubscher, 1972).

5.3 Tectonic evolution of the Hawasina nappes in the Sufrat ad Dawh Range

The tectonic evolution of the Hawasina Complex in the study area may be divided in three stages (figure 5-1).

Stage 1, figure 5-1(a)

The early stage of telescoping led to the formation of imbricate thrust systems of distinct lithostratigraphic units, and to their tectonic superposition in the order generally displayed in the Oman Mountains. The metamorphic rocks of the Haybi Complex represent sedimentary and volcanic lithologies that were metamorphosed along the sole thrust of the Semail ophiolite during its earliest stage of displacement (Searle, 1980; Searle and Malpas, 1982)

Local pinching out of some of the nappes reflects the variation in the amount of surface area originally covered by the lithostratigraphic units now telescoped in these nappes.

Stage 2, figure 5-1(b) and (c)

Folding of the nappes along E-W trending axes took place either simultaneously or sequentially at distinct intervals across the strike of the allochthons. This stage is considered to be associated with the development of high-angle compressional faults in the core of the folds. In the south, where the Hamrat Duru nappe is thinner, the wavelength of the folds was shorter.

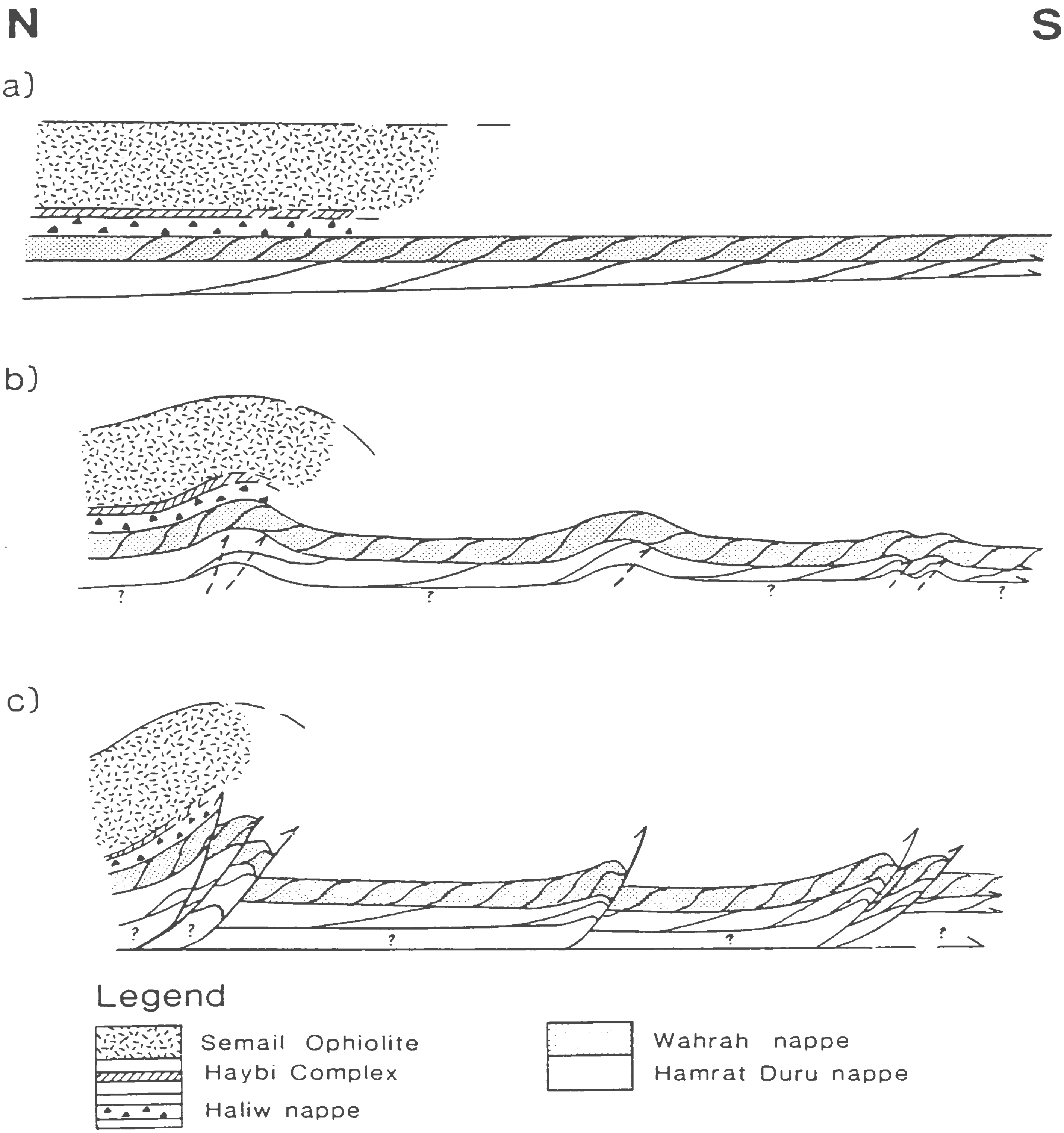


Figure 5-1: Tectonic evolution of the Hawasina Complex in the Sufrat ad Dawh Range (see text for discussion).

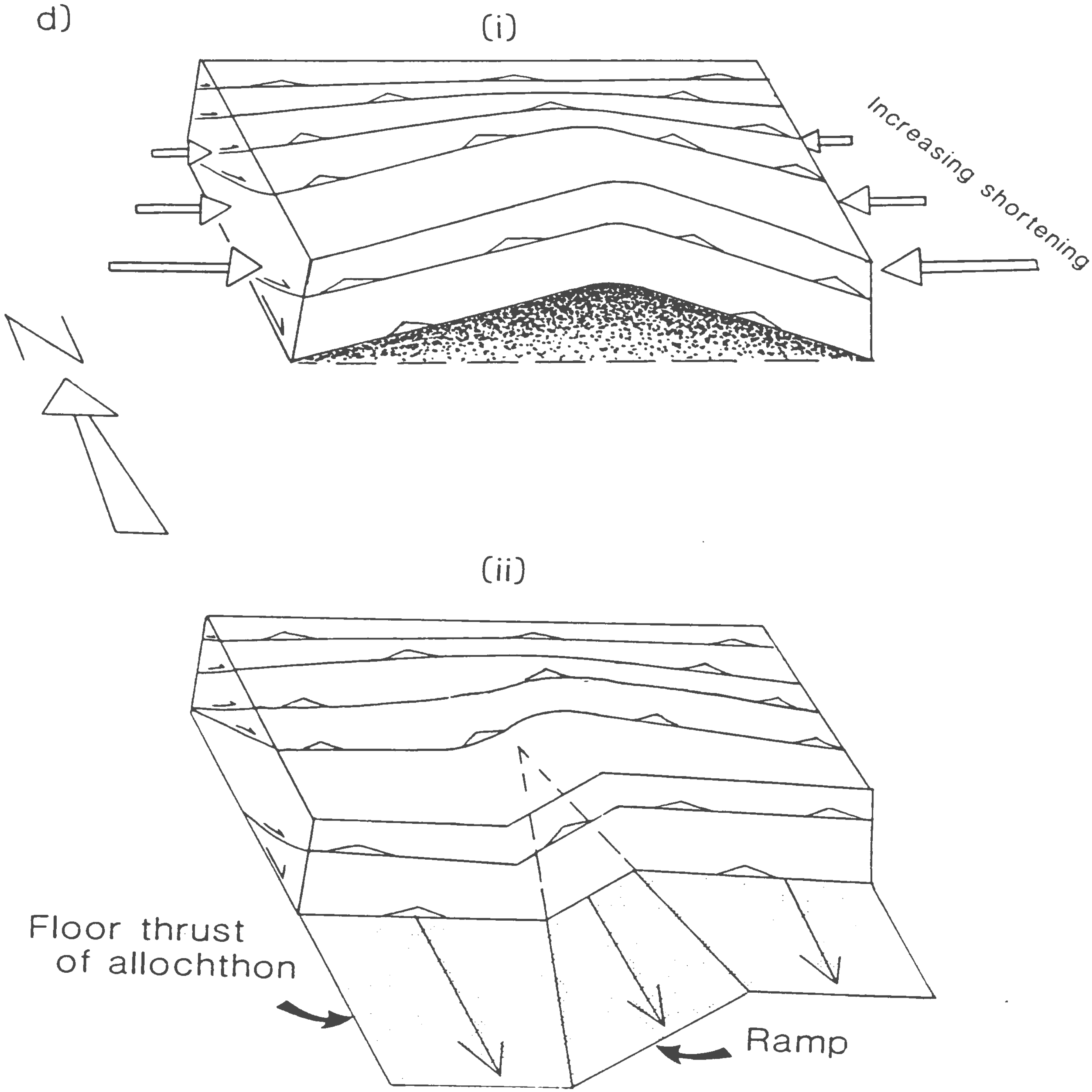


Figure 5-1, continued.

There is no indication as to how far south the upper Hawasina and the Semail nappes extended during this event with respect to the fold structures. However, diagenetic features of the Hawasina sediments occurring directly south of the present-day, erosional front of the Semail nappe suggest that these sediments were never covered by a substantial overburden (D. Bernoulli, pers. comm.). This is also indicated by the colour index (clear white) of conodonts retrieved from the blocks of reefal limestone of the anomalous olistostromal succession, occurring in the northern Hamrat Duru belt (L. Fahraeus and T. Calon, pers. comm.).

Additional shortening caused the reverse faults, initiated earlier, to propagate upward, thus disrupting the limbs of the folds, and causing the re-imbrication of the Hamrat Duru and the Wahrah nappes. These faults are regarded as belonging to a major re-imbrication system whose sole thrust lies beneath the Wahrah nappe. The available information, however, does not allow a further appraisal of the depth of this décollement. The Hawasina nappes are known regionally to overlie either the Sumeini nappe, or the Hajar Super Group and its Aruma flysch cover (figure 2-4). Hence, the décollement may lie, (a), within the Hamrat Duru nappe, (b), at the top of the Aruma Group, which is considered by most previous workers as the sole thrust of the Late Cretaceous allochthons in Oman, or (c), at a deeper structural level, within the Aruma or the Hajar units.

Stage 3, figure 5-1(d)

Folding along N-S oriented axial planes in the southern Hawasina nappes may have been the result of buckling due to an inhomogeneous compressional phase, oriented at a high angle to the structural grain of the nappes, only affecting the southern part of the Sufrat ad Dawh Range (figure 5-1(d), i). Alternatively, this shortening could have been induced by bending of the nappes as the sole thrust of the re-imbrication system climbed up-section along an N-S oriented lateral ramp (figure 5-1(d), ii). In the latter case, the fold structure would be expected to be asymmetrical, verging in the dip direction of the underlying ramp. In the study area, however, only one hinge is defined. It is not possible to determine if this hinge is part of an asymmetrical fold, or not.

5.4 Timing of deformation

5.4.1 Regional deformational events

The Late Cretaceous and Tertiary orogenic events are responsible for most of the deformation in the Mesozoic allochthons. Only where Maastrichtian and Tertiary rock units are present in the Oman Mountains, is it possible to estimate the relative proportion of the deformation resulting from either event. These rocks, however, do not occur in the Sufrat ad Dawh Range.

The horizontal tectonic translation of sedimentary sequences and the development of nappes (as defined by McClay, 1981), is known to be accompanied by a considerable amount of stratal shortening, achieved by the imbrication and folding of the sequences (Price and Mountjoy, 1970; Boyer and Elliott, 1982). The first imbrication episode leading to the formation of the nappes, correlates with the deformation of the Hawasina nappes in other parts of the Oman Mountains, shown to be related to their emplacement on the Arabian continental margin (Allemann and Peters, 1972; Glennie et al., 1973, 1974; Graham, 1980). Hence, this early imbrication episode can confidently be assigned to the Late Cretaceous orogeny. The timing of the later events, however, cannot be established. Consequently, the time at which the nappes finally reached their present position and configuration is uncertain.

It is believed that gravity sliding of the Hawasina Complex and the overlying Semail ophiolite, induced by the uplift of the J.Akhdar-J.Nakhl-Saih Hatat antiformal culmination trend, may have played a role, also, in the deformation recorded in the study area. Gravity collapse structures have so far been reported only locally along the limbs of this structure (Glennie et al., 1974; Michard et al., 1984; Coffield, 1984). Folding and thrusting of layered strata as a consequence of gliding over a tilted base, have been amply documented from other fold and thrust belts (for example, Mudge, 1970; Price, 1971; Hose and Danes, 1973; Lemoine, 1973), and also shown in experiments

(Blay et al., 1977; Guterman, 1980). The feasibility of such a sliding event in Oman, however, needs to be assessed.

Figure 5-2 is a schematic NW-SE oriented cross-section, joining Jebel Akhdar and the northern part of the Sufrat ad Dawh Range. The Hawasina Complex is shown to overlie directly the Aruma sequences and the Hajar shelf carbonates. This is in accordance with the regional tectonostratigraphic relationship of these units (figure 2-4). The thickness of the Hawasina Complex is thought to exceed 1000 meters, depending on the degree of stratal shortening of the lithologies within the nappes. The Semail ophiolitic nappe lies above the Hawasina Complex. Its original thickness is estimated as 5000 meters (Searle, 1980). Thus, the minimal cumulative thickness of the sliding sheet (the Hawasina Complex and the Semail ophiolitic nappe) before erosion is thought to exceed 6000 meters.

As a working hypothesis, the top of the Aruma Group is assumed to represent the surface along which sliding of the sheet may have occurred along the southern flanks of Jebel Akhdar. "A" and "B" are at the top and the bottom extremity, respectively, of a south-easterly inclined surface, representing the average slope gradient of the Aruma and the Hajar units. The angle θ of this slope with respect to the horizontal can be determined from the equation:

$$\sin \theta = x/y, \text{ or}$$
$$\theta = \arcsin x/y \quad (1)$$

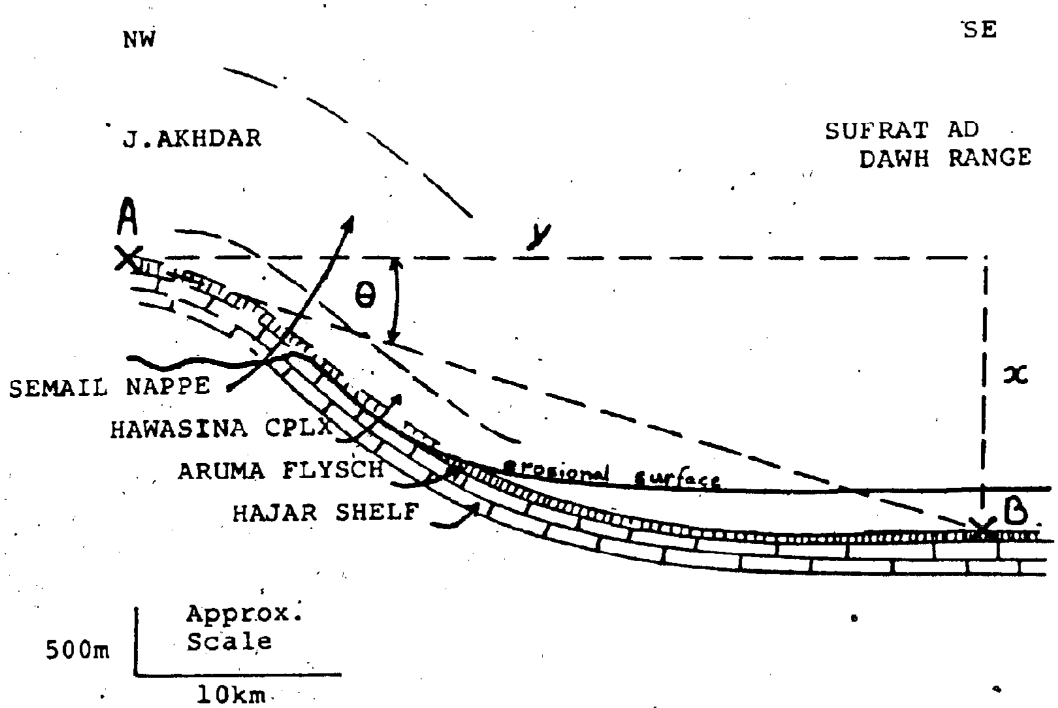


Figure 5-2: Schematic cross-section joining the J. Akhdar antiformal culmination and the Sufrat ad Dawh Range (see figure 2-3 for location of the section). The details are discussed in the text.

where "x" is the difference in elevation between A and B, and "y" is the horizontal distance between these two markers. The relief of the antiform reaches 3000 meters. In figure 5-2, the Aruma Group is projected above the erosional surface, along the hinge of the antiform, to an estimated additional height of 1000 meters. Thus, marker A is at 4000 meters above the base of the culmination. To the south-east, the Aruma Group is thought to lie at a minimum of 500 meters in sub-surface, below the Sufrat ad Dawh Range (see the projection of the map structures in the northern Hamrat Duru belt, figure 4-12). Consequently, the total difference in elevation between A and B, "x", is 4500 meters. The horizontal distance "y" between Jebel Akhdar and the Sufrat ad Dawh Range is approximated as 40 kilometers. The average slope gradient of the Aruma and the Hajar units, from equation (1), is then 6.5°.

Hubbert and Rubey (1959) and Hsu (1969) have shown that a mass of rocks 6 to 10 kilometers in thickness should slide under its own weight on an inclined surface, providing that a high pore pressure exists along this surface. It is conceivable that the shaly lithologies of the Aruma Group might have provided such elevated pore pressure. Further, sliding of the Hawasina Complex and the Semail ophiolitic nappe above the Aruma sequences should have been facilitated by the fact that this surface was the site of a pre-existing décollement, the one along which the Hawasina Complex was first emplaced on the continental margin.

The décollement associated with the sliding event can also lie within or below the Hajar shelf sequences (as discussed in the previous section). Evaporitic sequences are reported in the pre-Permian sequences in southern Oman (Gorin et al., 1982). These lithologies are often found along overthrust surfaces, in other orogenic belts. They have low shear strength and are known to provide high fluid pressure (Heard and Rubey, 1966), and thus offer an ideal gliding horizon along which gravity sliding may have taken place.

In summary, there are three major events that could have contributed to the deformation of the Hawasina Complex in the Sufrat ad Dawh Range. These are, firstly, a deformation associated with the accretion and emplacement of the allochthons; secondly, a Tertiary compressional event regionally oriented in a NE-SW direction, that is known to have affected the Maastrichtian and Tertiary neo-autochthonous carbonate cover in the Oman Mountains; thirdly, gravity sliding along the flanks of the J.Akhdar-J.Nakhl-Saih Hatat culmination.

5.4.2 Alternatives for the timing of deformation in the Sufrat ad Dawh Range

Various scenarios may be envisaged for the timing of the deformation recorded in the Sufrat ad Dawh Range. These are shown in table 5-1. The numbers 1,2 and 3 refer to the three deformational stages described in the previous section (5.3). The timing of deformation (the horizontal scale of the table) is divided into 1) the deformation associated with the emplacement of the Late Cretaceous allochthons, and 2) the deformation post-dating and kinematically unrelated with the emplacement of the allochthons. The post-emplacement deformation comprises the deformation associated with the Tertiary orogeny, and the gravity sliding along the southern limb of the Jebel Akhdar culmination. The J.Akhdar-J.Nakhl-Saih Hatat culmination, interpreted by most previous workers as having developed in the Tertiary, may also have formed in the Late Cretaceous during the emplacement of the nappes, in response to deep-seated ramping (section 2.5). In either case, the sliding would have postdated the emplacement of the nappes.

Scenarios A, B, C and D consider that only the first stage of deformation recorded in the Sufrat ad Dawh Range (stage 1) occurred during the Late Cretaceous orogeny. In scenario A, the re-imbrication event (stage 2) is caused by the N-S oriented compression associated with the Tertiary orogeny, which is also responsible for the formation of the J.Akhdar-J.Nakhl-Saih Hatat antiformal culmination. Subsequent gravity sliding off the flank of Jebel Akhdar could have produced stage 3 in the study area, by translating the Hawasina Complex further southwards along the sole thrust of the re-imbrication system, above a N-S striking ramp (as shown in figure 5-1(a), ii).

Scenario B assigns the formation of the J.Akhdar-J.Nakhl-Saih Hatat culmination to the Late Cretaceous emplacement of the nappes. Subsequent gravity sliding along the southern limb of Jebel Akhdar, led to the re-imbrication event in the study area (stage 2). Minor shortening in the E-W direction (stage 3) is Tertiary in age, and could have resulted from buckling in the E-W direction (figure 5-1(d), i, of a similar nature as the origin of the NE-SW oriented segment of the J.Akhdar-J.Nakhl-Saih Hatat culmination. Stage 3 could also have resulted from further translation of the Hawasina allochthons above a N-S trending ramp (figure 5-1(d), ii.

Table 5-1: Timing of deformation of the Hawasina Complex in the Sufrat ad Dawh Range. The numbers 1,2 and 3 are the three stages of deformation recorded in the study area. (See text for discussion).

SCENARIOS	TIMING OF DEFORMATION			
	Late Cretaceous Emplacement of the nappes	Post-emplacement		
		Gravity sliding	Tertiary Orogeny	Gravity sliding
A	1		2	3
B	1	2	3	
C	1		2,3	
D	1	2,3		2,3
E	1,2,3			
F	1,2		3	
G	1,2	3		

Scenario C assigns stages 2 and 3 to the Tertiary orogeny. If gravity sliding occurred along the limbs of Jebel Akhdar, it did not contribute to the deformation of the Hawasina Complex in the Sufrat ad Dawh Range.

In scenario D, the Tertiary orogeny did not affect the study area. This scenario considers stages 2 and 3 as resulting from gravity sliding along the southern limb of Jebel Akhdar, regardless of whether this culmination formed in the Late Cretaceous or in the Tertiary. The latter case, however, is not likely in this scenario, because if the Tertiary orogeny caused the formation of the J.Akhdar structure, it would likely have affected the Hawasina Complex in the study area, as well.

Scenario E assigns all three stages of deformation in the study area to the Late Cretaceous orogeny. It implies that neither the Tertiary compressional event, nor the postulated gravity sliding off the flank of Jebel Akhdar, have played a role in the deformation of the Hawasina Complex in the study area. In this scenario, E-W oriented shortening in the study area (stage 3) would have resulted from bending of the Hawasina Complex over a N-S trending ramp at depth (figure 5-1(d), f1). Stage 3 would then represent the latest increment in a progressive deformation associated with the emplacement of the nappes.

The neo-autochthonous Maastrichtian and Tertiary carbonate cover is sparsely distributed in the Oman Mountains (see figure 2-3). These rocks all record shortening, reflected by broad folding of various styles (Glennie et al., 1974; Searle, 1982, unpubl. ESRI rep.). This suggests that the Tertiary orogeny affected, to a minimal extent, the whole of the Oman Mountains. Hence, scenarios D and E are thought to be unlikely.

Scenarios F and G differ from E in that the latest deformational stage (stage 3), postdates the emplacement of the nappes. In F, stage 3 is associated with the Tertiary orogeny. This stage may either be the result of inhomogeneous buckling (figure 5-1(d), i) of the same nature as the origin of the NE-SW trending segment of the J.Akhdar-J.Nakhl-Saih Hatat culmination, or it could have been related to bending above a N-S trending ramp (figure 5-1(d), ii). In scenario G, stage 3 is caused by gravity sliding of the nappes in response to the formation of the Jebel Akhdar culmination, in the Late Cretaceous. This scenario is unlikely, for the same reason as mentioned for D and E.

From the available information, it is not possible to determine which of these seven scenarios is the most feasible for the deformational history of the Hawasina Complex in the Sufrat ad Dawh Range. All, with the exception of scenarios D, E and G, appear equally valid.

5.5 Regional implications

Jebel Salakh, Jebel Madamar and Jebel Madar are elongated elliptical to rounded hills of outcrop, each defining a doubly-plunging anticline that exposes the carbonate shelf sequences of the Hajar Supergroup (figure 5-3). These structures, along with smaller circular outcrop exposing the Aruma as well as the Hajar lithologies, form an E-W trending, arcuate belt of culminations, with variably plunging axes, situated near the southern margin of the Sufrat ad Dawh Range. The proximity of the Hajar and the Aruma units to the southern Hamrat Duru belt indicates that the surface trace of the sole thrust of the Hawasina allochthons lies very close to the southern margin of the Sufrat ad Dawh Range (figure 5-3). The absence of Sumeini lithologies in this area suggests that the imbricates of the Hamrat Duru belt rest directly on the Aruma lithologies.

The geological map of Glennie *et al*. (1974) shows that the J.Salakh and J.Madamar culminations are bounded along their southern edges by E-W trending faults (as shown in figure 5-3). Furthermore, these structures "have slightly overturned south-western flanks, suggesting partial detachment from the basement by a compressive movement directed from the north." (Glennie *et al*., 1974, p.338). This geometry, illustrated in figure 5-4, compares well with the geometry of the re-imbrication structures recorded in the Sufrat ad Dawh Range. These faults are thought to flatten at depth, showing that, at least in the southernmost

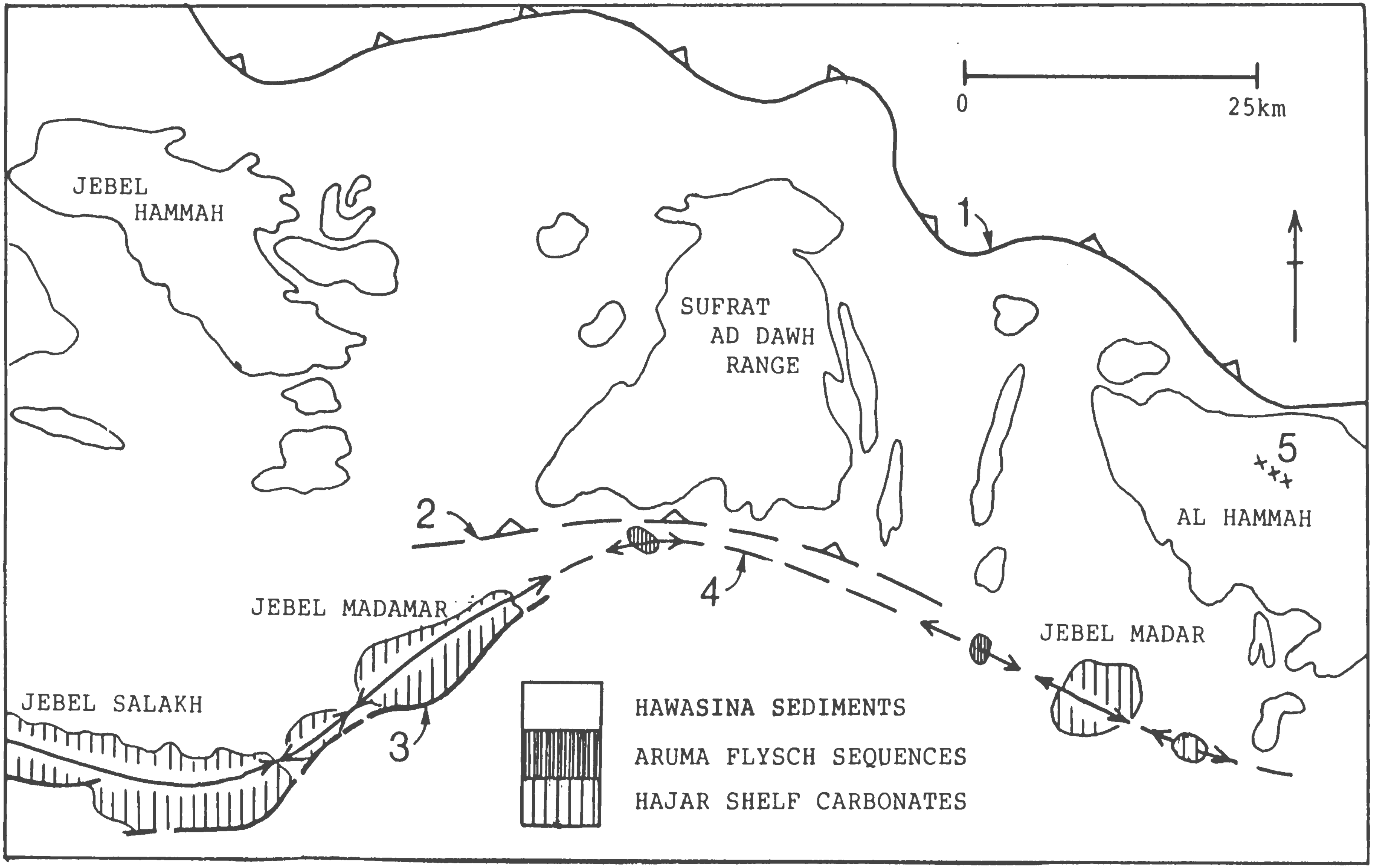


Figure 5-3: Tectonic setting of the J.Salakh, J.Madamar and J.Madar anticlines. (1: sole thrust of the Semail ophiolite, 2: sole thrust of the Hawasina allochthons, 3: fault trend along the southern margin of the J.Salakh and J.Madamar antiforms, 4: J.Salakh-J.Madamar-J.Madar antiformal axis, 5: dolomite breccias in Al Hammah).

part of the western foothills, the re-imbrication may have affected the Hajar shelf sequences.

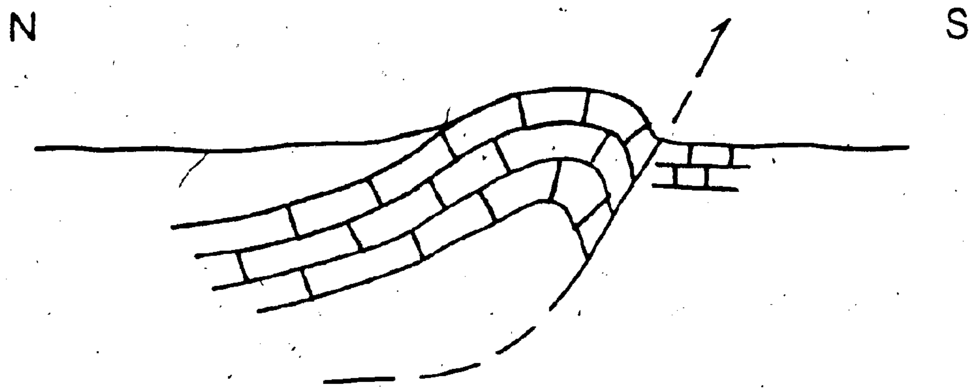


Figure 5-4: Structural configuration postulated for the J. Salakh and the J. Madamar anticlines.

Imbrication of the Mesozoic carbonate shelf sequences was documented from the Musandam peninsula, in the northern Oman Mountains, by Searle et al. (1983). The age of this deformation was assigned by these workers to the Tertiary.

Jebel Madar is a structural dome that is currently interpreted to have formed in response to sub-surface salt diapirism (Glennie et al., 1974; Gorin et al., 1982). In view of its structural relationship with J.Salakh and J.Madamar, it is thought that the J.Madar culmination may instead be the result of a compressional event of the same nature as the origin of the J.Salakh and the J.Madamar structures. The J.Madar anticline may thus be geometrically associated with a reverse fault, as shown in Figure 5-4, representing the eastern extension of a major E-W striking, arcuate fault surface exposed along the southern margins of J.Salakh and J.Madamar, but whose surface trace is otherwise hidden in the gravel plain.

North-east of J.Madar, within the Hawasina nappes of the Al Hammah Range, Glennie et al. (1974, p.338) reported the presence of a small, E-W trending, "linear plug" consisting of "fetid black dolomite breccias". This occurrence was interpreted by these workers, and later by Gorin et al. (1982), as being related to near surface salt diapirism. Recent detailed geological investigations by P. Cawood and K. Green (1984, unpubl. ESRI rep.) have shown that these breccias lie along an E-W trending regional fault, cross-cutting pre-existing imbricate fault planes of the Hawasina nappes. Cawood and Green further compared the dolomitic breccias to carbonate slope-type lithologies similar to some of the units of the Sumeini Group. It follows that, rather than being related to salt diapirism, the dolomitic breccias may have been brought up from beneath the Hawasina nappes, where the Sumeini nappe presumably lies, along a major re-imbrication fault. This scenario is similar to that documented in the Sufrat ad Dawh Range.

Since little detailed structural work has been published from the Oman orogenic belt, it is not known to what extent the two-stage imbrication history documented in this study has taken effect in other parts of the belt.

Graham (1980a, and b) proposed a two-stage model for the emplacement of the late Cretaceous allochthons to explain north-east facing folds in the Hawasina window, and the truncation of the Hawasina units by the floor thrust of the overlying Semail nappe. The first stage is related to continental underthrusting and imbrication of the Sumeini, Hawasina and Haybi nappes. The later stage is represented by the subsequent emplacement of the Semail ophiolite by gravity. While the Semail ophiolite nappe may not have originally extended as far south as the Sufrat ad Dawh Range, it may have contributed to the deformation in this area by "pushing" the Hawasina nappes in front of its toe. This scheme would then imply that the re-imbrication event in the Sufrat ad Dawh Range is late Cretaceous in age.

Glennie et al. (1974) reported other local exceptions to the "stacking rule", and it is possible that these exceptions are also related to the re-imbrication of an already established tectonostratigraphy.

Chapter 6

CONCLUSION

The deformational style in the Sufrat ad Dawh Range is dominated by a regular, hinterland-facing imbrication, whose structural grain trends in an E-W orientation, paralleling the regional tectonic strike of the late Cretaceous allochthons in the Oman Mountains. Two major, geometrically distinct, sets of imbricate faults are recognised. The predominant set is related to the southward telescoping of the lithologies of the Hamrat Duru Group and the Wahrah Formation into two separate thrust systems, or nappes. This imbrication is thought to have occurred concurrently with the tectonic superposition of the Hawasina nappes in the Sufrat ad Dawh Range, in the stacking order generally displayed in the Oman Mountains.

The second set of imbricate faults resulted from additional shortening of the Hawasina nappes in a N-S direction. It caused the re-imbrication of the Hawasina tectonostratigraphy in the northern and the southern parts of the Sufrat ad Dawh Range. In the north, this event is preceeded by the formation of a large-scale E-W trending antiformal culmination, folding the Hamrat Duru, the Wahrah, the Al Ayn and the Semail ophiolite nappes. Increasing amplification of this antiform resulted in brittle failure along its limbs, causing the Hamrat Duru nappe to be emplaced in a southward direction over the Wahrah nappe. A similar scenario is proposed for the re-imbrication of the Hamrat Duru and the Wahrah nappes in the southern part of the Sufrat ad Dawh Range, but there, the folding associated with this shortening event was at a smaller scale. A re-imbrication event, affecting the Wahrah nappe, is also recorded in the central Sufrat ad Dawh Range. In addition, the central and the southern part of this range record subsequent large-scale open folding along a N-S oriented axial plane. This event may have resulted from bending of the Hawasina nappes above a N-S oriented lateral ramp at depth. Alternatively, these nappes could have been buckled by an inhomogeneous compressional event oriented in an E-W direction.

The timing of the deformation in the study area cannot be clearly established. While the early episode of imbrication is believed to be related to the late Cretaceous emplacement of the nappes, later deformation may be assigned to the same process of emplacement, to a Tertiary orogenic event, or to gravity sliding along the flanks of the large J.Akhdar-J.Nakhl-Saih Hatat antiformal culmination.

Hence, this study confirms the occurrence, reported by Glennie *et al.* (1974), of an antiformal culmination centered along the northern Hamrat Duru belt, and of a reversal in the tectonostratigraphy in the south part of the Sufrat ad

Dawh Range. It further demonstrates that these features were caused by a major re-imbrication episode systematically affecting the Hawasina Complex in the study area. Since Glennie et al. (1974) referred to this reversal in the tectonostratigraphy of the Late Cretaceous allochthons as a local exception to an otherwise consistent stacking rule, it may indicate that the re-imbrication of the Hawasina nappes is particular to the Sufrat ad Dawh Range and does not generally occur in other parts of the Oman Mountains. Alternatively, it is thought that re-imbrication of the Late Cretaceous allochthons may be a common feature in Oman but can only be outlined by more detailed structural investigations.

Most previous workers have placed the sole thrust of the late Cretaceous allochthons in the Oman Mountains at the top of the Aruma Group, i.e. the Aruma Gp, the Hajar Supergroup and the pre-Permian units are considered autochthonous. There is no direct evidence to indicate to what depths the surface structures may extend in the Sufrat ad Dawh Range. However, the proximity of the J.Salakh-J.Madamar-J.Madar antiformal trend to the southern margin of the Sufrat ad Dawh Range demonstrates that the Hajar shelf carbonate sequences lie at a relatively shallow structural level beneath the Hamrat Duru imbricates of the southern Hamrat Duru belt. Moreover, the geometrical relationship of the J.Salakh and J.Madamar anticlinal structures with reverse faults bounding their southern limbs is shown to be very similar to the geometry that resulted from the re-imbrication event, affecting the Hawasina thrust systems in the Sufrat ad Dawh Range. It is thus conceivable that the Hajar shelf sequences are affected by imbrication, and are therefore not, as interpreted by previous workers, strictly autochthonous.

REFERENCES

Adamia, S., Bergougnan, H., Fourquin, C., Haghipour, A., Lordkipanidzé, M., Ozgul, N., Ricou, L. and Zakariadze, G., 1980, The Alpine Middle-East between the Aegean and the Oman traverses, pp. 122-136, in: Aubouin, J., Debelmas, J. and Latreille, M. (Eds.) : Geology of the Alpine chains born of the Tethys, Memoire du B.R.G.M., 115, 355 p.

Allemann, F. and Peters, T., 1972, The ophiolite-radiolarite belt of north Oman Mountains: Eclogae Geol. Helv., 65, pp. 657-697.

Bally, A.W., Gordy, P.L. and Stewart, G.A., 1966, Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains: Bull. Can. Petrol. Geol., 14, pp. 337-381.

Blay, P., Cosgrove, J.W. and Summers, J.M., 1977, An experimental investigation of structures in multilayers under the influence of gravity: J. Geol. Soc. London, 133, p.329.

Boyer, S.E., 1978, Structure and origin of Grandfather Mountain window, North Carolina: Ph.D. thesis, Johns Hopkins University.

Boyer, S.E. and Elliott, D., 1982, Thrust systems: Am. Ass. Petrol. Geol. Bull., 66, pp. 1196-1230.

Butler, R.W.H., 1982, Terminology of structures in thrust belts: J. Struct. Geol., 4, pp. 239-245.

Campbell, J.D., 1958, En echelon folding: Econ. Geol., 53, pp. 448-472.

Coffield, D.Q., 1984, Geology of the Fanjah saddle, Oman: M.Sc. thesis, University of South Carolina.

Coleman, R.G., 1981, Tectonic setting for ophiolite obduction in Oman: J. Geoph. Res., 86, pp. 2497-2508.

Coney, P.J., 1973, Plate tectonics of marginal foreland thrust-belts: Geology, 1, pp. 131-134.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bull. Can. Petrol. Geol., 18, pp. 332-406.

Dewey, J.F., 1976, Ophiolite obduction: Tectonophysics, 31, pp. 93-120.

De Sitter, L.U., 1964, Structural Geology: 2nd Edition, New York, McGraw Hill, 551 p.

Elliott, D., 1976, The motion of thrust sheets: J. Geoph. Res., 81, pp. 949-963.

Falcon, N.L., 1967, The geology of the north-east margin of the Arabian basement shield: Adv. Sci., 24, pp. 31-42.

Gealey, W.K., 1977, Ophiolite obduction and geologic evolution of the Oman Mountains and adjacent areas: Geol. Soc. Am., 88, pp. 1183-1191.

Gee, D.G., 1978, Nappe displacement in the Scandinavian Caledonides: Tectonophysics, 47, pp. 393-419.

Ghent, E.D. and Stout, M.Z., 1981, Metamorphism at the base of the Samail ophiolite, south-eastern Oman Mountains: J. Geoph. Res., 86, pp. 2557-2471.

Girdler, R.W., 1980, The mechanisms of continental drift and plate tectonics: Some boundary conditions from surface phenomena, in: Davies, P.A. and Runcorn S.K., Mechanisms of continental drift and Plate Tectonics: Academic Press, New-York, 362 p.

Glennie, K.W., Boeuf, M.G.A., Clark, M.W.H., Moody-Stuart, M., Pilaar, W.F.H. and Reinhardt, B.M., 1973, Late Cretaceous nappes in the Oman Mountains and their evolution: Am. Ass. Petrol. Geol. Bull., 57, pp. 5-27.

Glennie, K.W., Boeuf, M.G.A., Clark, M.W.H., Moody-Stuart, M., Pilaar, W.F.H. and Reinhardt, B.M., 1974, Geology of the Oman Mountains: Koninkl. Nederlands Geol. Mijnb. Genoot. Verh., 31, pp. 1-423.

Gorin, G.E., Racz, L.G. and Walter, M.R., 1982, Late Precambrian-Cambrian sediments of Huqf Group, Sultanate of Oman: Am. Ass. Petrol. Geol. Bull., 66, pp. 2609-2627.

Graham, G.M., 1980a, Structure and sedimentology of the Hawasina window, Oman Mountains: Ph.D. thesis, Open Universtity.

Graham, G.M., 1980b, Evolution of a passive continental margin and nappe emplacement in the Oman Mountains, pp. 414-423, in: Panayiotou, A. (Ed.), Proc. International Ophiolite Symposium, Nicosia, Cyprus.

Guterman, V.G., 1980, Model studies of gravitational gliding tectonics: Tectonophysics, 65, pp. 111-126.

Heard, H.C. and Rubey, W.W., 1966, Tectonic implications of gypsum dehydration: Geol. Soc. Am. bull., 77, pp. 741-760.

Hopson, C.A., Coleman, R.G., Gregory, R.T., Pallister, J.S. and Bailey, E.H., 1981, Geologic section through the Samail Ophiolite and associated rocks along a Muscat-Ibra transect, south-eastern Oman Mountains: J. Geoph. Res., 86, pp. 2527-2544.

Hose, R.K. and Danez, Z.F., 1973, Development of the Late Mesozoic to Early Cenozoic structures of the Eastern Great Basin, pp. 429-441, in: De Jong, K.A. and Scholten, R. (Eds), Gravity and Tectonics, J.Wiley & Sons, New-York, 502 pp.

Hsu, K.J., 1969, Role of cohesive strength in the mechanics of overthrust faulting and of landsliding: Geol. Soc. Am. bull., 80, pp. 927-952.

Hsu, K.J. and Bernoulli, D., 1978, Genesis of the Tethys and Mediterranean, in: Hsu, K.J., Montadert, L., et al. (Eds), pp. 943-949, in: Initial reports of the deep sea drilling project, 42, part I, Washington, pp. 943-949.

Hubbert, M.K. and Rubey, W.W., 1959, Role of fluid pressure in mechanics of overthrust faulting (part I): Geol. Soc. Am. bull., 70, pp. 115-166.

Laubscher, H.P., 1972, Some overall aspects of Jura dynamics: Am. J. Sci., 272, pp. 293-304.

Lees, G.M., 1928, The geology and tectonics of Oman and of parts of south-estern Arabia: Quart. J. Geol. Soc. London, 84, pp. 585-670.

Lemoine, M., 1973, About gravity gliding tectonics in the Western Alps, pp. 201-217, in: De Jong, K.A. and Scholten R. (Eds), Gravity and Tectonics, J. Wiley & Sons, New-York, 502 pp.

Lovelock, P.E.R., Potter, T.L., Walsworth-Bell, E.B. and Weimer, W.M., 1981, Ordovician rocks in the Oman Mountains: the Amdeh Formation: Geol. Mijn., 60, pp. 487-496.

McClay, K.R., 1981, What is a thrust? What is a nappe?, pp.7-9, in: McClay, K.R. and Price, N.J. (Eds), Thrust and nappe tectonics: Geol. Soc. London, Spec. Publ. 9, 539 pp.

Michard, A., Bouchez, J.L. and Ouazzani-Touhami, M., 1984, Obduction-related planar and linear fabrics: J. Struct. Geol., 6, pp. 39-49.

Morton, D.M., 1959, The geology of Oman: Proc. 5th World Petrol. Cong., New-York, Section 1, paper 14, pp. 227-280.

Mudge, M.R., 1970, Origin of the disturbed belt in NW Montana: Geol. Soc. Am. Bull., 81, pp. 377-392.

Murris, R.J., 1980, Middle-East stratigraphic evolution and oil habitat: Am. Ass. Petrol. Geol. Bull., 64, pp. 597-618.

Powers, R.W., Ramirez, L.F., Redmond, C.D. and Elberg, E.L., 1966, Geology of the Arabian peninsula - sedimentary geology of Saudi Arabia: U.S. Geol. Surv. Prof. Paper 560-D, pp. D1-D147.

Price, R.A., 1971, Gravitational sliding and the foreland thrust and fold belt of the North American Cordillera: Discussion: Geol. Soc. Am. bull., 82, pp. 1133-1138.

Price, R.A., Mountjoy, E.W., 1970, Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca Rivers - a progress report, pp. 7-26, in: Wheeler, J.O. (Ed.), Geol. Ass. of Canada Spec. paper 6, 166 p.

Ramsay, J.G., 1967, Folding and fracturing of rocks: McGraw-Hill, New-York, 568 p.

Reinhardt, B.M., 1969, On the genesis and emplacement of ophiolites in the Oman Mountains geosyncline: Schweiz. Min. Petrog. Mitt., 49, pp. 1-30.

Ricou, L.E., 1971, Le croissant ophiolitique péri-arabe, une ceinture de nappes mises en place au Crétacé Supérieur: Revue Géogr. Phys. Géol. Dyn., 16, pp. 327-350.

Ricou, L.E., 1976, Evolution structurale des Zagrides de la région clef de Neyriz (Zagros Iranien): Mem. Soc. Géol. Fr., 125, pp. 1-140.

Searle, M.P., 1980, The metamorphic sheet and underlying volcanic rocks beneath the Semail ophiolite in the northern Oman Mountains of Arabia: Ph.D. thesis, Open University.

Searle, M.P. and Graham, G.M., 1982, Oman exotics - Oceanic carbonate build-ups associated with the early stages of continental rifting: Geology, 10, pp. 43-49.

Searle, M.P., James, N.P., Calon, T.J. and Smewing, J.D., 1983, Sedimentological and structural evolution of the arabian continental margin in the Musandam Mountains and Dibba zone, United Arab Emirates: Geol. Soc. Am. Bull., 94, pp. 1381-1400.

Searle, M.P. and Malpas, J., 1980, Structure and metamorphism of rocks beneath the Semail ophiolite of Oman and their significance in ophiolite obduction: Royal Soc. of Edinb. Trans., 71, pp. 247-262.

Searle, M.P. and Malpas, J., 1982, Petrochemistry and origin of sub- ophiolitic metamorphic and related rocks in the Oman Mountains: J. Geol. Soc. London, 139, pp. 235-248.

Stöcklin, J., 1974, Possible ancient continental margins in Iran, pp. 873-887, in: Burk, C.A. and Drake, C.L. (Eds.), The geology of continental margins: Springer-Verlag, New-York.

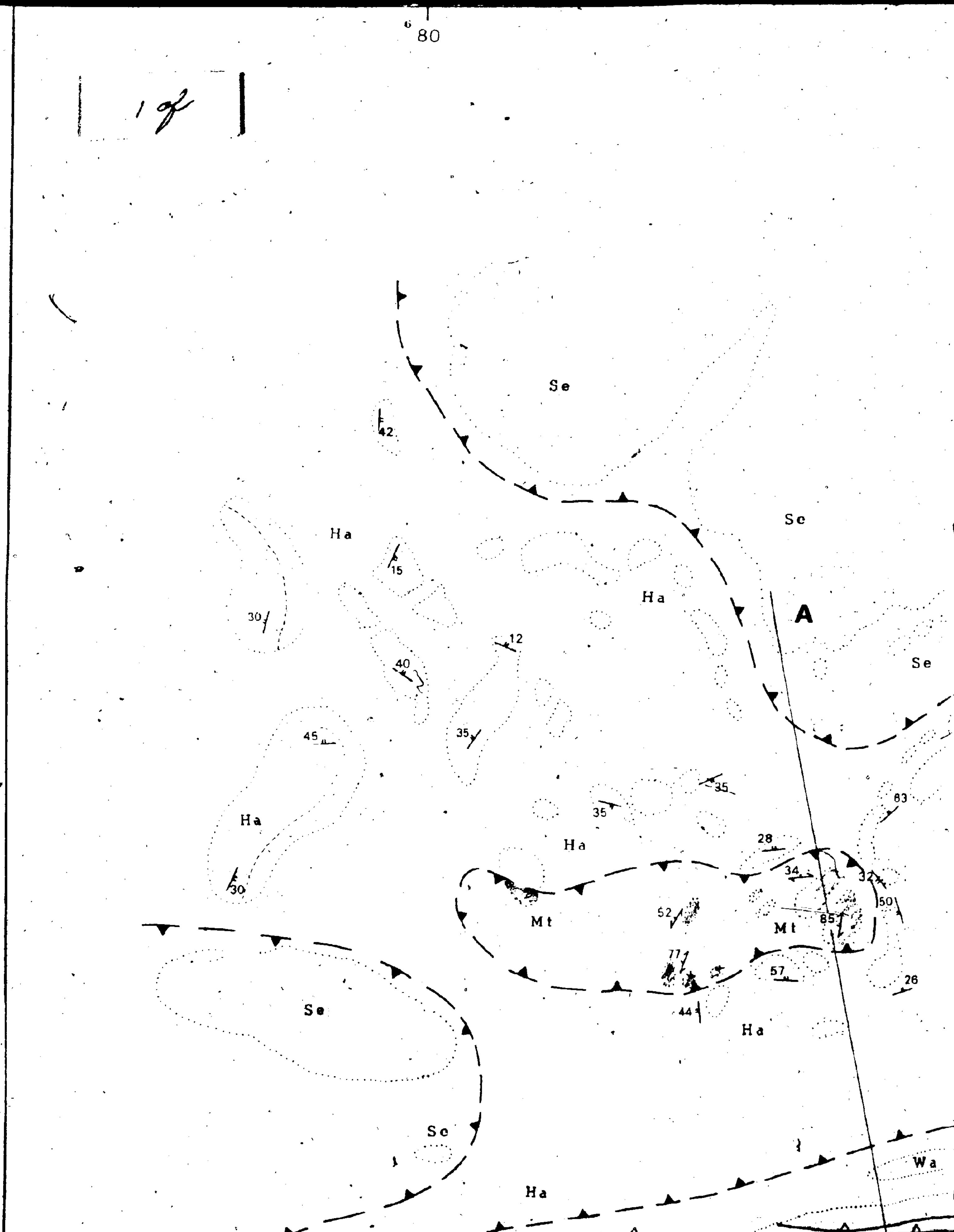
Stoneley R., 1975, On the origins of ophiolite complexes in the southern Tethys region: Tectonophysics, 25, pp. 303-322.

Tschopp, R.H., 1967, The general geology of Oman: Proc. 7th World Petrol. Cong. Mexico, 2, pp. 243-250.

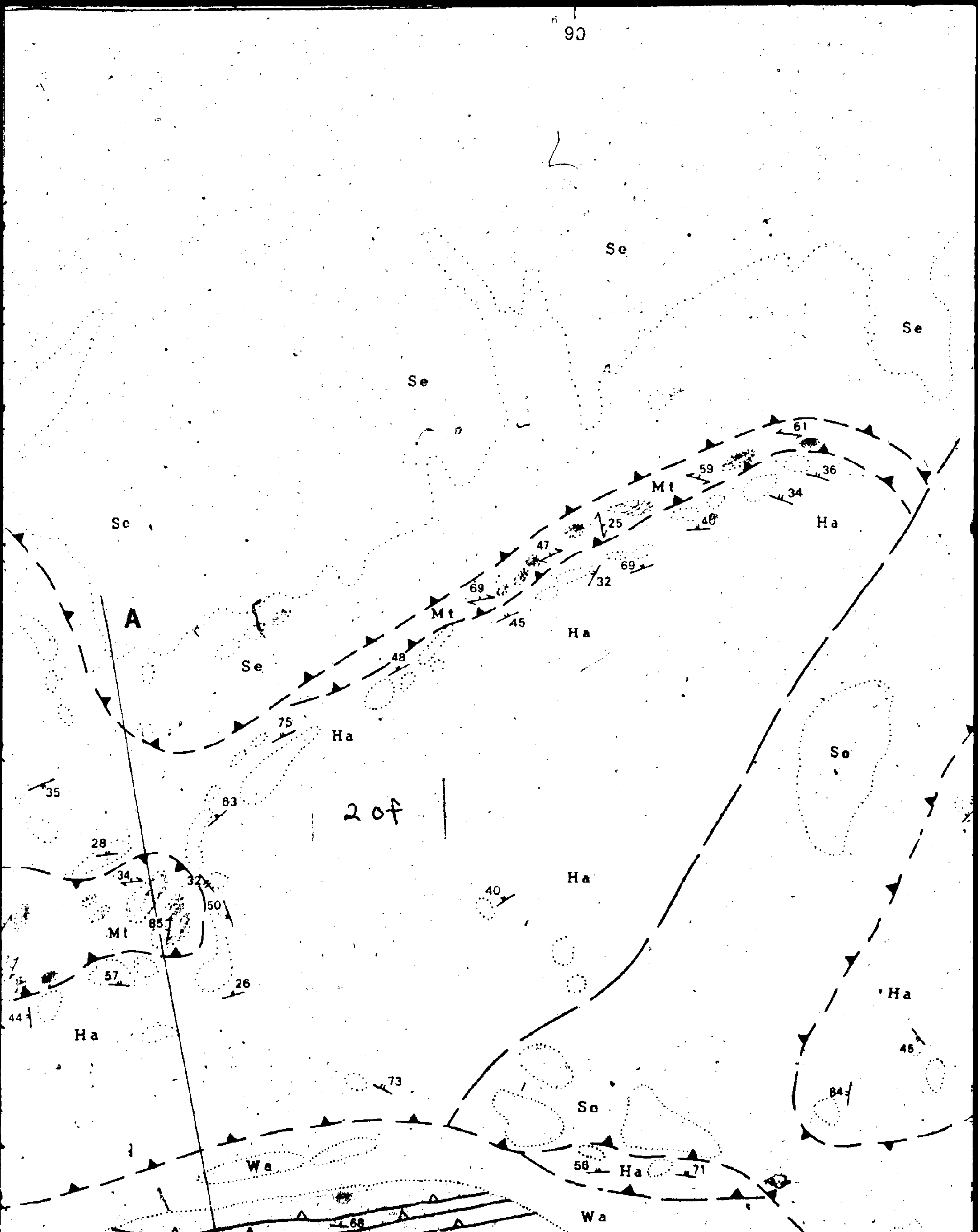
Welland, M.J.P. and Mitchell, A.H.G., 1977, Emplacement of the Oman ophiolite: Geol. Soc. Am. Bull., 88, p.1081.

Wilson, H.H., 1969, Late Cretaceous eugeosynclinal sedimentation, gravity tectonics and ophiolite emplacement in the Oman Mountains, SE Arabia: Am. Ass. Petrol. Geol. Bull., 53, pp. 626-671.

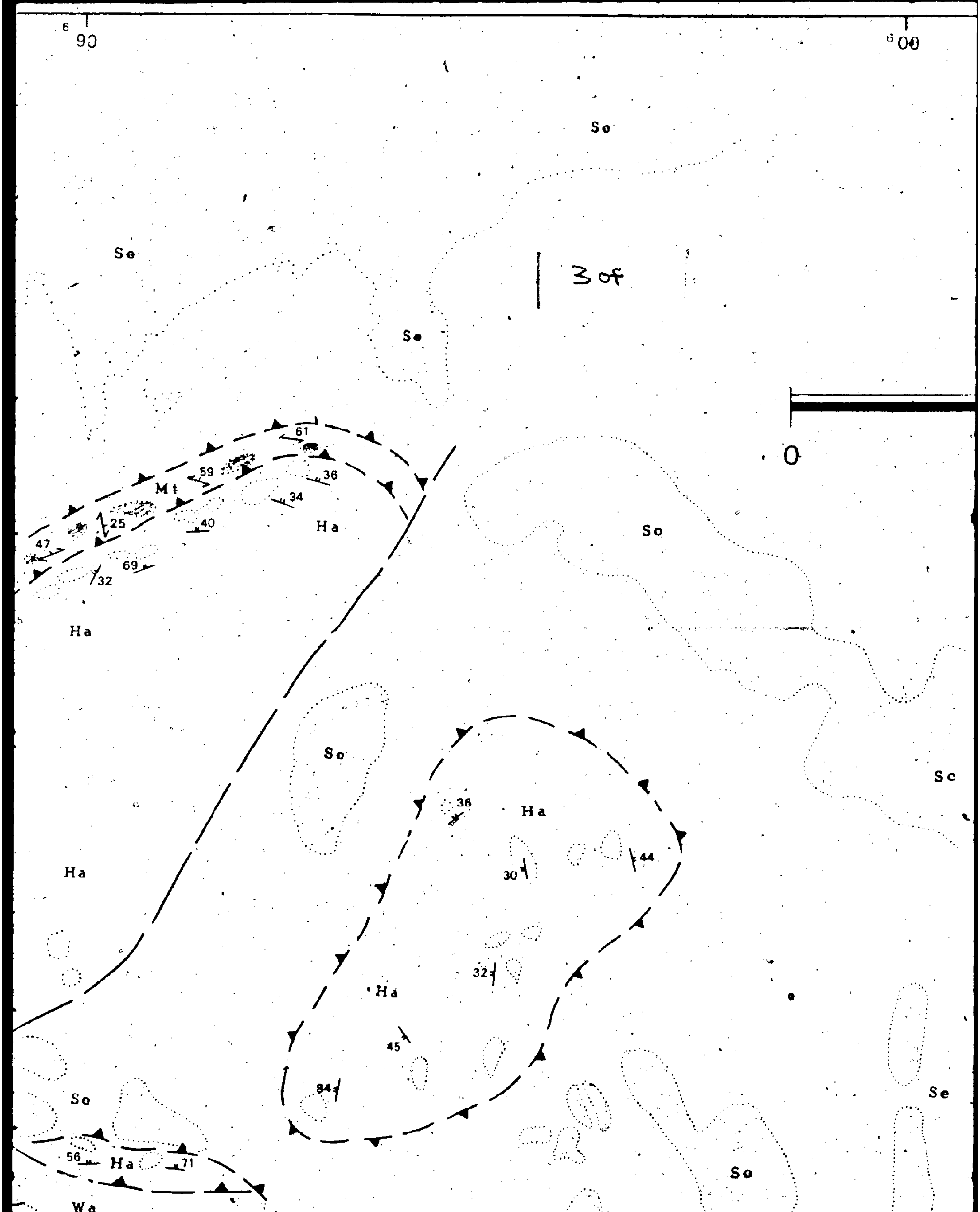
Williams, H., 1975, Structural succession, nomenclature and interpretation of transported rocks in Western Newfoundland: Can. J. Earth Sci., 12, pp. 1874-1894.



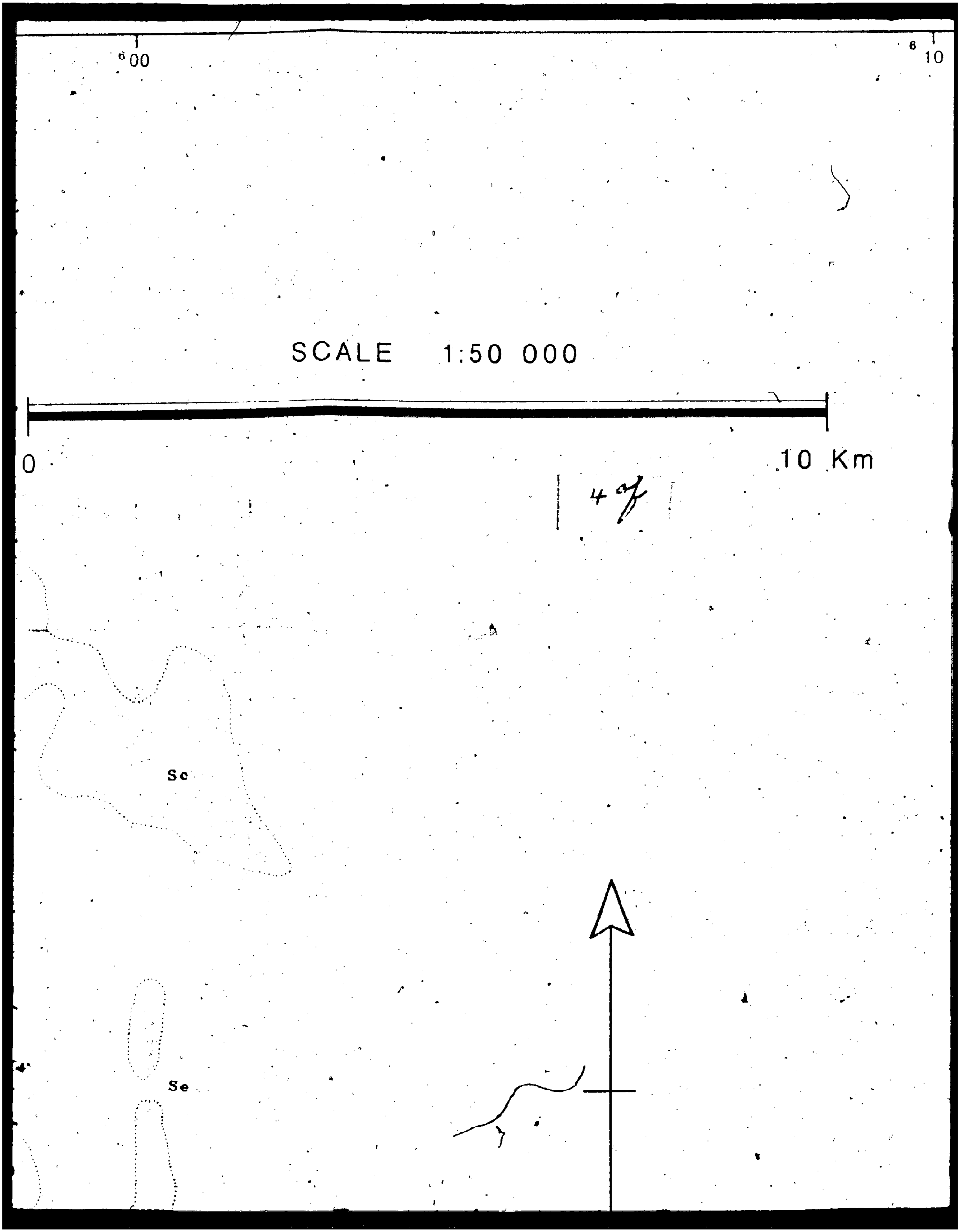
80
1 of 1
Se
Se
Se
Se
Se
A
Ha
Ha
Ha
Ha
Ha
Ha
Mt
Mt
Wa
42
15
30
12
40
45
35
35
35
30
28
34
32
63
50
85
52
77
57
44
26

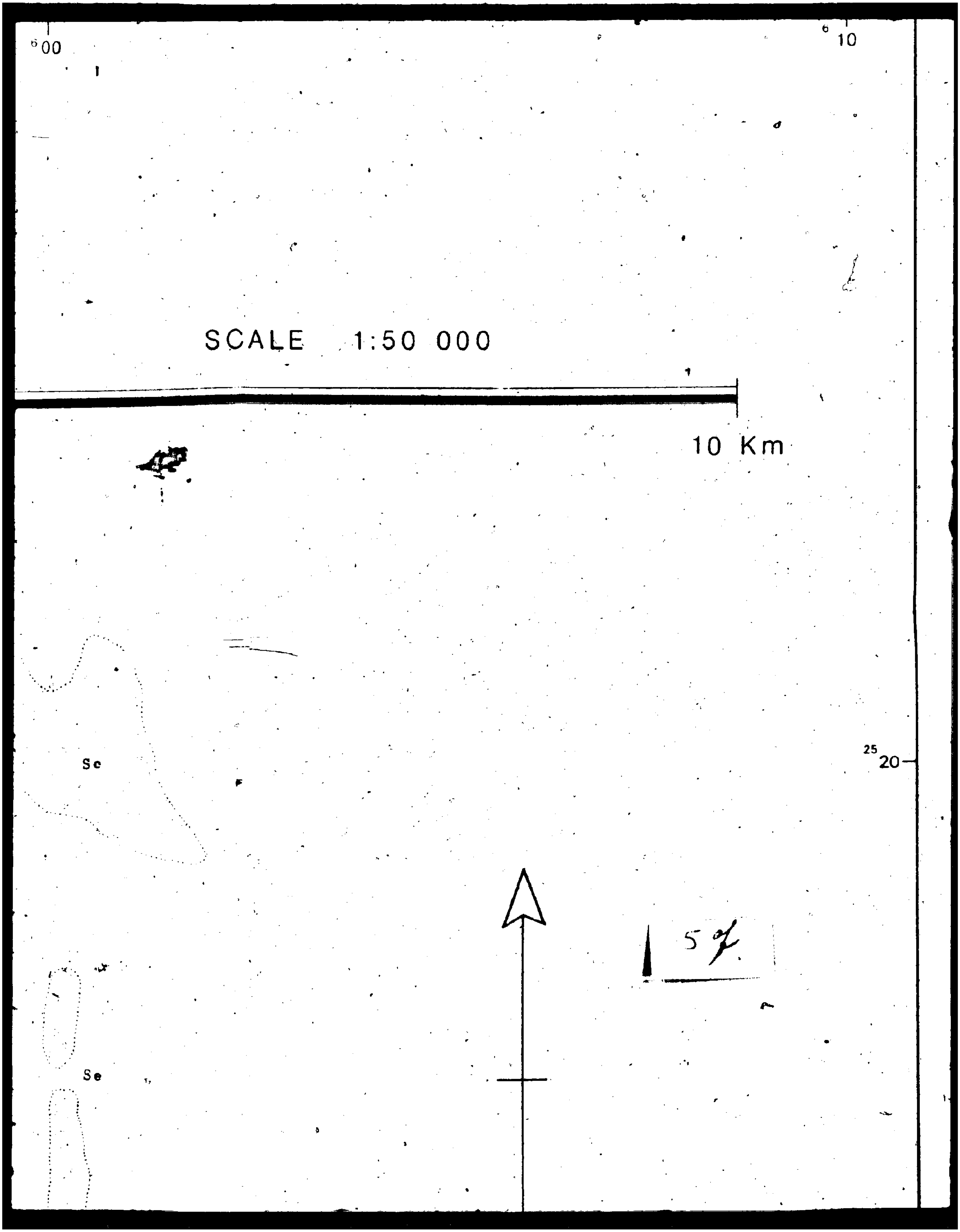


Se
Se
Se
Se
Se
Mt
Mt
Mt
Ha
Ha
Ha
Ha
Ha
Ha
Ha
So
So
Wa
Wa
A
2 of

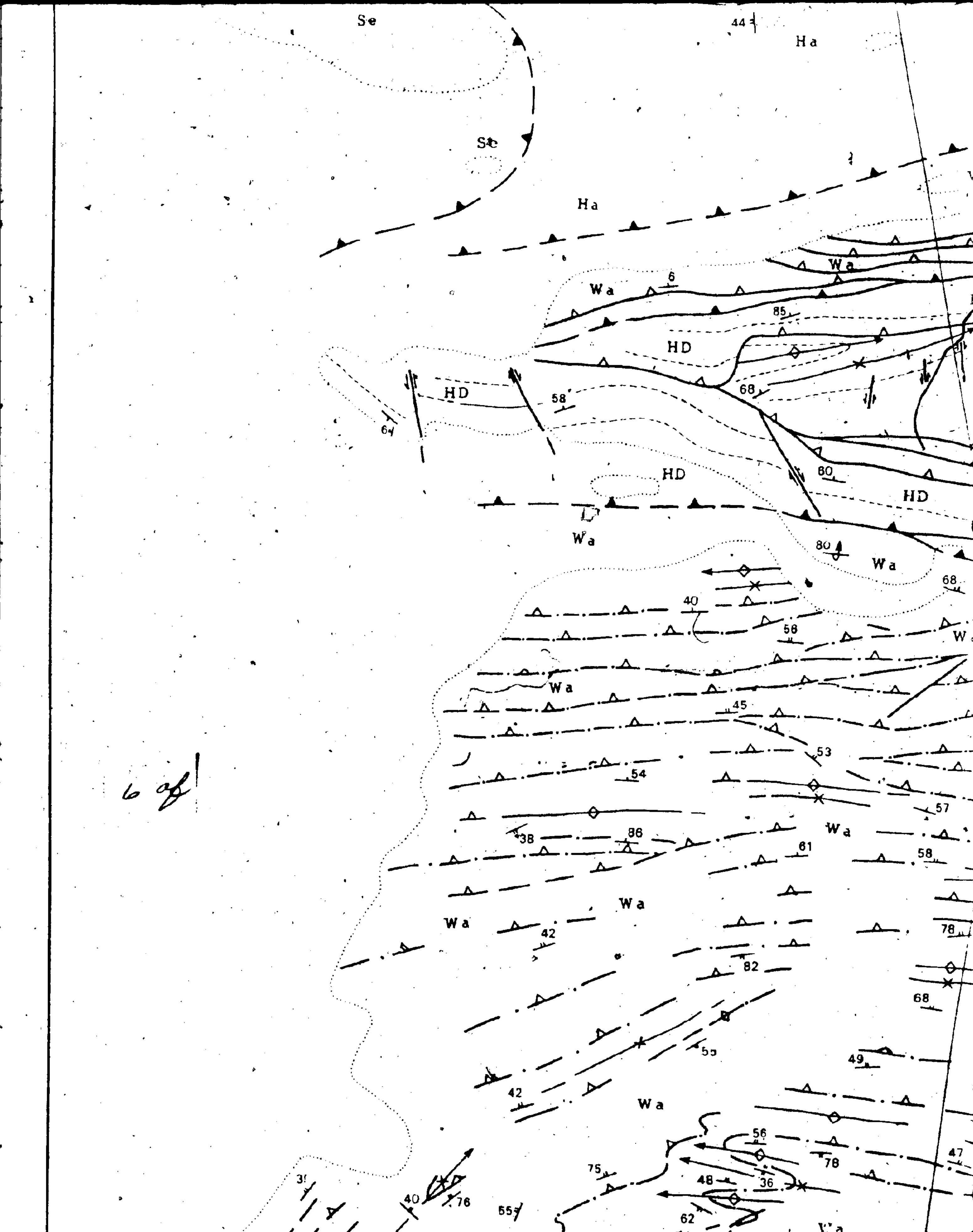


6
90
6
00
So
Se
Se
3 of
0
61
59
Mt
36
34
25
40
Ha
47
69
32
So
Ha
Ha
So
36
Ha
Sc
44
30
32
Ha
45
84
Se
So
56
Ha
71
So
Wa

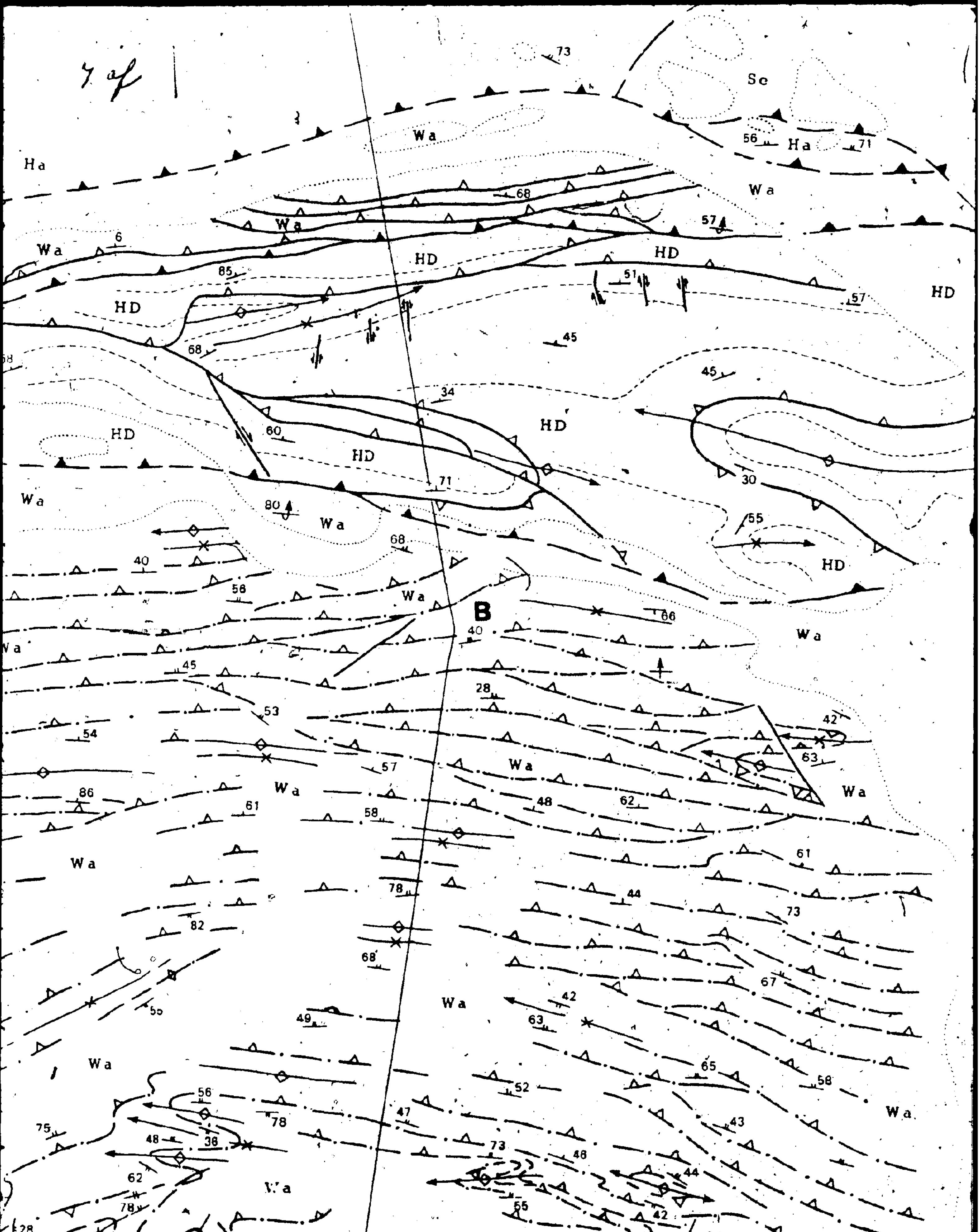

600
610
SCALE 1:50 000
0
10 Km
4 of
Sc
Se



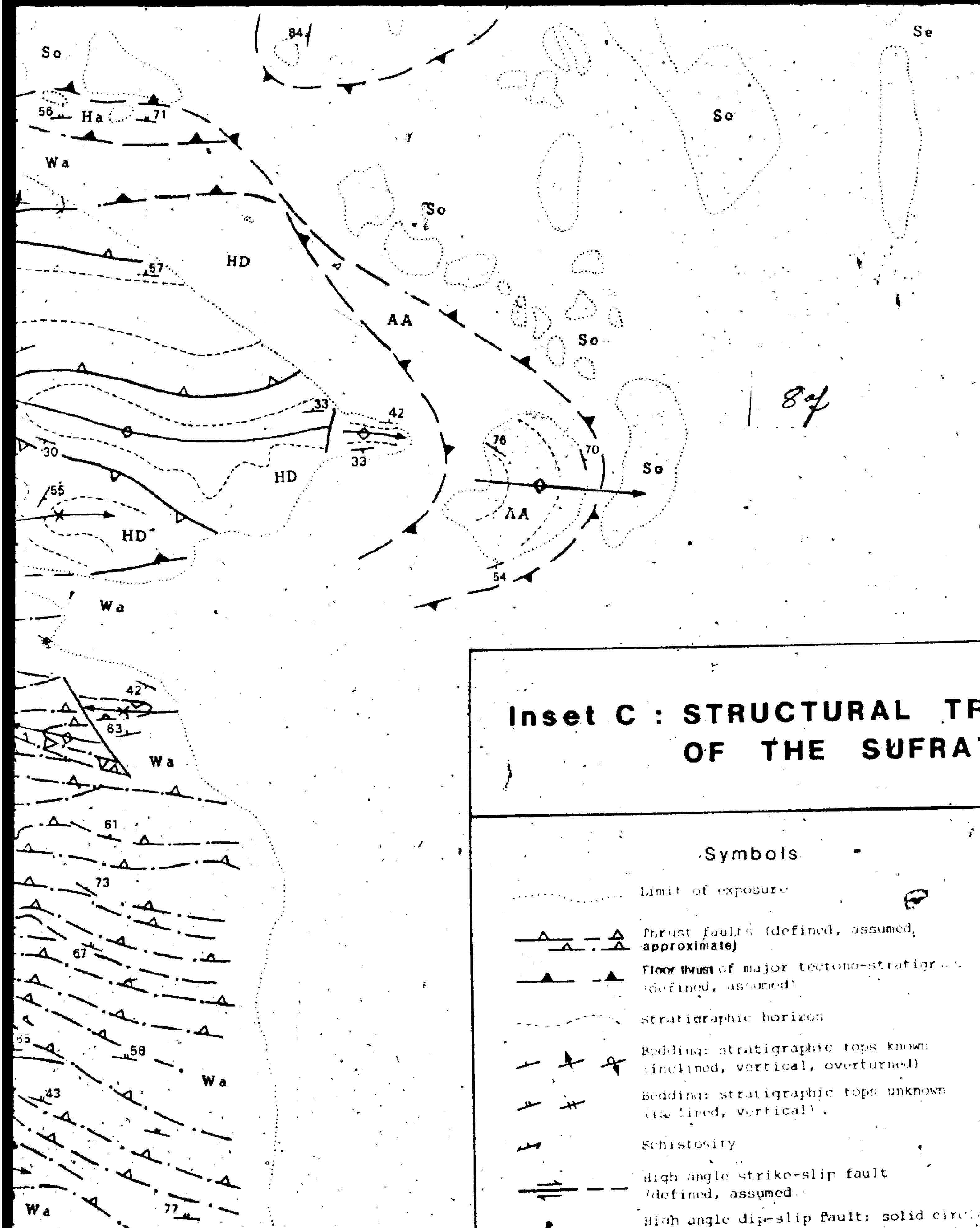
600
610
SCALE 1:50 000
10 Km
Se
2520
Se
5%

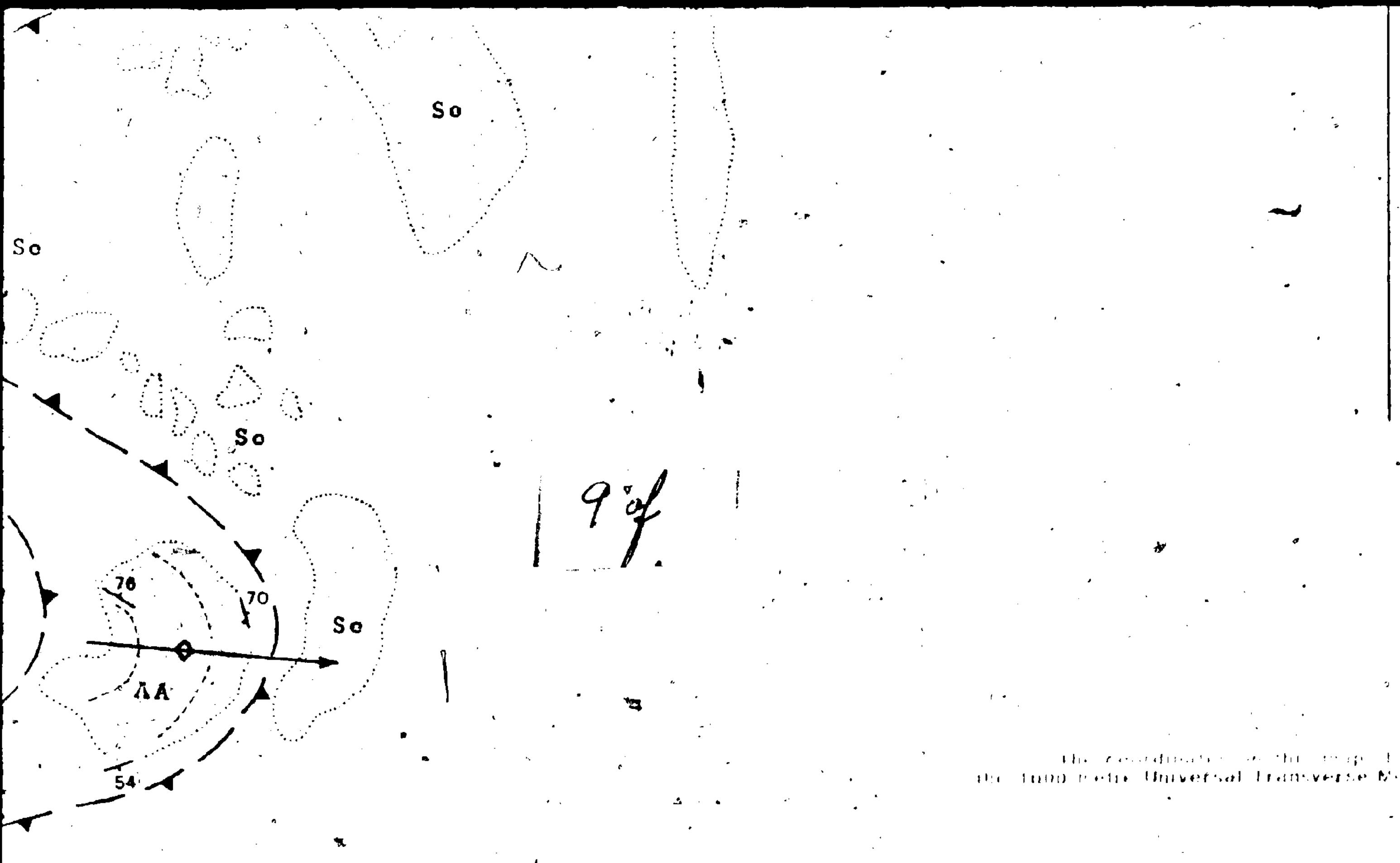


Se
Ha
Se
Ha
Wa
HD
HD
HD
HD
Wa
Wa
Wa
Wa
Wa
Wa
Wa
Wa



Se
Ha
Wa
HD
B


Inset C : STRUCTURAL TR
OF THE SUFRAT
Symbols
Limit of exposure
Thrust faults (defined, assumed, approximate)
Floor thrust of major tectono-stratigr
(defined, assumed)
Stratigraphic horizon
Bedding: stratigraphic tops known (inclined, vertical, overturned)
Bedding: stratigraphic tops unknown (inclined, vertical).
Schistosity
High angle strike-slip fault (defined, assumed)
High angle dip-slip fault: solid circ
So
Se
Ha
Wa
HD
AA
8 of



Inset C : STRUCTURAL TRANSECT OF THE SUFRAT AD DAWH RANGE

P. D. Barrette,

Symbols

Limit of exposure

Thrust faults (defined, assumed, approximate)

Floor thrust of major tectono-stratigraphic unit (defined, assumed)

Stratigraphic horizon

Bedding: stratigraphic tops known (inclined, vertical, overturned)

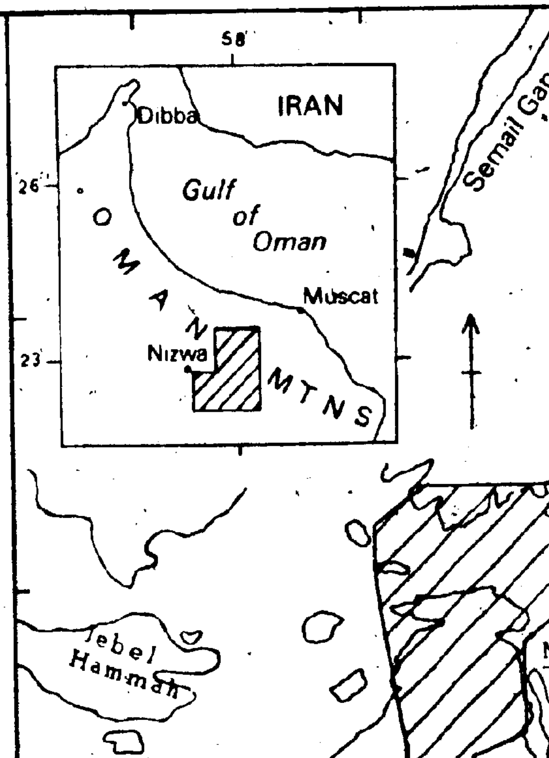
Bedding: stratigraphic tops unknown (inclined, vertical)

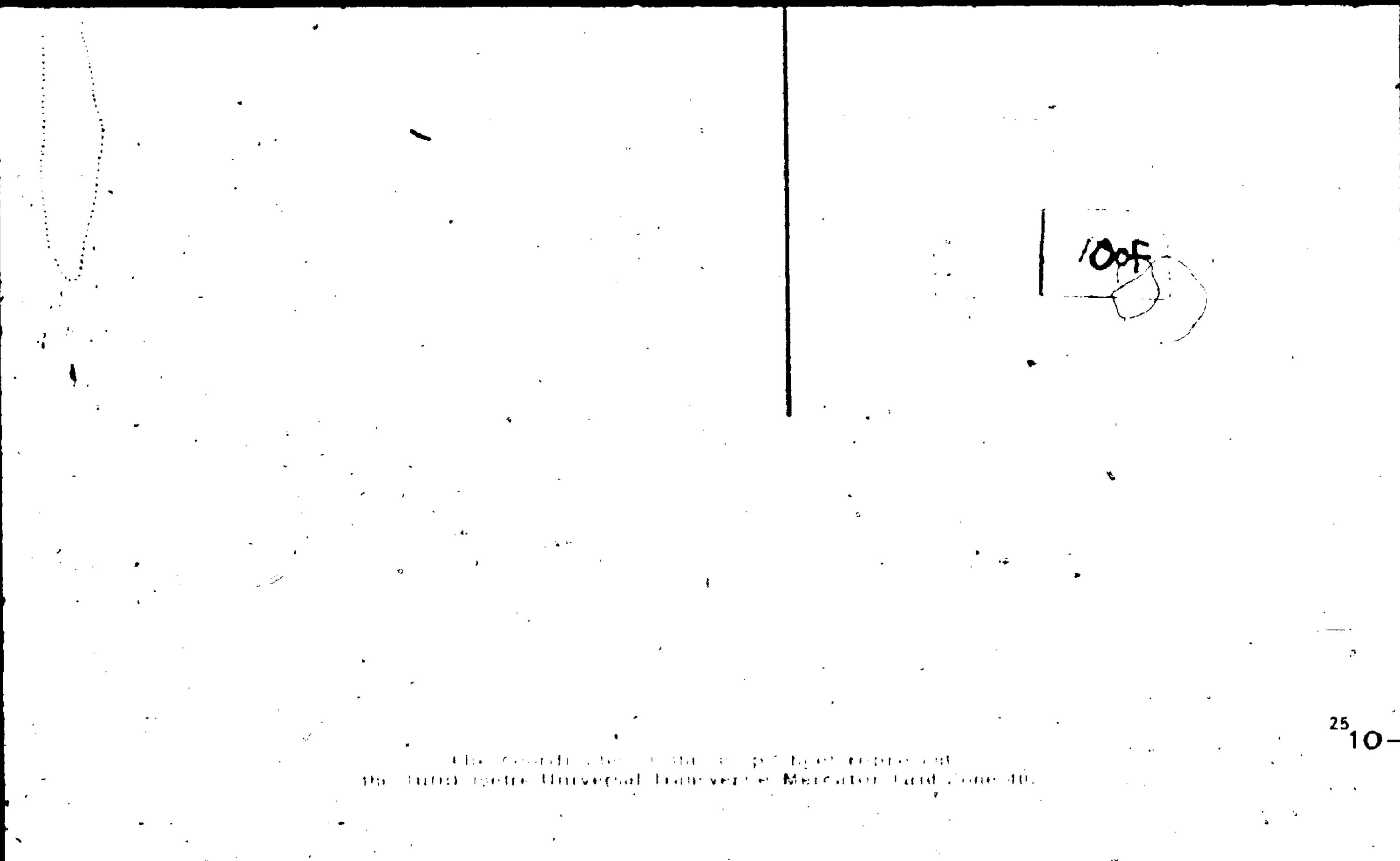
Schistosity

High angle strike-slip fault (defined, assumed)

High angle dip-slip fault: solid circle on downthrown side (defined, assumed)

High angle fault: net slip unknown

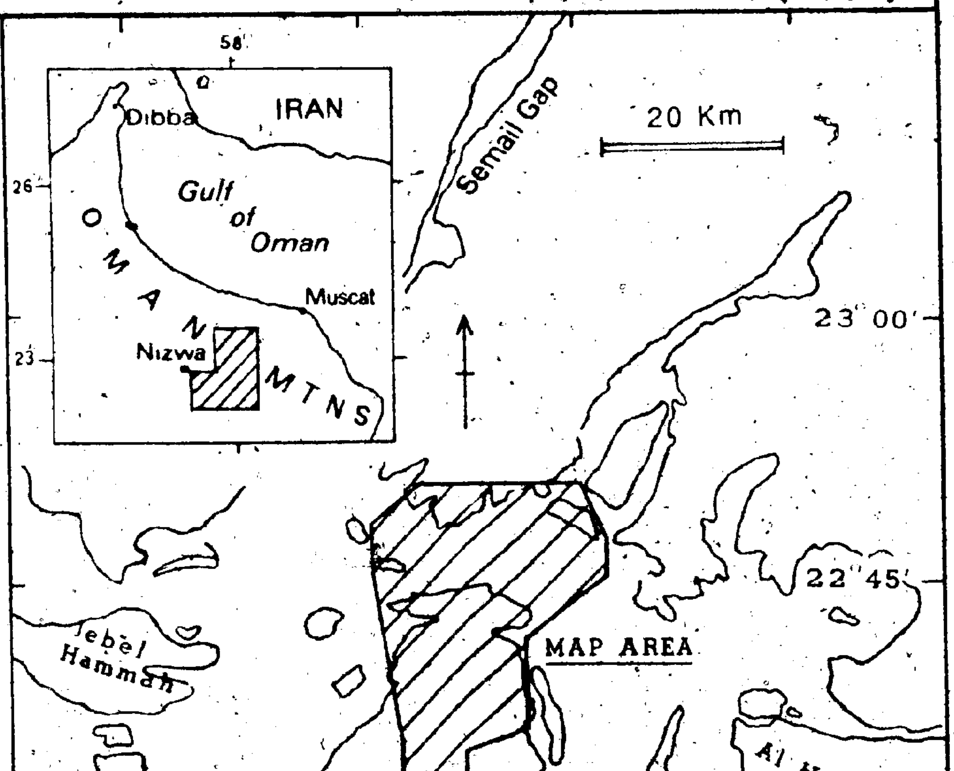


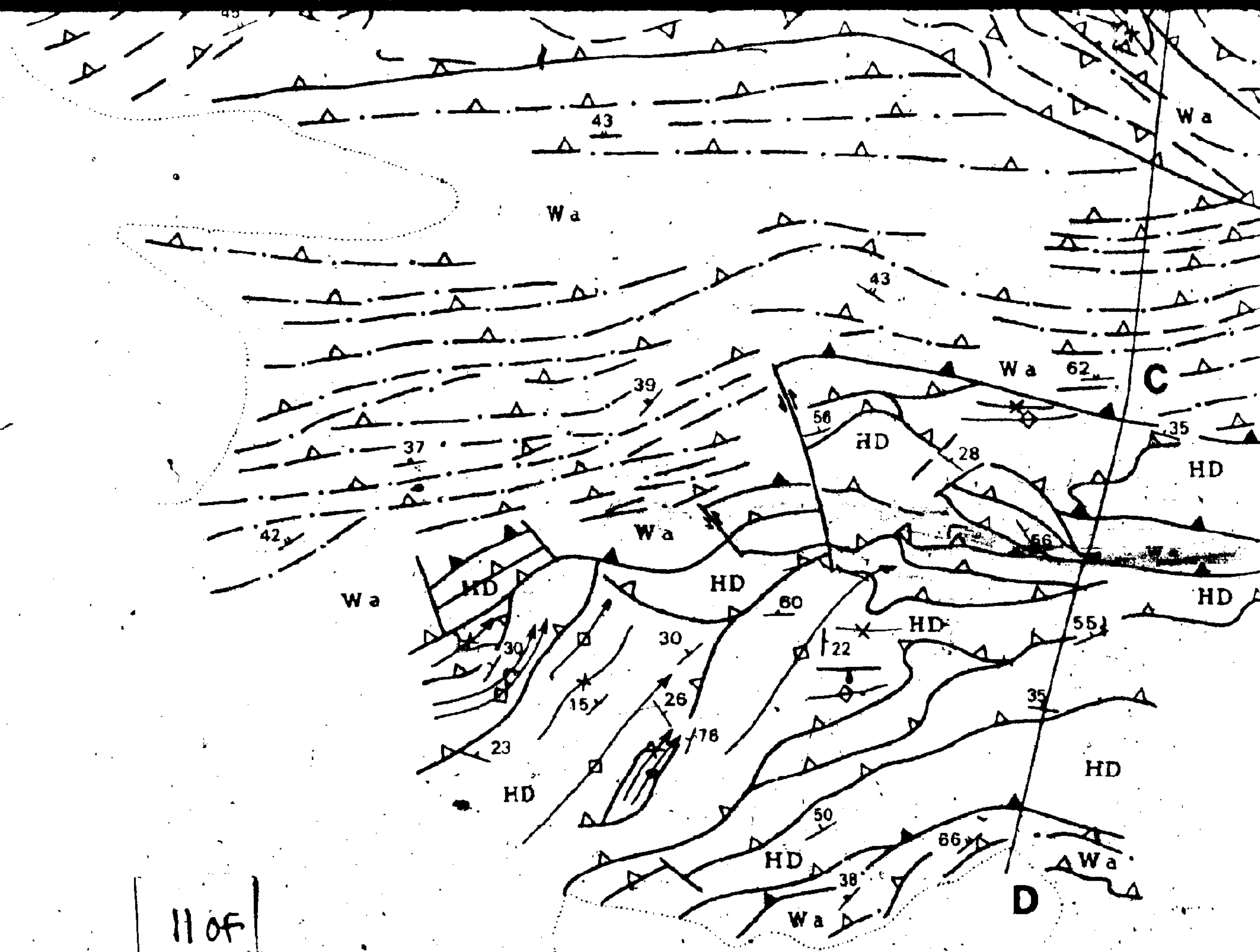


RAL TRANSECT
SUFRAT AD DAWH RANGE

P. D. Barrette, M.Sc. thesis (1985)

assumed
-stratigr...
ps known
rturned)
ps unknown
ult
t; solid circle
ned, assumed
ip unknown

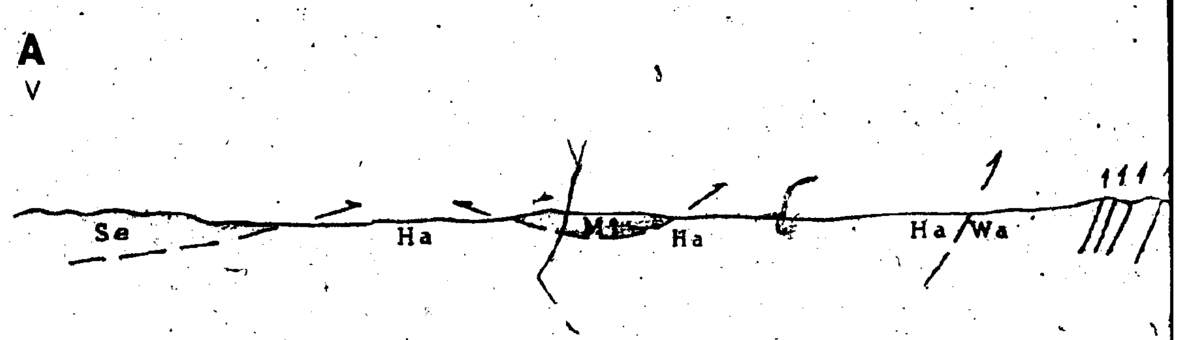


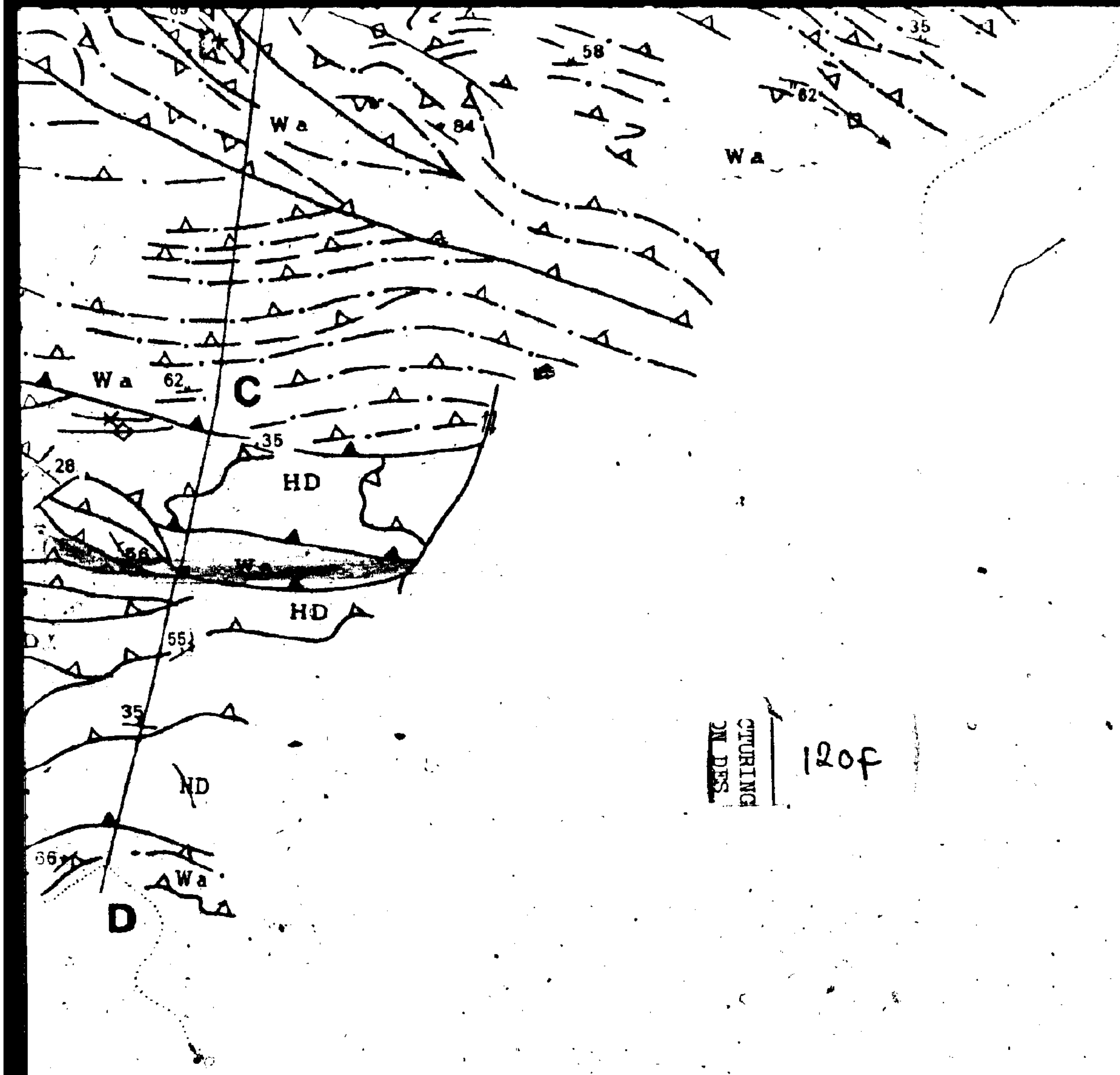


11 of

Structural Cross Section

(vertical = 2x horizontal)

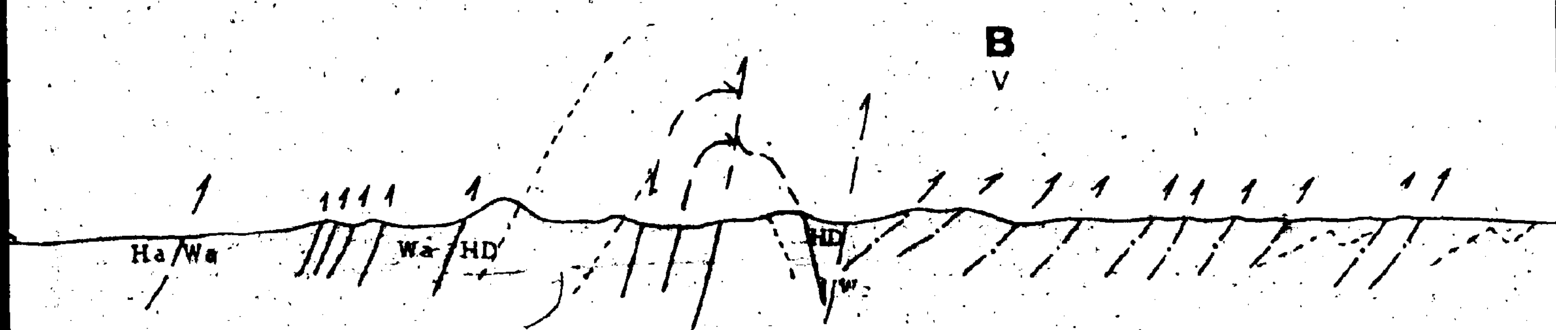




CTURING
ON DES

120f

horizontal)



(defined, assumed)

Synform with plunging direction (defined, assumed)

Overturned synform with plunging direction

Lithologies

Semail Ophiolite

Se — Undifferentiated mafic to ultramafic igneous rocks

Haybi Metamorphic Rocks

MH — Quartz Pelitic Schists

Hawasina Complex

Ha — Haliw Formation: mainly centimeter-bedded red radiolarian cherts, centimeter-to-decimeter bedded grey grainstones, white reefal lithoclasts, centimeter-bedded light coloured marlstones; fine grained mafic igneous rocks

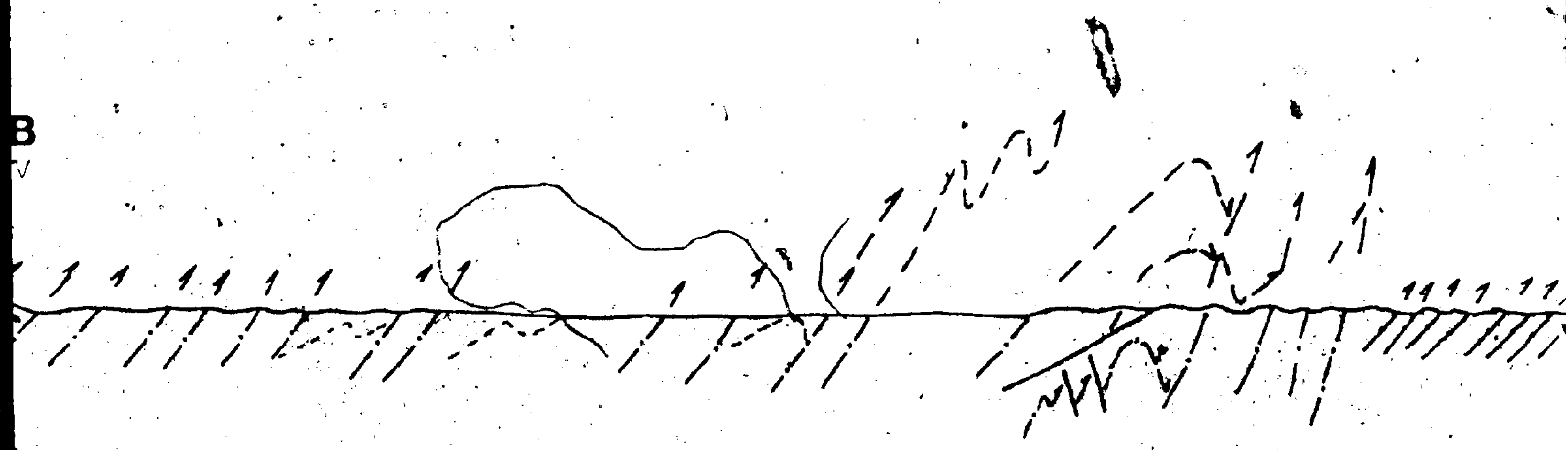
AA — Al Ayn Formation: decimeter bedded dark turbiditic quartz arenites, grey grainstones, locally intruded by fine- to coarse-grained mafic igneous rocks

Wa — Wahrah Formation: decimeter-to-meter bedded turbiditic grainstones, centimeter-bedded red radiolarian cherts and shales, light-colored centimeter-bedded marlstones

HD — Hamrat Duru Group: Divided into three formations, from bottom to top: Guweyza Fm: decimeter-to-meter bedded brown to light grey oolitic grainstones; Sid'r Fm: centimeter-to-decimeter bedded silicified rusty brown turbiditic grainst. and mudstones; Nayid Fm: centimeter-to-decimeter bedded yellow-grey turbiditic grainstones and mudstones

13 oF

B



direction

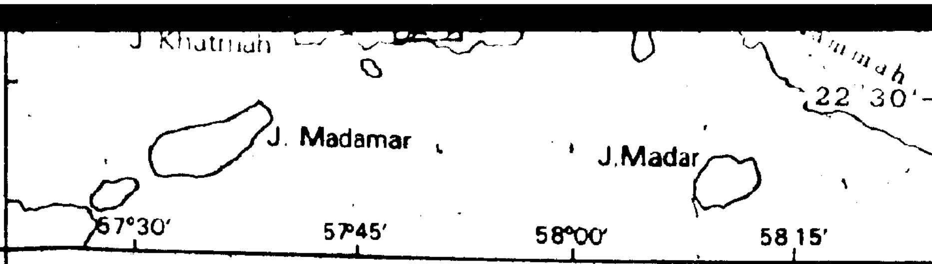
n plunging direction

ramafic igneous

meter-bedded red
er-to-decimeter
e reefal lithoclasts,
ored marlstones;
cks
bedded dark
rey grainstones,
coarse-grained

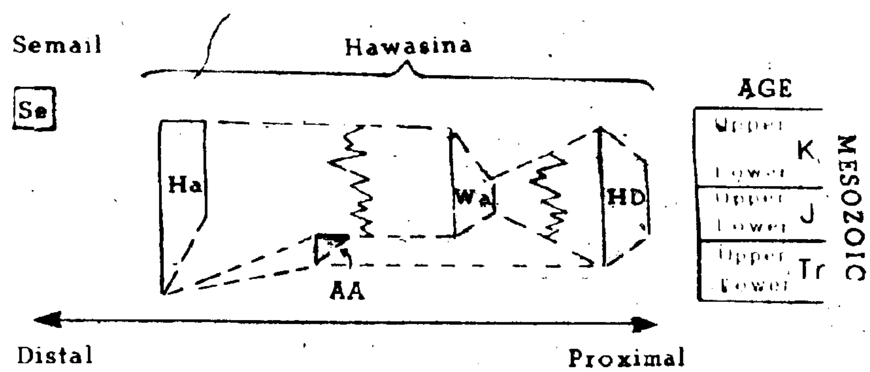
to-meter bedded
meter-bedded red
s, light-colored

to three formations,
Fm: decimeter-
grey oolitic
meter-to-decimeter
turbiditic grainst.
timeter-to-decimeter
grainstones and

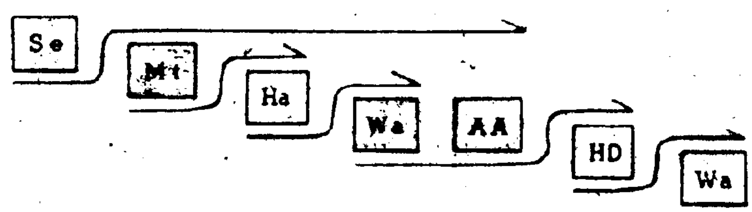


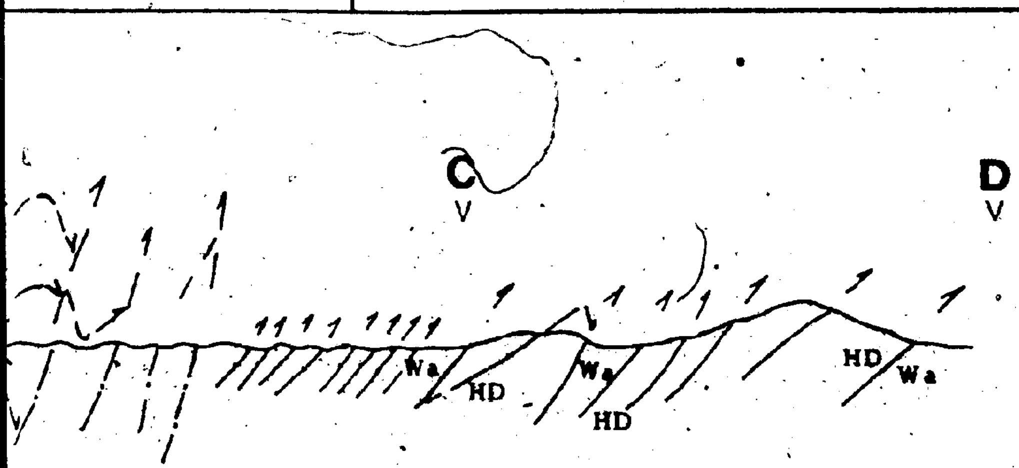
25 00

Palinspastic Reconstruction and Chronostratigraphy of the Hawasina and the Semail Nappes (after Glennie et al., 1974)



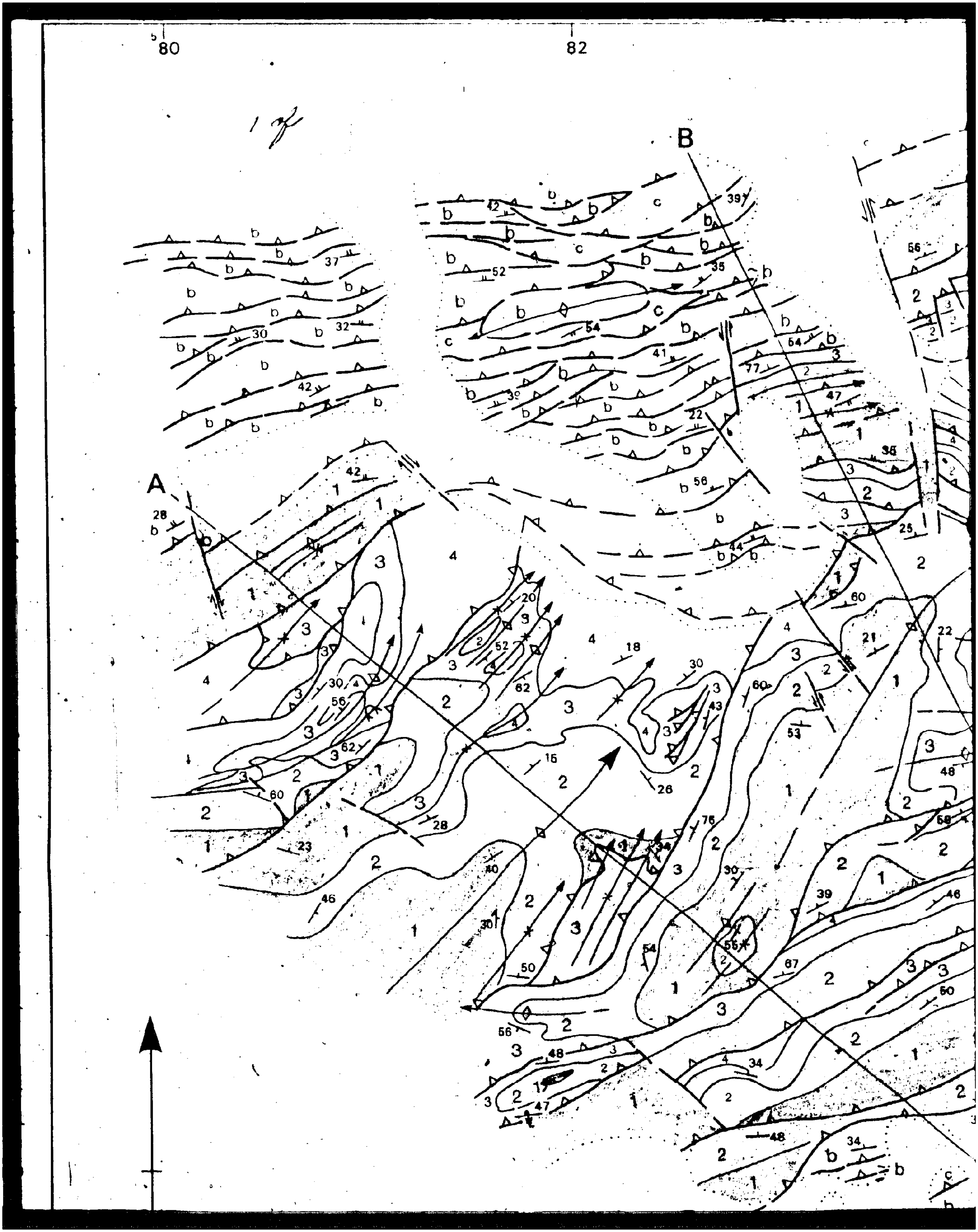
Tectonostratigraphy

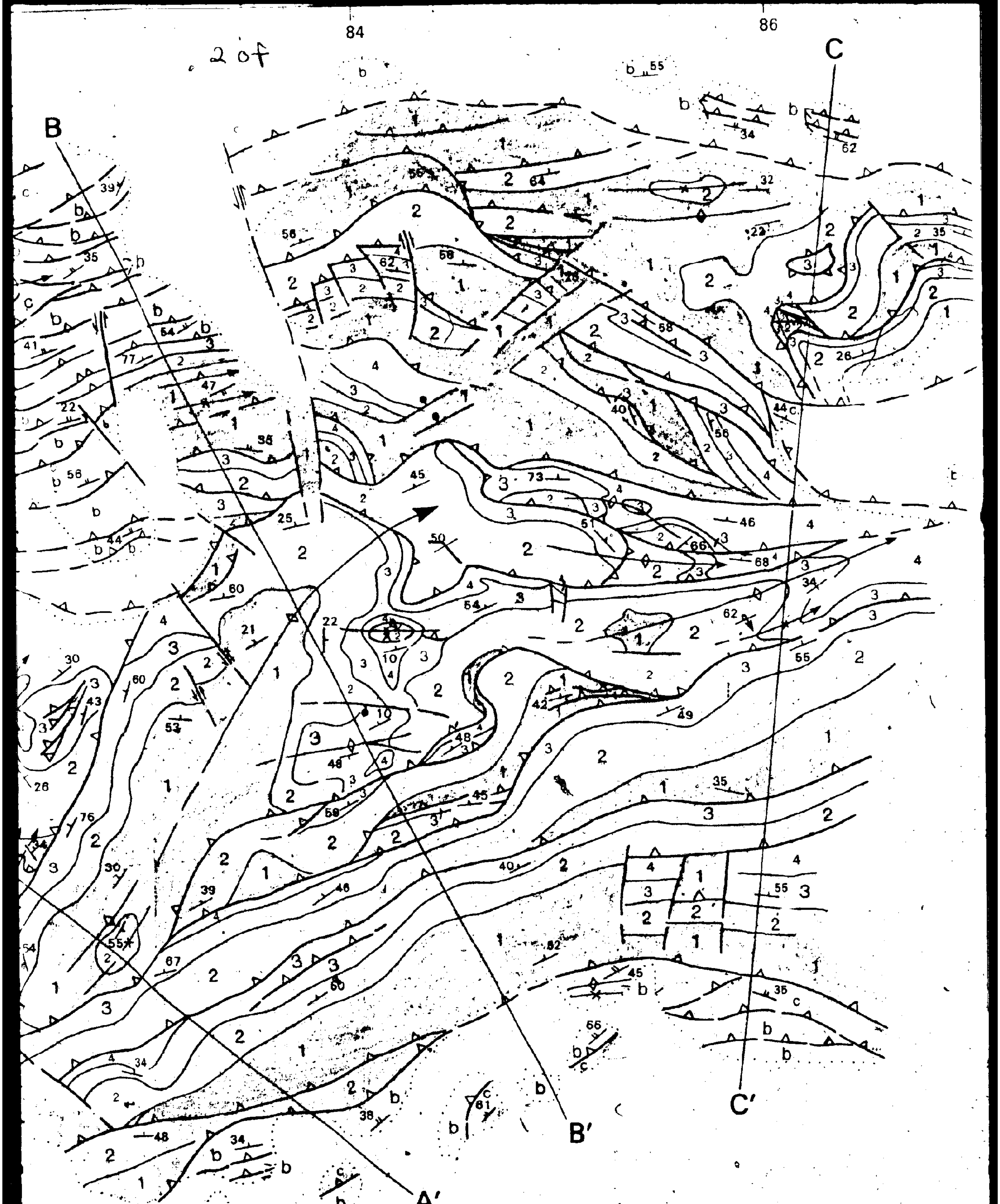


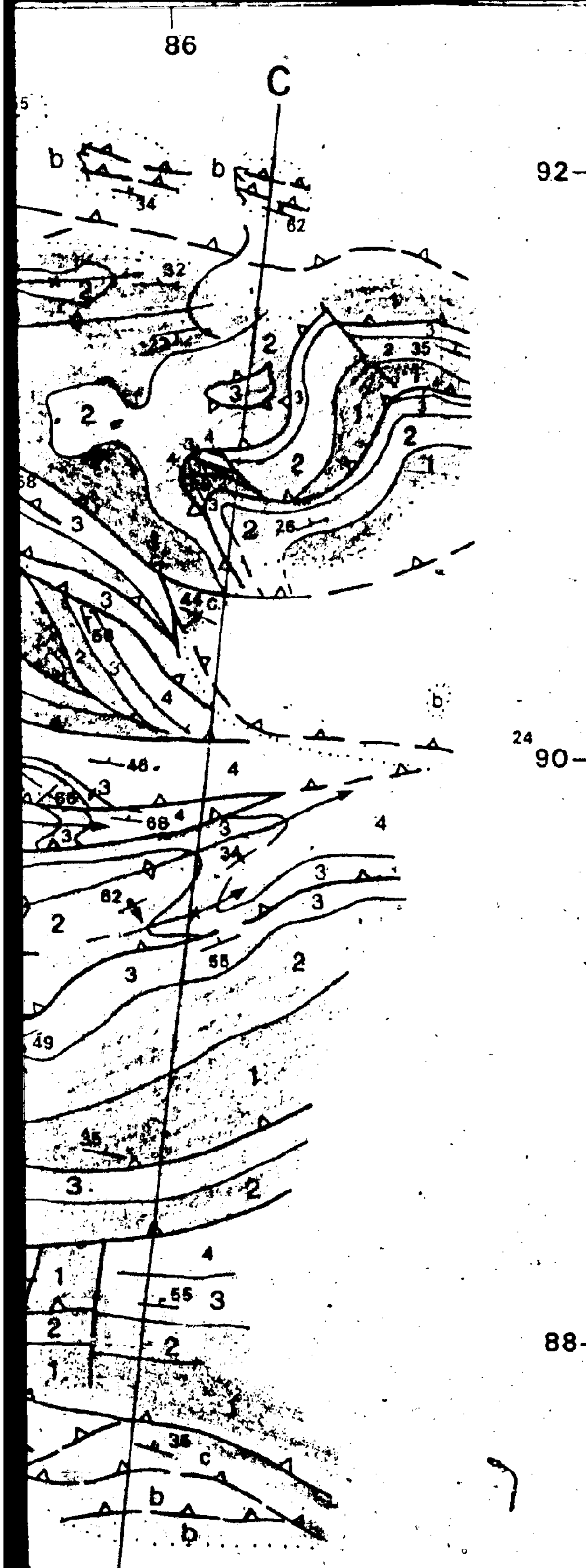


14 of 14

25 90

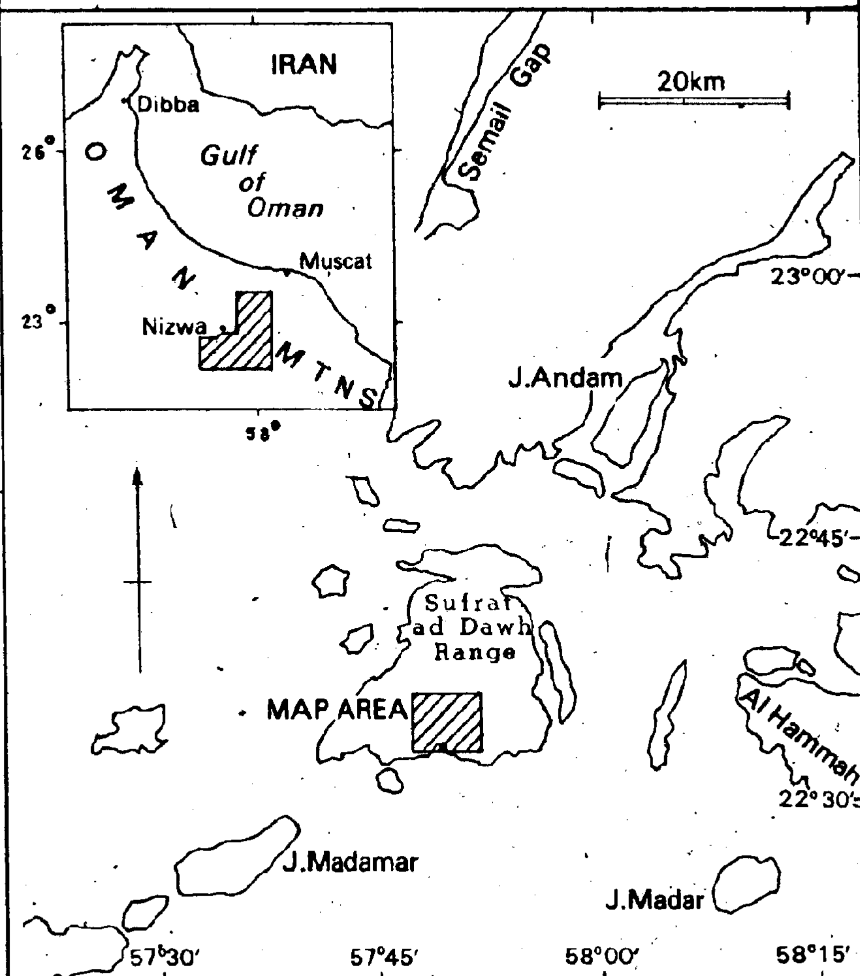

80
82
A
B


2 of
84
86
B
C
B′
C′
A′



3 of

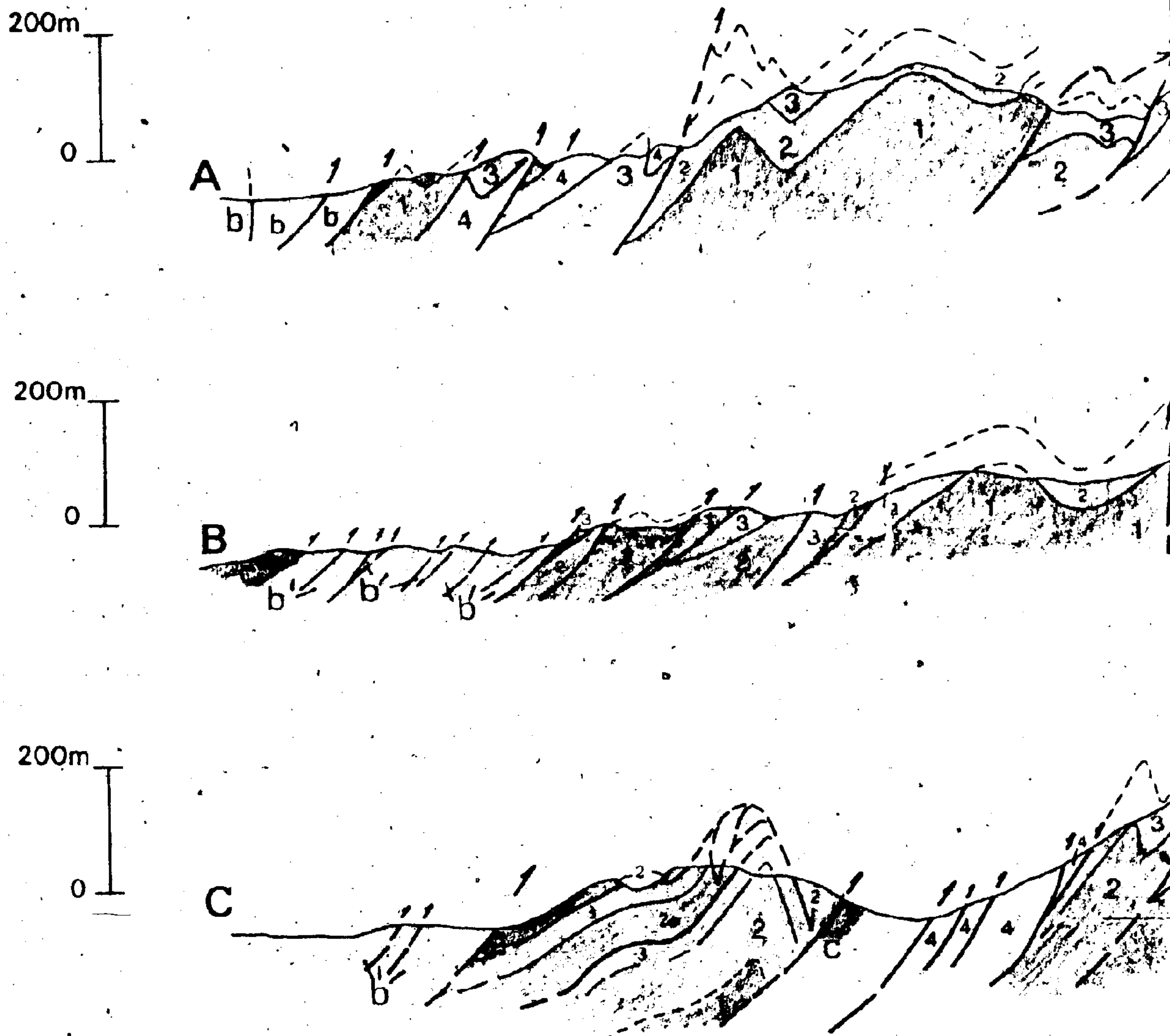
Inset B: Geology of the Central Southern Hamrat Duru Belt in the Sufrat ad Dawh Range



Symbols

- Limits of outcrop
- Geological boundary (defined, assumed)
- Bedding: stratigraphic tops known (inclined, overturned)
- Bedding: stratigraphic tops unknown
- Thrust fault: teeth in hanging wall (defined, assumed)
- High angle fault: predominantly strike slip (defined, assumed)
- High angle fault: predominantly dip slip with solid circle on downthrown side (defined, assumed)
- High angle fault: net slip unknown

Structural Cross Sectio

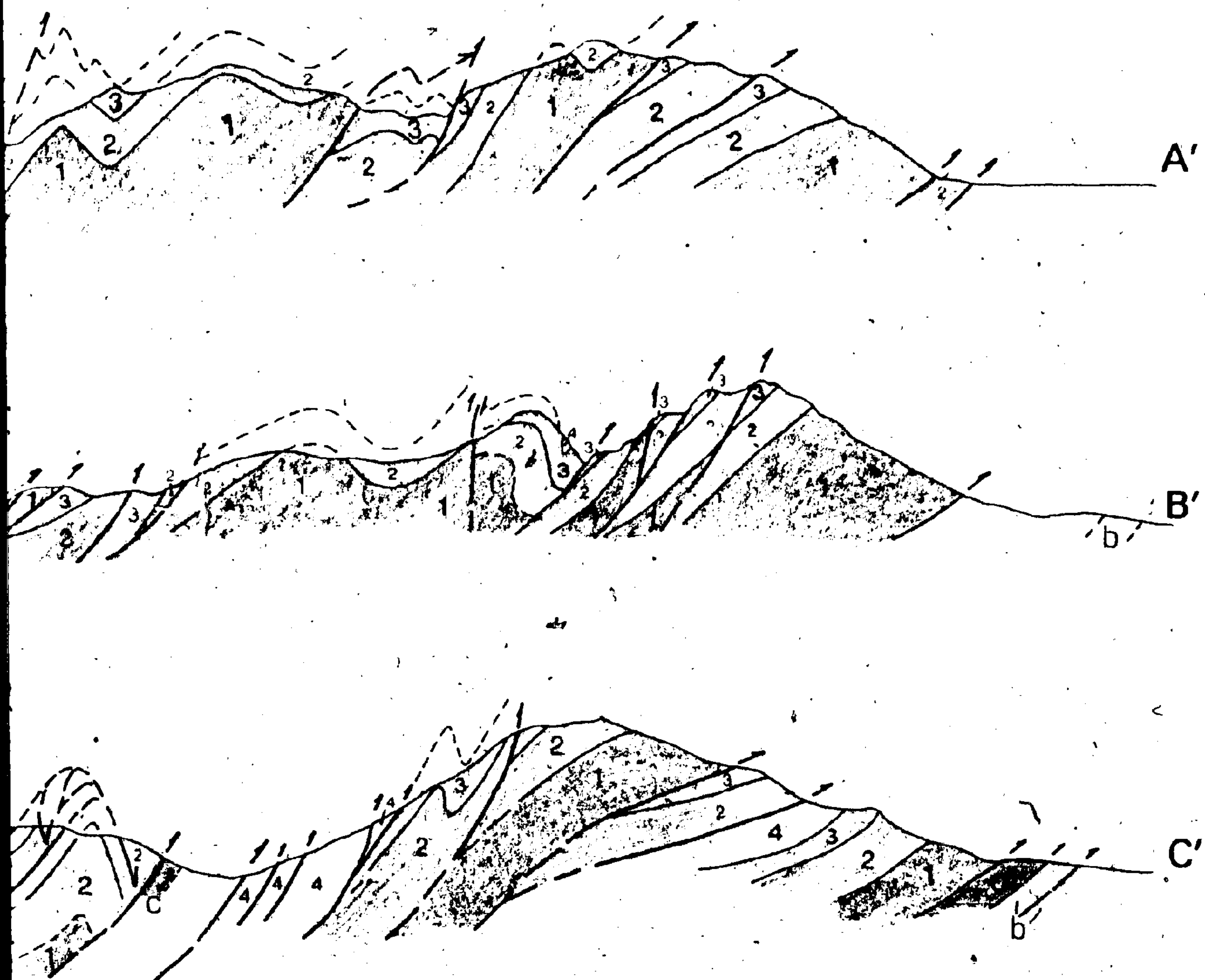


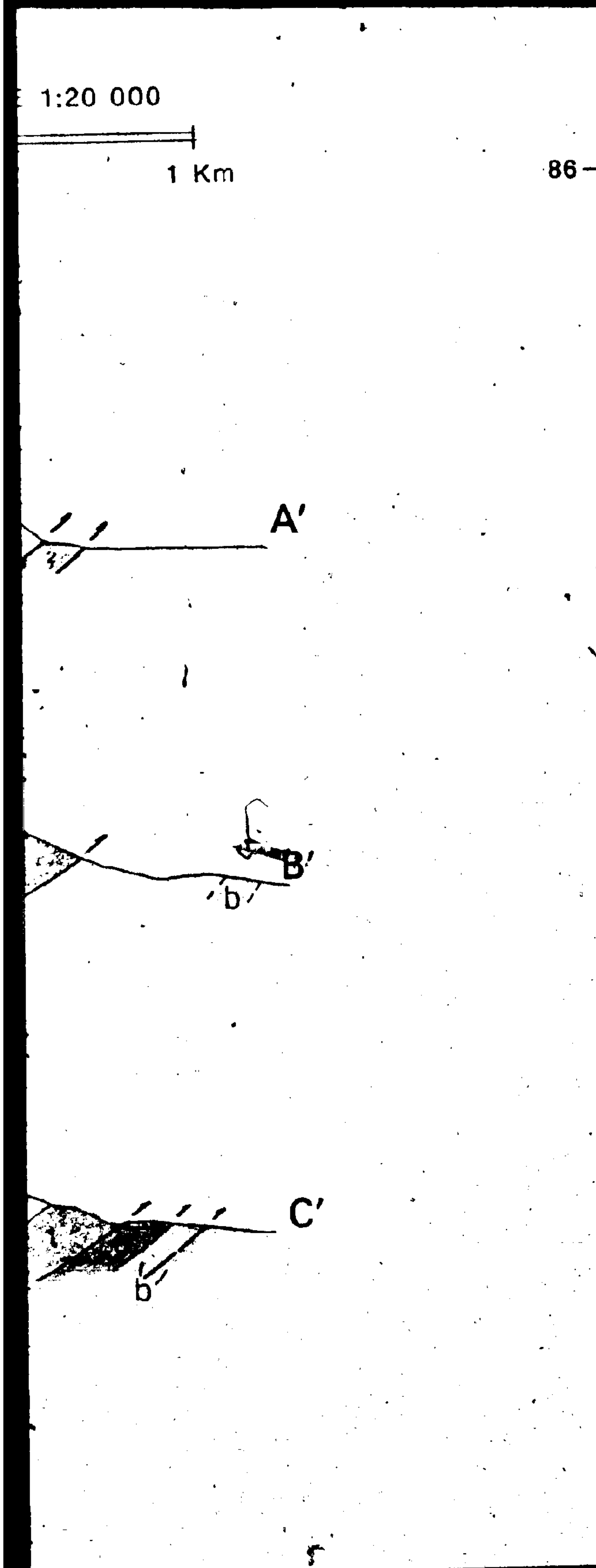
4 of

SCALE 1:20 000

0 1 Km

Structural Cross Sections





(defined, assumed)

Synform with plunge direction (defined, assumed)

Overturned synform with plunge direction

Lithologies

Hamrat Duru Group

4 Nayid Formation: centimeter-to-decimeter-bedded partly silicified yellow grey turbiditic grainstones and mudstones

3 Sid'r Formation: centimeter-to-decimeter-bedded largely silicified, rusty brown turbiditic grainstones and mudstones.

Guwayza Formation:

Limestone member: decimeter-to-meter bedded light grey oolitic grainstones

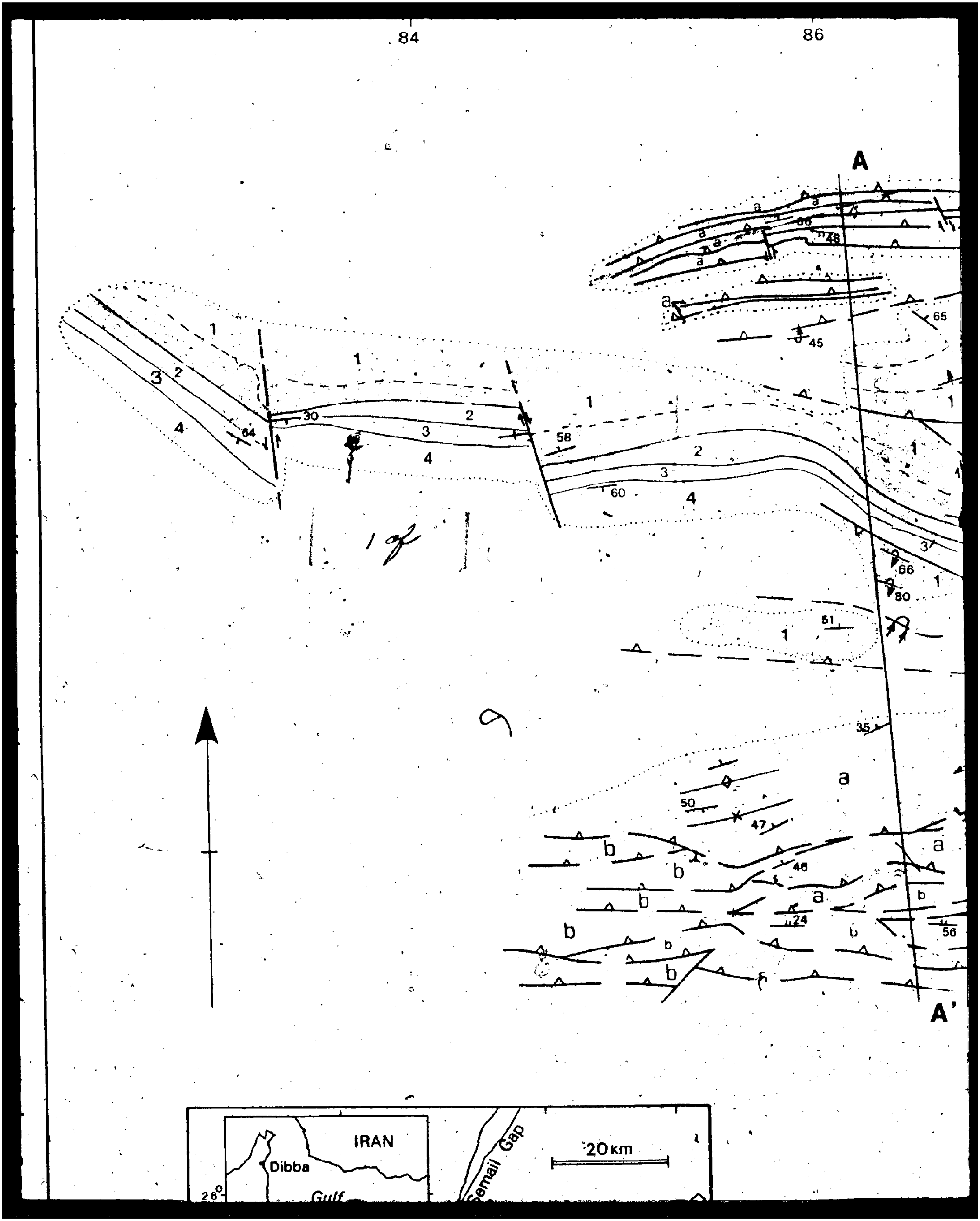
Sandstone Member: decimeter-to-meter bedded brown oolitic grainstones with variable amount ofdetrital quartz; minor intervals of light colored centimeter-bedded marlstones

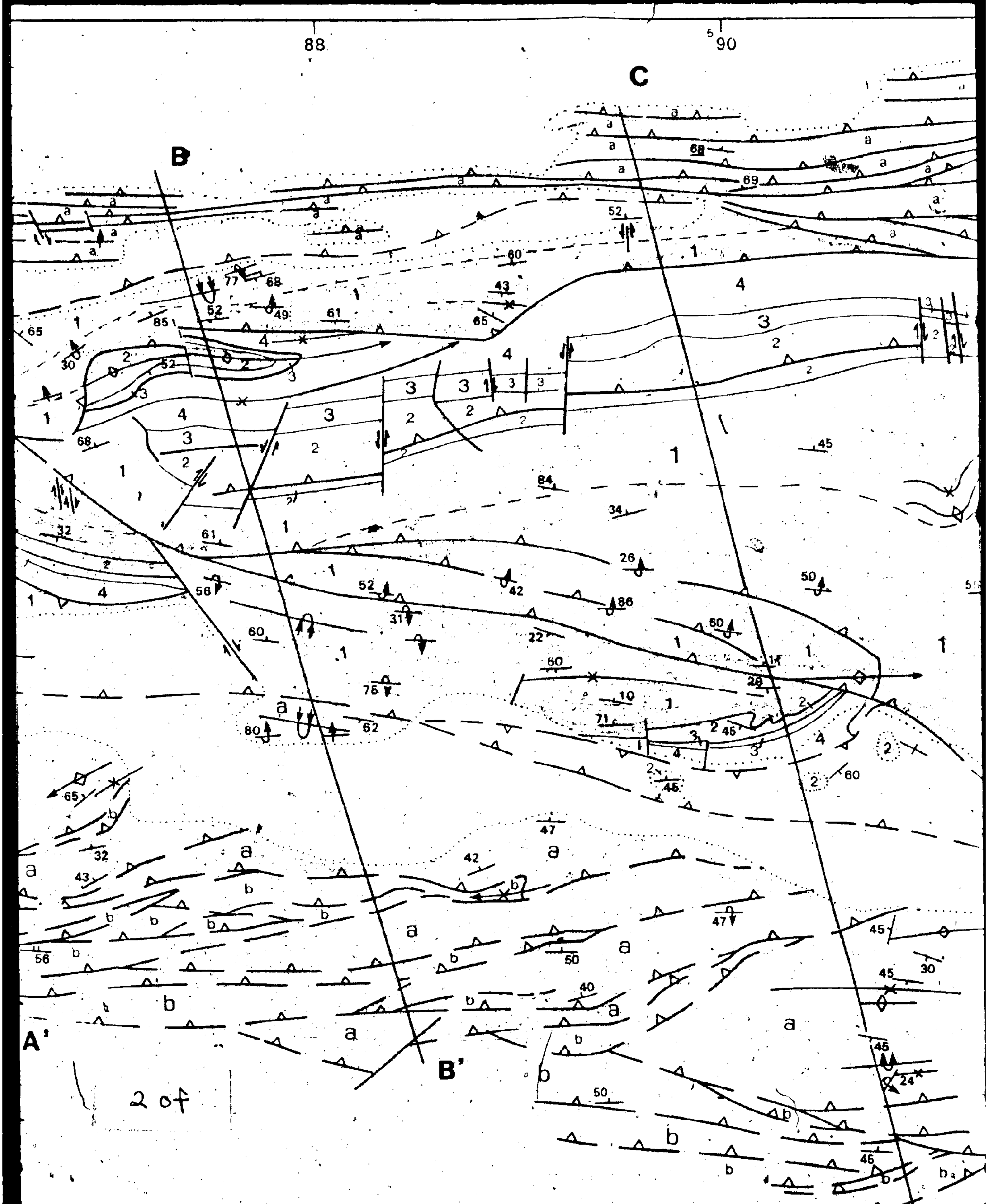
Wahrah Formation

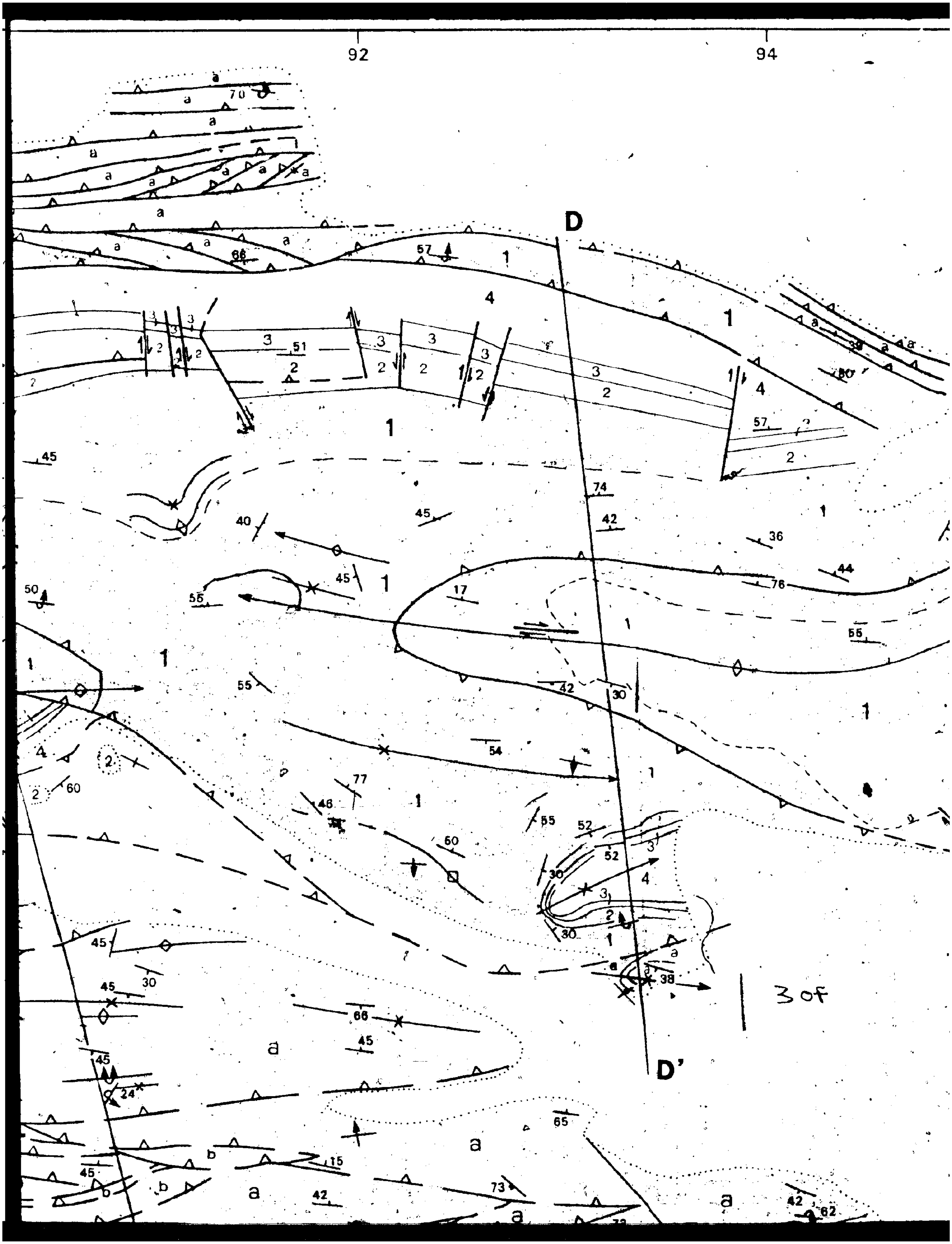
Upper limestone Member: centimeter-to-decimeter-bedded dark colcred turbiditic grainstones; minor marlstones

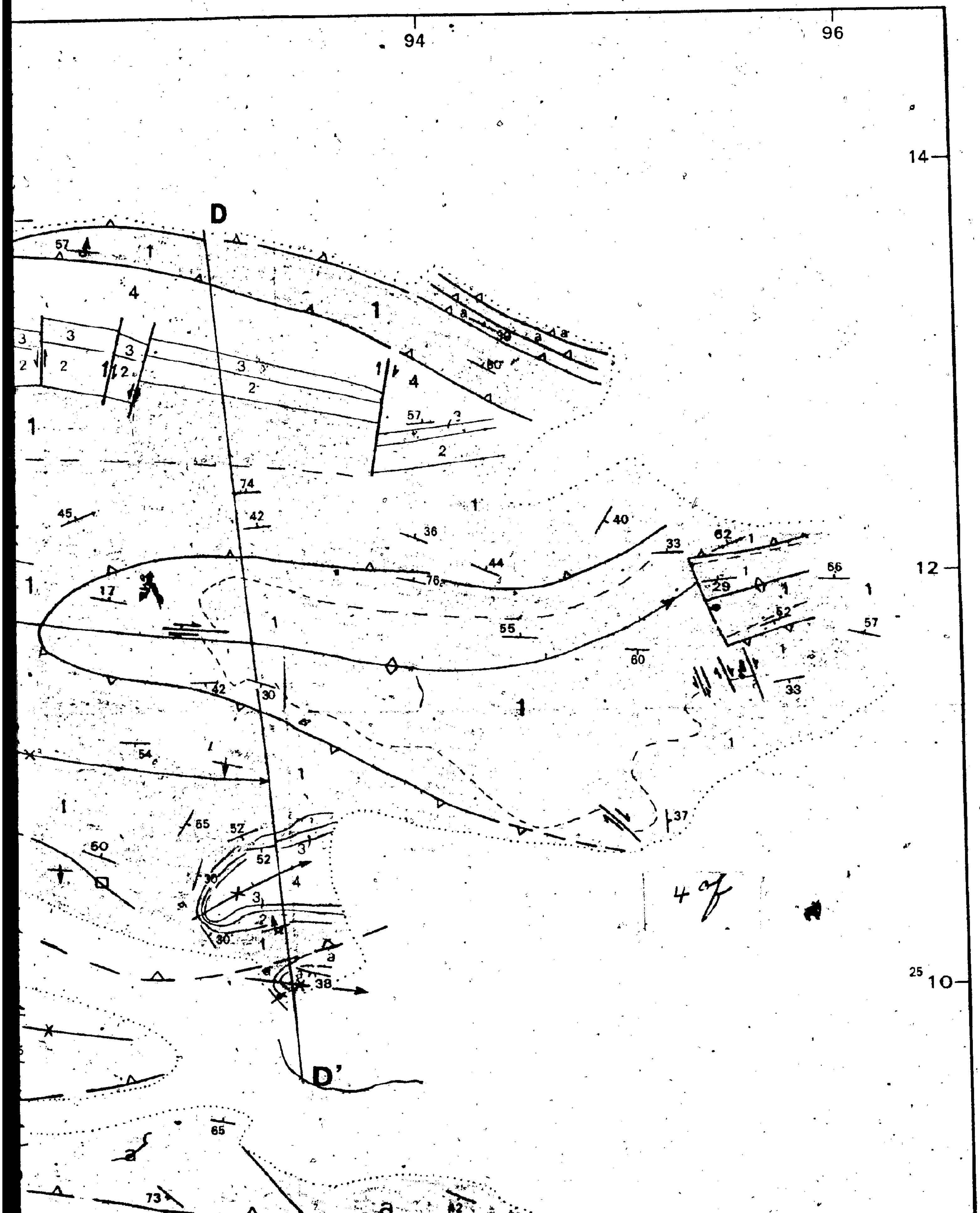
b Chert Member: centimeter-bedded red radiolarian chert; minor shaly intervals Undifferentiated from the Mudstone Member: centimeter-bedded light colored marlstones

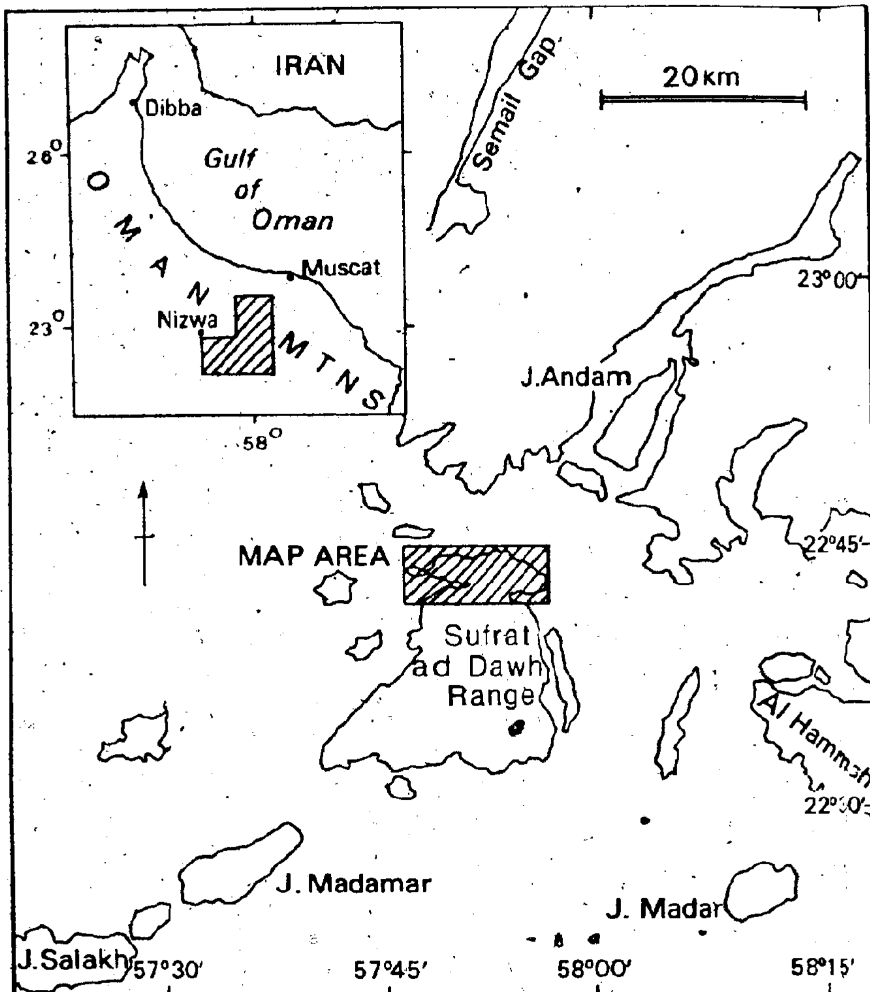
The coordinates on this map sheet represent the 1000 metre Universal Transverse Mercator Grid Zone 40.


84
86
A
A'
20 km
IRAN
Dibba
Gulf
Semail Gap
26°


88
90
C
B
B'
A'
2 of


92
94
D
D'
3 of


94
96
14
12
10
D
D'
4 af



0

The coordinate
the 1000 metre Univer

Inset A: Geolog
Northe
in the

Symbols 5 ✓

- Limits of outcrop
- Geological boundary (defined, assumed)
- Bedding: stratigraphical tops known (inclined, overturned, vertical)
- Bedding: stratigraphical tops unknown (inclined, vertical)
- Thrust fault: teeth in hanging wall (defined, assumed)
- Strike-slip fault (defined, assumed)
- Dip-slip fault: solid circle on downthrown side (defined, assumed)
- High-angle fault: net slip unknown (defined, assumed)
- Antiform with plunge direction (defined, assumed)
- Synform with plunge direction (defined, assumed)
- Overturned antiform or synform (defined, assumed)

L

Hamrat Duru Grou

4 — Nayid Format partly silifie and mudston

3 — Sid'r Formati largely silici grainstones a

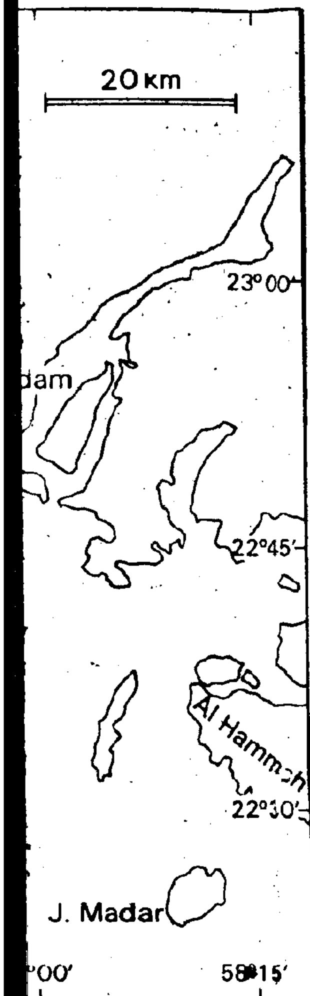
2 — Guwayza Form Limestone Me light grey oo and centimet

1 — Sandstone Me brown oolitic of detrital qu

Wahrah Formation

b — Chert and Mu centimeter-be shales, centir

a — Lower Limest light brown coloured mar



SCALE 1:20 000

0

6 of

The coordinates on this map sheet represent
the 1000 metre Universal Transverse Mercator Grid Zone 40.

Inset A: Geology of the Northern Hamrat Duru Belt in the Sufrat ad Dawh Range

Lithologies

Hamrat Duru Group

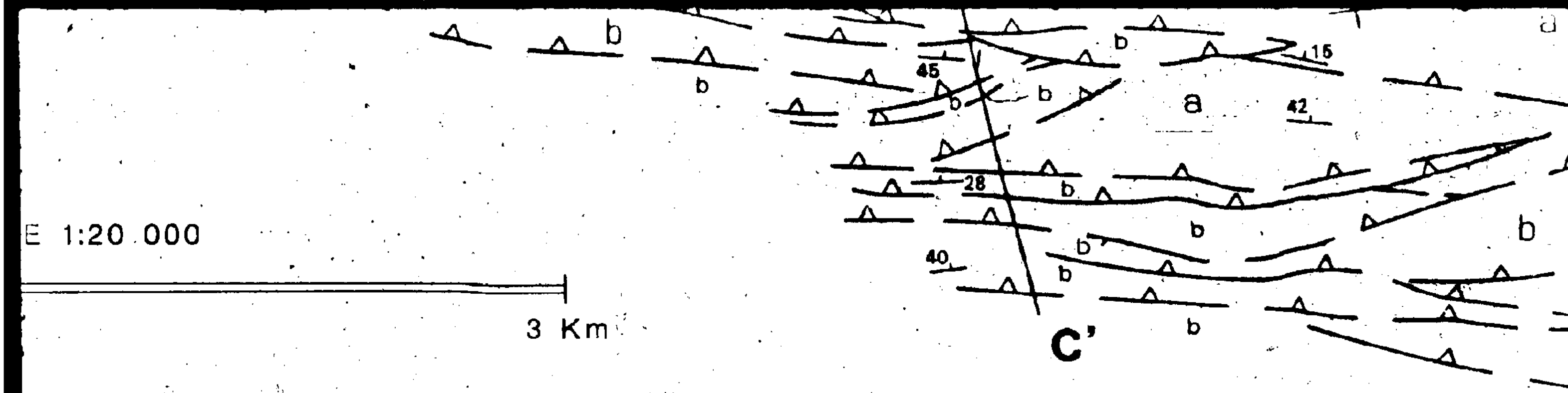
4	Nayid Formation: centimeter- to decimeter-bedded partly silified yellow-grey turbiditic grainstones and mudstones
3	Sid'r Formation: centimeter- to decimeter-bedded, largely silicified, rusty brown turbiditic grainstones and mudstones
	Guwayza Formation:
2	Limestone Member: decimeter- to meter-bedded light grey oolitic grainstones, and centimeter-bedded yellow marlstones
1	Sandstone Member: decimeter- to meter-bedded brown oolitic grainstones with variable amount of detrital quartz

Wahrah Formation

b	Chert and Mudstone Members (Undifferentiated): centimeter-bedded red radiolarian chert and shales, centimeter-bedded light-coloured marlstones
a	Lower Limestone Member: decimeter- meter-bedded light brown turbiditic grainstones and light coloured marlstones

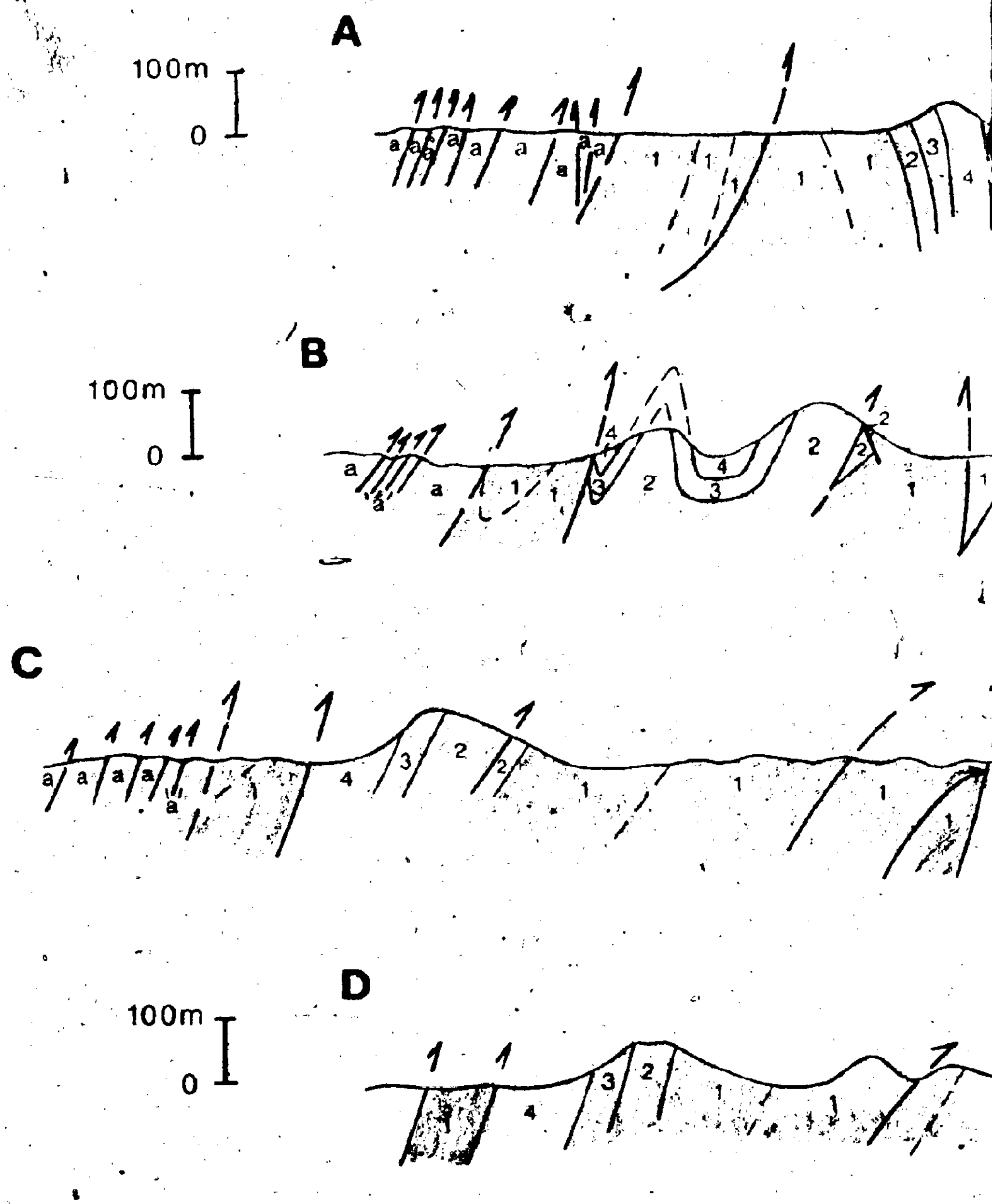
ry
d)
hical tops known
rned, vertical)
phical tops
d, vertical)
in hanging wall
d)
efined, assumed)
d circle on
(defined, assumed)
et slip
, assumed)
nge direction
d)
ge direction
d)
rm or synform
d)

100m
0



Structural

40.



Belt
Range

eter-bedded
rainstones

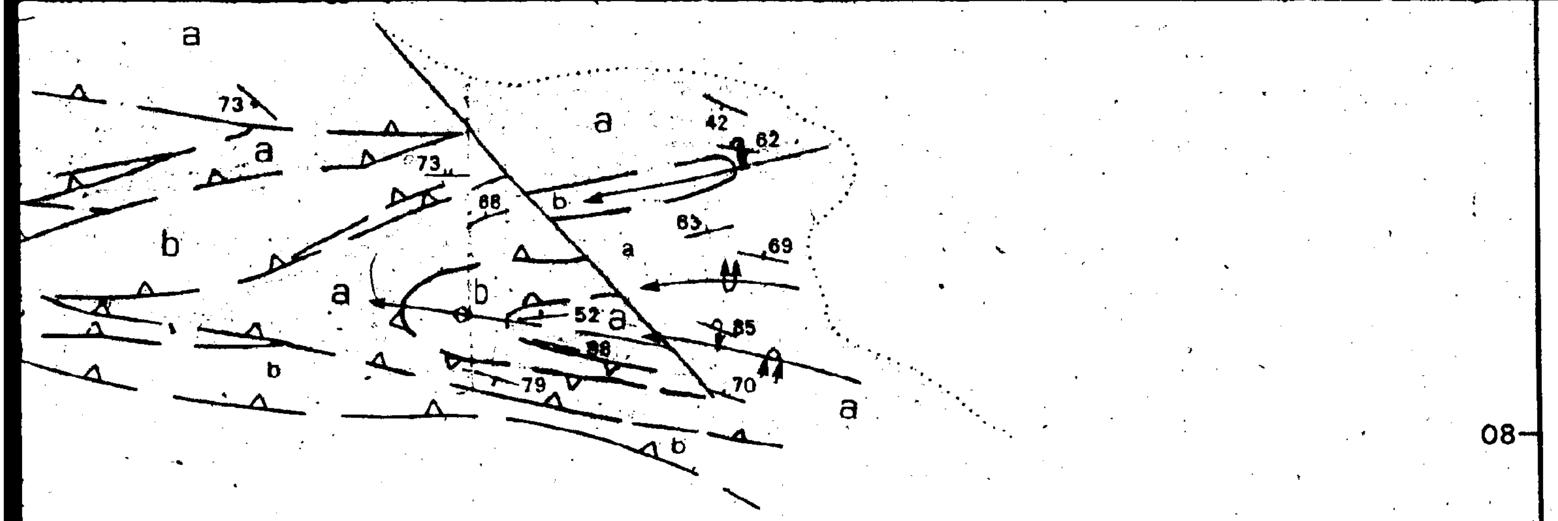
ter-bedded ,
tic

r-bedded

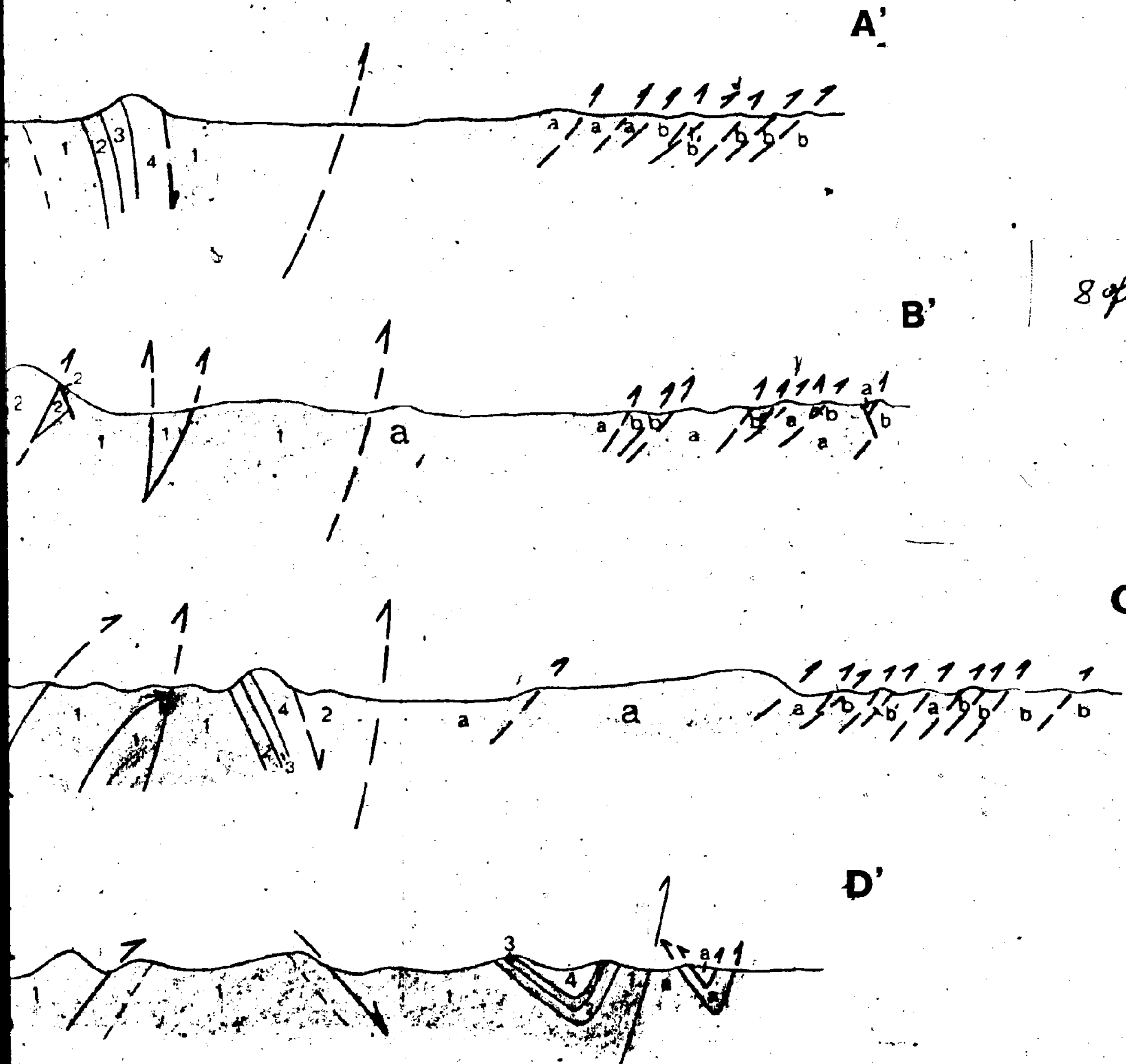
nes
r-bedded
e amount

rentiated):
rt and
ed marlstones

eter-bedded
light



ructural Cross-Sections



8 of 8